A Review on Potential Plant-Based Water Stress Indicators for Vegetable Crops

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Abstract: Area under vegetable cultivation is expanding in arid and semi-arid regions of the world to meet the nutritional requirements of an ever-growing population. However, water scarcity in these areas is limiting vegetable productivity. New water-conserving irrigation management practices are being implemented in these areas. Under these irrigation management practices, crops are frequently exposed to some extent of water stress. Vegetables are highly sensitive to water stress. For the successful implementation of new irrigation practices in vegetable crops, it is of immense importance to determine the threshold water deficit level which will not have a detrimental effect on plant growth and yield. Along with this, plant response and adaptation mechanisms to new irrigation practices need to be understood for the successful implementation of new irrigation practices. To understand this, water stress indicators that are highly responsive to water stress; and that can help in early detection of water stress need to be identified for vegetable crops. Plant-based water stress indicators are quite effective in determining the water stress level in plants because they take into account the cumulative effect of water stress due to declining soil moisture status and increased evaporative demand of the atmosphere while determining the water stress level in plant. Water stress quantification using plant-based approaches involves direct measurements of several aspects of plant water status and indirect measurements of plant processes which are highly sensitive to water deficit. In this article, a number of plant-based water stress indicators were critically reviewed for (1) their efficacy to determine the level of water stress, (2) their potential to predict the yield of a crop as affected by different water-deficit levels and (3) their suitability for irrigation scheduling in vegetable crops.

Keywords: water stress indicator; deficit irrigation; vegetables; plant-based approaches; threshold water stress

1. Introduction

Irrigated crop production is important for global food security because it contributes around 40% to the total food supply for the entire world [1]. Irrigated agriculture covers only 20% of total arable land, however, it consumes more than two-thirds of the total available freshwater [2]. The world population is growing at an alarming rate, and the demand for good quality, non-saline water is increasing [3]. Additionally, climate change is also putting high pressure on the hydrological cycle [4]. Considerable warm weather in recent years may augment the likelihood and severity of drought, possibly due to decreased precipitation and increased evapotranspiration in some areas of the world [5]. The groundwater level is declining rapidly in these areas. For instance, the Ogallala aquifer which is a primary source of supplemental irrigation in the high plains of United States has faced an overall decline in water level by 4.8 m for the entire aquifer, and by 12 m for the West Texas part since 1950s [6]. The problem of an increasing water scarcity is posing a challenge to food production especially in arid...
and semi-arid areas [7]. Therefore, there is a need to adopt the water-conserving strategies that have the potential to enhance water productivity in water-limited areas [8].

Deficit irrigation (DI) and irrigation scheduling are the important irrigation management practices, which are becoming popular to conserve water and sustain crop production in water deficit regions. Under DI, a lower amount of irrigation water than the full crop water requirement is applied at various crop growth stages or sometimes throughout the whole growing season [9]. Therefore, under DI, plants are subjected to a certain degree of water stress. However, plants can tolerate water stress only up to a certain limit (threshold level) and beyond that limit, there is a severe decline in yield [10–12]. Hence, it is crucial to determine the threshold level of water deficit to which plants can be exposed without causing a significant decrease in plant growth and yield. This threshold can only be determined by having a deeper understanding of plant response to water stress [13]. On the other hand, irrigation scheduling is a decision-making process to decide about when to irrigate and how much to irrigate a particular crop [14]. For effective and efficient irrigation scheduling, it is of immense importance that irrigation should be initiated before the water stress in plants reaches to a detrimental level. Hence, there is a need to determine the threshold values of water stress at which irrigation can be initiated.

There are various approaches available to detect the water stress, and to determine the threshold level of deficit irrigation and water stress for irrigation scheduling. These approaches range from several conventional water-balance and soil moisture-based methods to those based on measuring plant response to water stress. Out of these, plant-based approaches have an advantage because they can measure the plant response to cumulative effect of soil moisture status, water uptake capacity of the plant–root interface, internal hydraulic conductivity and evaporative demand [15]. Generally, plants exposed to water stress have lower evapotranspiration which further leads to the development of certain water stress symptoms such as leaf wilting, reduced leaf area, decrease in stem diameter growth and stunted plant growth [16] and changes in physiological and biochemical processes such as stomatal conductance, leaf water status, photosynthesis, sap flow, leaf temperature, hormonal balance, osmotic adjustments. Therefore, water stress quantification from plant-based approaches involves direct measurement of several aspects of plant water status and indirect measurements of plant processes which are highly sensitive to water deficit.

Several plant-based approaches are available to detect and quantify the water stress in plants. However, from all the available choices the one to be used depends on the relative sensitivity of that approach to water stress [15]. A reliable water stress indicator is the one that can be used to precisely determine the level of water stress in the plant so that yield of the crop can be predicted precisely from the determined water stress level. In other words, a particular water stress indicator can be considered as reliable one, when a change in the value of that indicator is consistent with the corresponding change in the yield of a crop as affected by different water deficit levels. In this way, threshold value of a reliable water stress indicator can be used to determine the threshold level of deficit irrigation for a particular crop species. This threshold level of deficit irrigation can be implemented successfully for sustainable crop production without causing significant decrease in plant growth and yield while saving a considerable amount of irrigation water. Similarly, for effective and efficient irrigation scheduling, threshold value of a reliable water stress indicator can be used to start the irrigation before the plants get exposed to detrimental level of water stress.

Vegetables are crucial for balanced diets since they are a good source of minerals, vitamins, phytochemicals and dietary fibers [17]. Therefore, the global demand for vegetables is rising to meet the food and nutritional requirements of an ever-increasing population. Over the years, the area under vegetable cultivation has expanded, specifically in the arid and semi-arid areas where droughts are quite frequent [18]. Moreover, in these areas, water conserving irrigation management practices are being implemented, which also lead to development of some degree of water stress in crops. However, compared to agronomic crops, vegetable crops are generally more sensitive to water stress mainly due to two reasons. First, most of the vegetables are shallow-rooted with an effective root zone up to 60 cm below the soil surface [19]. Second, vegetables are succulent and composed of 80–95% of
Moreover, vegetables are sold based on fresh weight and appearance. Hence, due to high susceptibility of vegetable crops to water stress, the implementation of water-conserving irrigation management practices in vegetable crops may significantly decrease their yield and quality especially in drought-prone arid and semi-arid regions. Hence, understanding the response and adaptability of vegetable crops to water stress conditions is of utmost importance for implementation of water conserving irrigation practices and for sustainable vegetable production in water-limited areas. Therefore, in this study, a number of plant-based approaches have been critically evaluated for their potential to (1) detect and measure the water stress, (2) predict the yield as affected by different water stress conditions and (3) schedule irrigation in vegetables.

2. Plant-Based Water Stress Indicators

2.1. Leaf Water Potential

Plant water status is the key factor affecting the yield and quality of horticultural crops. It is crucial to maintain the optimum plant water status. If the plant water status declines beyond a certain limit (threshold level), there is a severe decline in yield and quality of vegetable crops. Hence, there is a need to determine the threshold plant water status. A number of methods have been adopted for the measurement of plant water status over the years. Nowadays, water potential is increasingly being used as a method to measure plant water status. Water potential is the main driving force to transport water from roots to the leaves. Water moves in response to water potential gradient from higher potential towards lower potential. Water potential is in decreasing order for the soil, roots, stem, leaves and atmosphere, respectively. In response to this decreasing order of water potential, water flows through the transpiration stream from roots to leaves and then subsequently lost to atmosphere. Though water potential can be measured at several points in plants, the development of pressure chamber has made the measurement of leaf water potential (LWP) quite easy. The LWP is a good determinant of leaf water status. The more negative (lower) value of LWP of a plant indicates a more dehydrated leaf (water stressed).

Different crops respond differently to progressively declining soil water content. Most plants exert some degree of autonomous control on their shoot or leaf water status, in order to maintain constant shoot water status even under declining soil moisture conditions or increased evaporative demands conditions. For short term response, plants respond to water stress by changing leaf angle, stomatal conductance and hydraulic conductivity of plant while for the long-term response, plants maintain relatively constant shoot water status by changing leaf expansion and root extension rate. Dry soil conditions and consequently, declining soil and root water potentials generate chemical (abscisic acid (ABA)) and/or hydraulic signals that are transmitted to the leaves through xylem pathways. In some crop species, receptors are present in and nearby the stomatal guard cells, which respond to the chemical and hydraulic signals. In response to chemical and/or hydraulic signals, receptors induce the closing of stomata so that LWP can be maintained to some extent, even under declining soil water potential conditions. These plants close stomata to reduce the water loss to atmosphere up to a certain limit so as to prevent the occurring of a detrimental water deficit inside the plant. These plants maintain relatively constant LWP during the day and periods of minor to moderate water stress, independent of soil water potential. Such crops are referred as isohydric crops. In these crops, LWP is maintained due to the regulation of stomatal conductance by water potential through an interaction with xylem ABA. Even though LWP has a regulating effect on stomatal conductance, still there is no statistical relationship between LWP and stomatal conductance in these crops. However, Jones reported that stomatal conductance is sensitive to decreasing soil water potential and can give a precise measurement of water stress developed due to declining soil water potential. In these crops, there is no good association between the soil water potential and LWP, rendering LWP as an imperfect tool for irrigation scheduling. While in other crop species, initially receptors and guard cells do not respond to chemical and/or hydraulic signals and hence there is no
control over the stomatal conductance [31]. In such crops, LWP starts declining in response to declining soil and root water potential until it reaches a threshold value after which stomata will start closing to prevent the water loss (ABA receptors will initiate the stomatal closure) [30]. As LWP decreases, ABA receptors become more sensitive, but LWP has no regulatory effect on stomatal conductance [32]. Such crops are referred as anisohydric crops. In these crops, LWP has a good association with the soil water potential. In anisohydric crops, stomatal conductance cannot be used accurately for irrigation scheduling as it cannot sense the initial decline in soil water potential [27]. Hence, the sensitivity of LWP to declining soil moisture availability varies among the crop species (isohydric or anisohydric) and its use for irrigation scheduling could be challenging in all crops. It can be used only for crops in which LWP changes in correspondence to change in soil moisture status (anisohydric crop species). For this, there is a need to categorize the crops as isohydric or anisohydric on basis of the association of LWP with soil water potential. In this way, for crops categorized as anisohydric, LWP can be successfully used for irrigation scheduling.

In Table 1, a number of studies that demonstrate the effect of water stress on LWP in various vegetable crops are summarized. Comparing studies on deficit irrigation by Pazzagli, et al. [33] on tomato (*Solanum lycopersicum*), Kochler, et al. [34] on cauliflower (*Brassica oleracea* var. botrytis) and Liu, et al. [12] on potato (*Solanum tuberosum*), it can be interpreted that sensitivity of LWP to water stress varies among different crop species. For instance, there was no significant difference in LWP for cauliflower and potato between FI (full irrigation = water applied to meet the full water requirement of crop) and DI-50 (DI = deficit irrigation, DI-50 = water applied equal to 50% of FI), while it was significantly lower for tomato even at DI-70 (DI = deficit irrigation, DI-70 = water applied equal to 70% of FI) compared to FI. However, potato yield declined significantly for DI-50 compared to control even though LWP was statistically similar between irrigation treatments. While in tomato, yield decreased significantly corresponding to a significant decrease in LWP. Based on above studies, LWP was consistent with yield results in case of tomato but not for potato. Based on the LWP results of these two studies, it can be said that cauliflower and potato are isohydric crops, they had maintained constant LWP while tomato is an anisohydric crop, its LWP declined along with a decline in stomatal conductance in response to declining soil water status. These differences in sensitivity of LWP to water stress can also be due to differences in environmental conditions at the locations of the studies. Based on LWP and stomatal conductance results of a study by Kochler, et al. [34] on cauliflower and by Zhang, et al. [35] on eggplant, it can be said that cauliflower and eggplant are anisohydric. In a study by Gallardo, et al. [36] on lettuce, it was found that stomatal conductance declined earlier than the decline in LWP under water stress conditions, suggesting that lettuce is an isohydric crop. In contradiction to these broad interpretations about isohydric and anisohydric behavior of crops, there is a report that concludes that different cultivars can sometimes exhibit different hydraulic behavior, making it difficult to categorize the crops as isohydric or anisohydric [37].
Table 1. Effect of water stress on leaf water potential and yield of various vegetable crops.

| Crop      | Irrigation Treatment | Leaf Water Potential (LWP)                                                                 | Yield                                                                 | References                  |
|-----------|----------------------|--------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|-----------------------------|
| Eggplant  | FI, DI-80, DI-60, DI-40 and DI-20. Ghor Al-Safi: No significant difference in LWP among FI, DI-80 and DI-60; and among DI-60, DI-40 and DI-20 while significant differences between (DI-80 and DI-60) and between (DI-60 and DI-40) | Ghor Al-Safi: No significant difference in yield between (FI and DI-80); and between (DI-40 and DI-20) while significant differences between (DI-80 and DI-60) and between (DI-60 and DI-40) | Mohawesh [11] |
| Potato    | FI, DI-50 and PRD-50 | LWP decreased significantly in PRD-50 and was similar between FI and DI-50. Sail-Al-Karak: No significant differences in LWP between (FI and DI-80); (DI-80 and DI-60); and (DI-40 and DI-20) while significant difference in LWP between DI-60 and DI-40 | Significantly higher yield in FI and was similar between DI-50 and PRD-50 | Liu, et al. [12] |
| Tomato    | FI, DI-70 and PRD-70 | Significantly higher LWP in FI than in DI; LWP was similar between DI and PRD. Total dry biomass decreased significantly in DI-70 and PRD-70 | – | Pazzagli, et al. [33] |
| Cauliflower | FI, DI-50 and DI-0 | LWP was similar between FI and DI-50 while it decreased in DI-0 compared to FI. | Yield decreased significantly in PRD-60 | Kochler, et al. [34] |
| Eggplant  | FI and PRD-60 | Significant decrease in LWP in PRD-60. LWP started decreasing after the withheld of irrigation and became significantly lower after 20 days of withheld of irrigation in the water-stressed treatment | Shoot biomass decreased significantly in the water-stressed treatment | Zhang, et al. [35] |
| Lettuce (Lactuca seriola L.) | FI and irrigation withheld for 20 days | LWP was similar between FI and DI-50 while it decreased in DI-0 compared to FI. Shoot biomass decreased significantly in the water-stressed treatment | – | Gallardo, et al. [36] |
| Tomato    | FI, DI-50 and PRD-50 | No significant differences in LWP among the irrigation treatments. | Significant differences in yield among the irrigation treatments | Zegbe-Dominguez, et al. [38] |
| Potato    | Well-watered (WW) and drought stress (DS) (irrigation withheld for 14 days and 9 days at tuber initiation and tuber bulking stage, respectively) | At tuber initiation and tuber bulking stage, LWP decreased significantly after 8 and 5 days of withholding of irrigation, respectively, in DS plants | – | Liu, et al. [39] |
| Pepper    | FI, DI-50 and PRD-50 | 92 days after sowing (DAS), LWP started decreasing in all treatment, but at harvest, it was significantly lower in DI-50 and PRD-50. | Significant differences in yield among irrigation treatments. FI > PRD-50 > DI-50 | Dorji, et al. [40] |
| Pepper    | FI, DI-75, DI-50 and PRD-50 | 92 DAS, LWP started decreasing in all the treatments and at 130 DAS, its values (MPa) were -0.9 in DI-75, -1.1 in PRD-50 and -0.71 in FI. | Significant differences in yield among irrigation treatments. FI > DI-75 > PRD-50 > DI-50 | Sezen, et al. [41] |

Note: FI: irrigation amount equal to total water requirement of the crop. DI: deficit irrigation, DI-75: irrigation amount equal to 75% of FI, DI-70: irrigation amount equal to 70% of FI, PRD: partial root-zone drying and PRD-50: irrigation amount equal to 50% of FI applied to one half of root zone.
In a study, conducted by Zhang, et al. [42] on tomato, it was found that LWP was low for high vapor pressure deficit (VPD) plants in comparison to low VPD plants, when plants of both treatments are subjected to same soil moisture level. In this case, reduction in LWP was due to increased evaporative demand, but not due to decreased soil moisture potential. In another survey study on Semillon vines (Vitis vinifera ‘Sémillon’) across seven vineyards, Rogiers, et al. [43] found that the midday LWP depends not only on soil moisture, but also on VPD at that particular time of LWP measurements. In such situation, it will be hard to differentiate whether the decline in LWP is in response to declining soil moisture or due to increased evaporative demand. This means LWP cannot differentiate between the cause of water stress (decline soil moisture or increased evaporative demand). Thus, it can lead to under or over irrigation of a crop. Hence, LWP cannot be used for irrigation scheduling under frequently fluctuating environmental conditions. The above discussion indicates that the sensitivity of LWP to water stress depends on crop species (isohydric or anisohydric) coupled with the cumulative effect of soil and atmospheric conditions. However, LWP can be quite suitable to measure the water stress in a crop (anisohydric) exposed to different water-deficit levels under relatively stable environmental conditions, while in isohydric crop species, stomatal conductance need to be measured along with LWP to get more precise measurements of water stress.

Since fruits are more robust sink for water than the vegetative parts [44], so, at fruiting stage, less amount of water is allocated to leaves, consequently, LWP decreases at fruiting stage, particularly in water-limited treatments. For instance, Dorji, et al. [40] noticed a considerable decline in LWP at the start of the fruiting stage (92 days after sowing (DAS)) in all irrigation treatments in hot pepper (Table 1). In DI-50 and PRD-50 (PRD = partial root-zone drying, PRD-50 means amount of water equal to 50% of FI is applied to one half of root zone), values of LWP were −0.72 and −0.50 MPa, respectively at 92 DAS and −1.1 and −0.9 MPa, respectively at 130 DAS. In another study by Liu, et al. [39] on potato, it has been found that LWP started declining 8 days after withholding of irrigation at tuber initiation (early reproductive stage) stage while it started declining after 5 days of withholding of irrigation at tuber bulking stage (late reproductive stage) (Table 1). From these studies, it can be inferred that LWP is comparatively more sensitive to water stress at fruiting stage than at vegetative stage of plant growth.

2.2. Relative Water Content

Another method to quantify leaf water status is by measuring relative water content (RWC) of the leaf. The RWC is a comparison of the water content of a leaf to the maximum possible water content of that leaf at its full turgor [13]. The RWC is highly associated with the cell turgor and cell turgor further controls the cell expansion [23]. Although turgor pressure is a key factor for cell expansion, some studies have shown a reduction in leaf growth even for turgid leaves [45,46]. In a study by Ismail, et al. [47] on pepper, leaf elongation rate started to decline after second day of withholding of irrigation, while the decline in leaf turgor was apparent only after 5 days of withholding irrigation. This indicates that cell expansion is not always associated with turgor. Cell expansion depends also on the other metabolic and physical processes such as nutrient and metabolite deposition, which affect the cell wall extensibility, water uptake; and cell wall yielding (extend irreversibly) [48–50].

Table 2 summarizes the effects of deficit irrigation or water stress on the RWC of leaf in different vegetable crops.
Table 2. Effect of water stress on relative water content (RWC) and yield of various vegetable crops.

| Crop           | Irrigation treatment | Relative water content (RWC)                                                                 | Yield                                                                 | References                      |
|---------------|----------------------|---------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|---------------------------------|
| Onion         | FI, DI-85, DI-70, DI-55, DI-40, DI-25 and DI-10 | RWC decreased with increased levels of water stress and it decreased in all treatments with maturity | Yield decreased with increased levels of water stress                 | Wakchaure, et al. [10]          |
| Eggplant      | FI, DI-80, DI-60, DI-40 and DI-20           | RWC decreased with increased water stress and no significant difference among (FI, DI-80 and DI-60); and among (DI-60, DI-40 and DI-20) | Significant differences in yield among all treatments except between (FI and DI-80); and between (DI-60 and DI-40) | Mohawesh [11]                   |
| Lettuce (Lactuca seriola L.) | FI and irrigation withheld for 20 days | RWC started decreasing after the withheld of irrigation and became significantly lower in water-stressed treatment after 20 days of withheld of irrigation | Shoot biomass decreased significantly in the water-stressed treatment | Gallardo, et al. [36]           |
| Potato        | Well-watered (WW) and drought stress (DS) (irrigation withheld for 14 and 9 days at tuber initiation and tuber bulking stage, respectively) | RWC decreased significantly in DS plants after 10 and 6 days of withholding of irrigation at tuber initiation and tuber bulking stage, respectively | - | Liu, et al. [39] |
| Tomato        | Irrigating at 10, 20-, and 30-days interval | RWC decreased significantly with increased irrigation interval | Yield decreased with increased irrigation interval | Bahadur, et al. [51]           |
| Cucumber      | FI and DI-50           | Significant decrease in RWC in DI-50 compared to FI was observed | Yield decreases significantly in DI-50                               | Kirnak and Demirtas [52]        |
| Watermelon    | FI, DI-75, DI-50, DI-25 and DI-0            | Significant differences in RWC among all irrigation treatments in 2003 and 2004 except between FI and DI-75 in 2004 | Significant differences in yield among all the treatments in both years | Kirnak, et al. [53]            |
| Squash        | FI, DI-85 and DI-70     | RWC decreased significantly in DI-70 compared to FI                                      | Yield decreased significantly in DI-85 and DI-70 and no significant difference between DI-85 and DI-70 | El-Mageed and Semida [34]       |
| Cabbage       | FI, DI-80 and DI-60     | RWC decreased significantly with increased water stress                                    | Shoot weight decreased significantly with increased water stress      | Sahin, et al. [55]             |
| Spinach       | FI and DI-50           | RWC decreased significantly in DI-50                                                        | Leaf fresh weight decreased significantly in DI-50                   | Xu and Leskovar [56]           |

Note: FI: irrigation amount equal to total water requirement of the crop, DI: deficit irrigation, DI-X: irrigation amount equal to X% of FI, PRD: partial root-zone drying and PRD-X: irrigation amount equal to X% of FI applied to one half of root zone.
In most of these studies, RWC decreased with increased water stress. However, Liu, et al. [39] observed that RWC did not decline up to 10 days and 6 days after withholding of irrigation at tuber initiation and tuber bulking stages of potato, respectively. While most of the other physiological measurements started to decline earlier than RWC. Because potato is an isohydric crop; hence, RWC is not a reliable for early detection and measurement of water stress in isohydric crop species or genotypes. Additionally, in the results of the study by Kirnak, et al. [53] on watermelon (Citrullus lanatus), it was found that relative differences in RWC among the irrigation treatments were not consistent for two experimental years. These results infer that change in environmental conditions can affect the response of RWC to water stress. Based on the RWC results of a study by Kirnak, et al. [53] on watermelon, it can be inferred that watermelon is an anisohydric crop. Similarly, onion, squash (Cucurbita pepo L.), cucumber, cabbage and spinach can be considered as an anisohydric crops (Table 2). In the studies on watermelon, squash and eggplant, RWC results are inconsistent with the yield results (Table 2). From this discussion, it can be inferred that results of RWC are influenced by the cumulative effect of the plant species (isohydric or anisohydric), soil and environmental conditions. Hence, RWC cannot distinguish the cause of water stress and cannot be a true indicator of water stress due to declining soil moisture status in all crop species. However, in anisohydric crop species, RWC can fairly sense the water stress levels in a crop subjected to different levels of water deficit under relatively stable environmental conditions. But some plants often make osmotic adjustments in response to water deficit. Osmotic adjustments help to maintain turgor pressure even under declining soil moisture conditions and thus measurement of RWC becomes imperfect [57]. Therefore, use of RWC for irrigation scheduling could be challenging.

2.3. Photosynthesis

Photosynthesis is the key factor affecting biomass accumulation and economic yield. Under water-stressed conditions, overall photosynthesis decreases due to decrease in both leaf area and photosynthetic rate per unit of leaf area [58]. Under water stress, water uptake into the cytoplasm and vacuole of cell decreases, which reduces cell expansion, and subsequently, inhibits the leaf elongation. Inhibited leaf elongation restricts an increase in leaf area [23]. Because of this increase in net photosynthetic area gets inhibited and photosynthetic rate per unit leaf area declines due to stomatal closure under water stressed conditions. Stomatal closure inhibits the supply of carbon dioxide to parenchyma cells, which further affects the photosynthetic efficiency by inhibiting \( \text{CO}_2 \) assimilation and light reaction [59].

Other than stomatal closure effect, photosynthesis activity is also disturbed due to chlorophyll degradation, reduced activity of enzymes (such as Rubisco), reduced photochemical efficiency of Photosystem II (PS II) under water stress [60]. Under water stress, chlorophyll content decreases due to damage to chloroplast membrane and structure, photo-oxidation of chlorophyll, increased activity of chlorophyllase and suppression of biosynthesis of chlorophyll [61–63]. Chlorophyll is the primary pigment responsible for the absorption of light energy required for photosynthesis. Chlorophyll content is positively related to photosynthesis [64]. Apart from the degradation of photosynthetic pigments, water stress is also detrimental to whole photosynthetic apparatus [65]. Under water stress conditions, light-induced inhibition of activity of PS II occurs. This phenomenon is commonly known as photo-inhibition [66–68]. Although, light energy is the primary source of energy for the photosynthesis process, under certain circumstances, it leads to photo-inhibition, when absorbed light energy exceeds the light energy requirement for photosynthesis. Excess light energy generates reactive oxygen species (ROS) primarily by over reduction of photosynthetic electron transport components, i.e., plastoquinone \( Q_A \), subsequently reducing molecular oxygen to produce ROS. Owing high reactive capacity, ROS are highly detrimental and can inhibit the repair of PS II by inhibiting the synthesis of proteins necessary for PS II repair [69]. Degree of photo-inhibition depends on the equilibrium between the photo-damage and repair of PS II core [70]. Hence, activity of PS II is responsive to
water stress, and its measurements under water stress can provide quantitative information about the photosynthesis rate.

Activity of PS II can be quantified by measuring chlorophyll fluorescence. Chlorophyll fluorescence determines the amount of light re-emitted from PS II. Light energy absorbed by the chlorophyll has one of three possible fates (1) utilized to drive photosynthesis (photochemistry); (2) dissipated as heat energy; or (3) re-emitted as light (chlorophyll fluorescence). These three mechanisms run in competition to each other such that increased efficiency of one mechanism results in the decline in efficiency of the other two mechanisms. Use of light energy for photochemistry is known as photochemical quenching and dissipation of light as heat energy is referred to as non-photochemical quenching. Photochemistry provides energy and reducing power for CO$_2$ assimilation [71]. Hence, photochemistry has a profound impact on photosynthesis. Dissipation of heat energy is a photoprotective mechanism that removes excess excitation energy present inside the chlorophyll-containing complexes and inhibits the development of detrimental free radicals [72]. Hence chlorophyll fluorescence measurements provide quantitative information about efficiency of photochemistry and dissipation of heat energy.

A number of parameters associated with chlorophyll fluorescence are used to determine the activity of PS II. Initial fluorescence ($F_0$) represents fluorescence level at which the redox components of photosystems are completely oxidized [73]. Maximum fluorescence ($F_m$) represents the fluorescence level at fully saturating irradiance when electron acceptor QA (primary Quinone acceptor of photosystem II) is in a fully reduced state [74]. Variable fluorescence ($F_V$) is calculated by subtracting $F_0$ from $F_m$ and this represents the reduction of the primary electron acceptor at a particular time, which quenches fluorescence in its oxidized state [75]. The $F_V/F_m$ ratio represents the maximum quantum yield of the photochemistry of PS II, and this ratio is associated with photosynthetic rate of the plant [76]. Therefore, these chlorophyll fluorescence parameters can be used to determine the efficiency of photochemistry (photosynthesis) and heat dissipation.

Several studies on effect of water stress on chlorophyll fluorescence in various vegetable crops are summarized in Table 3. In most studies, $F_V/F_m$ decreased with increased level of water stress. In a study by Guang-Cheng, et al. [77] on pepper, $F_V/F_m$ decreased significantly by 9.5% in PRD-50 and by 12% in DI-50 compared to FI. Significant differences in chlorophyll parameters became evident earlier than the significant differences in photosynthesis rates among the irrigation treatments. Hence, chlorophyll fluorescence has the potential to early detect water stress. In another study by Bahadur, et al. [51], $F_V/F_m$ ratio in tomato was significantly higher for 10 days irrigation interval followed by 20 days and 30 days irrigation intervals. However, there were no significant differences in photosynthesis rate for different irrigation intervals. In most of the studies chlorophyll fluorescence results are consistent with the yield results for irrigation treatments. Therefore, chlorophyll fluorescence can be used to estimate yield results earlier than the actual yield results in response to different water-deficit levels. Moreover, these studies advocate that chlorophyll fluorescence can help in early detection of water stress and can serve as a reliable water stress indicator. However, ABA can help in protecting the water-stress-induced damage to the photosynthetic apparatus. Due to this reason, sometimes PS-II efficiency remains unaffected from water stress due to ABA accumulation [78]. Hence, based on these discussions, it can be said that chlorophyll fluorescence will be more sensitive to water stress in ABA deficient plant species or genotypes. Moreover, osmotic adjustments can also help in preventing the decline in PS-II efficiency. Because accumulating proline can help in scavenging ROS, which inhibit the repair of PS II by inhibiting the synthesis of proteins necessary for PS II repair [69,79]. Overall, chlorophyll fluorescence can be insensitive to minor water stresses in drought-tolerant species or genotypes (accumulation of ABA and osmotic adjustments can make it insensitive to water stress). To the best of our knowledge, there are no studies involving the use of chlorophyll fluorescence for irrigation scheduling. But based on the above discussions, it can be said that chlorophyll fluorescence parameters can be used to determine the threshold levels at which irrigation should be initiated. Hence, there is a need to test for practicability of chlorophyll fluorescence measurement for irrigation scheduling.
Table 3. Effect of water stress on chlorophyll fluorescence in various vegetable crops.

| Crop     | Irrigation Treatment                                                                 | Chlorophyll Fluorescence Parameters                     | Yield                                                                 | References          |
|----------|--------------------------------------------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------------|---------------------|
| Tomato   | Irrigating at 10 (I$_1$), 20 (I$_2$) and 30 (I$_3$) days interval.                   | $F_v$/$F_m$ was significantly higher for I$_1$ and I$_2$ compared to I$_3$ | The yield was significantly higher for I$_1$ and I$_2$ compared to I$_3$ | Babadur, et al. [51] |
| Squash   | FI, DI-85 and DI-70                                                                   | $F_v$/$F_m$ decreased significantly in DI-70 compared to FI | Yield decreased significantly in DI-85 and DI-70 and no significant difference between DI-85 and DI-70 | El-Mageed and Semida [54] |
| Spinach  | FI and DI-50                                                                          | $F_v$/$F_m$ was unaffected by the water stress           | Fresh leaf weight decreased significantly in DI-50                   | Xu and Leskovar [56] |
| Pepper   | FI, DI-50 and PRD-50                                                                  | $F_v$/$F_m$ decreased significantly by 9.5% and 12% in PRD-50 and DI-50, respectively | Total dry biomass decreased significantly in DI-50 and PRD-50. FI > PRD-50 > DI-50 | Guang-Cheng, et al. [77] |
| Tomato   | Control (75–80% of field capacity (FC)), I$_2$ (55–60% of FC), I$_3$ (45–50% of FC) and I$_4$ (35–40% of FC) | $F_v$/$F_m$ decreased significantly with increased water stress | Significant differences in yield among the irrigation treatments | Yuan, et al. [80] |
| Potato   | FI and DI-0                                                                           | $F_v$ and $F_m$ decreased significantly in water-stressed plants. | Yield decreased significantly for the water-stressed plants.        | Jeffers [75,81]    |
| Watermelon | FI and withholding of irrigation for 10 days.                                           | $F_v$ and $F_m$ decreased in water-stressed plants after 4 days of withholding of irrigation. | Total dry biomass decreased significantly in water-stressed plants after 10 of withholding of irrigation | Mo, et al. [82]    |
| Cucumber | FI and severe water stress due to the addition of 10% PEG 6000 in the nutrient solution. | $F_v$/$F_m$ decreased significantly in water-stressed plants | -                                                                  | Li, et al. [83]    |

Note: FI: irrigation amount equal to total water requirement of the crop, DI: deficit irrigation, DI-X: irrigation amount equal to X% of FI, PRD: partial root-zone drying and PRD-X: irrigation amount equal to X% of FI applied to one half of root zone.

2.4. Stomatal Conductance

Stomata play a key role in regulating the flow of water in the soil–plant–atmosphere continuum. Stomatal adjustments help to maintain plant water status under varying soil moisture and atmospheric conditions. Stomatal conductance is a measure of the degree of physical resistance to gas movement between air and leaf interior [84]. Gas exchange helps in CO$_2$ intake and water loss (transpiration) through the stomatal aperture. Both transpiration and gas exchange are crucial phenomena for the normal functioning of the plant. Transpiration helps to regulate the leaf temperature and maintaining optimum leaf temperature is critical for various metabolic activities of the plant [85–88]. Gas exchange regulates the supply of carbon dioxide to parenchyma cells, which consequently affects the photosynthetic activity [59].

Under water-stressed conditions, stomatal conductance decreases due to closure of stomata to maintain the leaf water status [89]. There are contradicting reports on mechanism responsible for stomatal closure. Some studies endorse that chemical signals are responsible for stomatal closure, while others support that the hydraulic signals are responsible. Abscisic acid (ABA) plays a key role in chemical signaling [90]. Under mild soil water deficit, ABA is synthesized in roots and transported to leaves resulting in ABA accumulation in leaves [89]. For details on the mechanism of chemical signaling refer to leaf water potential and hormonal balance section of this article. The pH is another chemical signal which has been reported to affect stomatal conductance [91]. An increase in pH of xylem can concentrate ABA around the guard cells without increasing ABA in the xylem. This too can act as a signal to stimulate guard cells to close the stomata [27]. In a study on potato, Liu, et al. [89] concluded that increased ABA concentration in the leaves decreased stomatal conductance prior to a decrease in leaf turgor. Liu, et al. [39] reported an exponential increase in ABA concentration in the xylem of potato plants with decreasing stomatal conductance during the progressive soil drying. This discussion supports that chemical signal is responsible for stomatal closure.
On the contrary, some researchers claim that stomatal adjustments occur in response to changing hydraulic parameters of the sap pathway, such as soil resistance, root resistance, shoot resistance; or whole plant hydraulic resistance [92–96]. Even though, numerous studies have been done to understand the mechanism of stomatal closing and opening, still, underlying mechanism has not been completely understood.

In Table 4, several studies that demonstrate the effect of water stress on stomatal conductance and yield of various vegetable crops are summarized. All of these studies demonstrate that stomatal conductance decreases with an increase in water stress. In most of the studies, stomatal conductance tends to have a positive relationship with the yield. It infers that stomatal conductance can be used to estimate the yield results in response to different water-deficit levels, however in anisohydric crops, LWP need to be measured along with measurements of stomatal conductance. Because sometimes, anisohydric crops can maintain the stomatal conductance by decreasing the LWP under water stress conditions. Working with potatoes, Liu, et al. [39] observed that stomatal conductance decreased significantly in water-stressed plants after 2 and 1 day of withholding of irrigation at tuber initiation and tuber bulking stages, respectively. While for these growth stages, RWC became significantly lower after 10 and 6 days, respectively. Hence, stomatal conductance decreases earlier than the decrease in leaf water status. This suggests that the potato is an isohydric crop. Stomatal conductance declined in order to maintain the LWP. In a tomato experiment, Zegbe-Dominguez, et al. [38] observed that the differences in stomatal conductance were statistically insignificant for FI and DI treatments. Moreover, there were no significant differences in LWP for FI and DI treatments. The authors asserted that low radiation on the measurement day, override the effect of water stress on the plants. These studies illustrate that generally, stomatal conductance can fairly determine the level of water stress in the plant, except in anisohydric crop species or genotypes where stomatal conductance remains insensitive to some extent of water stress. Moreover, for water stress to be detected precisely by the stomatal conductance, the plant should not be exposed to any other abiotic stress, which can possibly affect the stomatal conductance. Since stomatal conductance is responsive to water stress in isohydric crop species, it may be useful in irrigation scheduling in these crops. But to the best of our knowledge, there are no studies on evaluating the practicability of using the stomatal conductance for irrigation scheduling.
Table 4. Effect of water stress on stomatal conductance and yield of various vegetable crops.

| Crop          | Irrigation Treatment | Stomatal Conductance ($g_s$)                                                                 | Yield                                                                 | References            |
|---------------|---------------------|--------------------------------------------------------------------------------------------|----------------------------------------------------------------------|-----------------------|
| Potato        | FI, DI-50 and PRD-50| $g_s$ decreased significantly in PRD-50 compared to FI and was similar between FI and DI-50 on most of the measurement days | Significantly higher yield in FI and was similar between DI-50 and PRD-50 | Liu, et al. [12]     |
| Tomato        | FI, DI-70 and PRD-70| Significantly lower $g_s$ in DI-70 and PRD-70 than FI $g_s$ decreased significantly in DI-0 compared to FI while it was similar between FI and DI-50 | Total dry biomass decreased significantly in DI-70 and PRD-70 | Pazzagli, et al. [33]|
| Cauliflower   | FI, DI-50 and DI-0  | $g_s$ started decreasing after the withheld of irrigation and became significantly lower in water-stressed treatment after 20 days of withholding of irrigation | –                                                                   | Kochler, et al. [34] |
| Eggplant      | FI and PRD-60       | Significant decrease in $g_s$ in PRD-60 $g_s$ started decreasing after the withheld of irrigation | Yield decreased significantly in PRD-60                              | Zhang, et al. [35]    |
| Lettuce (Lactuca seriola L.) | FI and irrigation withheld for 20 days | Shoot biomass decreased significantly in the water-stressed treatment | –                                                                   | Gallardo, et al. [36]|
| Tomato        | FI, DI-50 and PRD-50| No significant difference in $g_s$ among the irrigation treatments | Significant differences in yield among the irrigation treatments     | Zegbe-Dominguez, et al. [38] |
| Potato        | Well-watered (WW) and drought stress (DS) (irrigation withheld for 14 days and 9 days at tuber initiation and tuber bulking stage, respectively) | Significant decrease in $g_s$ in DS plants | –                                                                   | Liu, et al. [39]     |
| Pepper        | FI, DI-75 and DI-50 and PRD-50 | Significant differences in $g_s$ among irrigation treatments | Significant differences in yield among irrigation treatments | Sezen, et al. [41]    |
| Cabbage       | FI, DI-80 and DI-60 | $g_s$ decreased significantly with the increased levels of water stress | Shoot weight decreased significantly with increased water stress | Sahin, et al. [55]    |
| Spinach       | FI and DI-50        | $g_s$ decreased significantly in DI-50 | Fresh leaf weight decreased significantly in DI-50 | Xu and Leskovar [56] |
| Tomato        | FI, PRD-50 and DI-50| $g_s$ decreased significantly in PRD-50 and DI-50 | Fruit yield decreased significantly in PRD-50 and DI-50 | Topcu, et al. [97]    |
| Tomato        | FI, DI-70 and PRD-70| $g_s$ decreased significantly in DI-70 and PRD-70 | Yield decreased significantly in DI-70 and PRD-70 | Savic, et al. [98]    |
| Cucumber      | FI and DI-50        | $g_s$ decreased significantly in DI-50 | –                                                                   | Hnilička, et al. [99]|
| Tomato        | FI, DI-70 and PRD-70| $g_s$ was lower in DI-70 and PRD-70 | No significant differences in yield among the irrigation treatments | Hashem, et al. [100] |
| Cabbage       | FI, DI-75 and DI-50 | $g_s$ was lower in DI-70 and DI-50 | Yield decreased with increase in water deficiency | Xu and Leskovar [101] |

Note: FI: irrigation amount equal to total water requirement of the crop, DI: deficit irrigation, DI-X: irrigation amount equal to X% of FI, PRD: partial root-zone drying and PRD-X: irrigation amount equal to X% of FI applied to one half of root zone.
2.5. Canopy Temperature

Maintaining optimum canopy temperature is crucial for the metabolic activities of a plant. Canopy temperature is regulated by transpiration. Transpiration takes off the latent heat of vaporization, thereby cools the leaf surface [85–88]. Under soil moisture deficit, a lower transpiration rate tends to rise the leaf temperature [102]. Increased temperature disturbs the enzymatic activity of the plant [103]. Higher temperature results in an inhibition of the activity of photosystem II, inactivation of Rubisco and disintegration of plasmalemma. These activities are vital for plant functioning. Photosystem II provides energy and reducing power for CO\textsubscript{2} assimilation. Similarly, Rubisco activity is fundamental for CO\textsubscript{2} assimilation. Disintegration of plasmalemma results in cell death [104]. Hence, an increase in canopy temperature under water stress conditions can be detrimental to normal functioning of the plant and can cause a severe decline in crop yield. This means that canopy temperature is responsive to water stress and can be used to monitor the water stress level in plants.

Canopy temperature measurement is a non-destructive and rapid method for determining water stress level in plants. With the derivation of crop water stress index (CWSI) from canopy temperature and air temperature, the use of canopy temperature to assess the level of water stress in plants has become more practical. The CWSI represents the linear relationship between canopy–air temperature difference ($T_c - T_a$) and vapor pressure deficit (VPD) of air for a crop transpiring at its potential rate. For determining the CWSI two baselines are used: 1) lower baseline and 2) upper baseline. The lower baseline ($T_c - T_a$) versus VPD represents the observed temperature difference of well-watered plant having maximum transpiration rate (no water stress) and the upper baseline ($T_c - T_a$) represents the temperature difference of a plant with no transpiration loss (maximum stress) [105]. Lower and upper limits can be calculated by following the procedure outlined by Idso, et al. [105]. The CWSI is determined by using Equation (1) [105]:

$$\text{CWSI} = \frac{(T_c - T_a) - (T_c - T_a)_{ll}}{(T_c - T_a)_{ll} - (T_c - T_a)_{ul}}$$

(1)

where $T_c$ is the canopy temperature ($^\circ$C), $T_a$ is the air temperature ($^\circ$C), $ll$ is the lower baseline and $ul$ is the upper baseline.

The CWSI ranges from 0 to 1, where 1 represents no transpiration loss and 0 represents the maximum transpiration rate [106,107].

The CWSI has been used in numerous studies on irrigation management. In most of the studies on effects of water stress on vegetables, CWSI increased with increased levels of water stress. In the most studies, CWSI results are consistent with yield results, and yield varied linearly with the CWSI in eggplant [108], broccoli [109], watermelon [110,111], pepper [41,112,113], tomato [114] and cucumber [115]. Linear equation developed for each crop can be used to predict the yield of the crop when the crop is subjected to different levels of water stress. Overall, the CWSI is responsive to water stress and has the potential to determine crop responses to water stress.

Orta, et al. [110] suggested that watermelon should be irrigated when CWSI is about 0.41, while Erdem, et al. [116] recommended irrigating watermelon at 0.6 CWSI. These differences in threshold values of CWSI can be due to genotypic differences or environmental variations between locations of studies. Çolak, et al. [108] recommended that the threshold value of CWSI ranges between 0.18 and 0.20 for irrigation scheduling in eggplant for higher and good quality yield. Sezen, et al. [112] has suggested different threshold values of CWSI for different irrigation systems (Drip = 0.26 and furrow = 0.38) for pepper. The above studies indicate that threshold values of CWSI for irrigation scheduling are dependent on the crop species and genotypes as well as on irrigation methods and environmental conditions.

In some locations with low VPD (between 11 and 15 kPa), CWSI values can exceed the upper limit. However, CWSI values can range between 0 and 1, only when VPD is between 20 and 40 kPa [117,118]. In case of lower canopy cover or lower plant population, particularly during the early
stages of plant growth, soil surface can affect the $T_c$ values, resulting in a poor estimation of CWSI [119]. Gardner, et al. [120] have reviewed the other possible causes of out of range CWSI values with possible remedies such as the use of a single baseline throughout the growth of the crop.

Although requirement of different threshold CWSI values for varied environmental conditions and also for irrigation systems poses limitations on the use of CWSI for irrigation scheduling, still CWSI is a relevant approach for predicting the yield response of a particular crop to water stress under relatively stable environmental conditions.

2.6. Hormonal Balance

While adapting to environmental stresses, plants undergo complex physiological and biochemical adjustments [121]. Similarly, adaption to water stress through water stress tolerance involves morpho-physiological alterations. During low soil moisture availability, root cells start dehydrating due to low water uptake by the cells. In response to dehydration, root cells start synthesizing ABA. This ABA is then transported to leaf apoplast via xylem vessels [122–124]. The ABA is also synthesized in water-stressed leaf cells [125–127]. As a result of the transportation of ABA from roots to the leaves and also due to synthesis in leaf cells, concentration of ABA in leaf apoplast increases. In leaves, receptor cells are present in and around the guard cells, which sense the increased ABA concentration to induce stomatal closure and help to maintain the plant water status until the onset of severe water stress [27,128]. Therefore, changes in ABA concentration can be early detectable than changes in plant water status [129]. Consequently, measuring the changes in ABA concentration can be a relevant approach to determine the water stress in plants.

Neill and Horgan [130] observed that under water stress, ABA deficient mutants of tomato had higher stomatal conductance and three times higher transpiration than wild type. Wild types closed their stomata in response to water stress, while stomata of mutants were open until their leaves showed severe wilting symptoms. Yuan, et al. [131] reported that ABA concentration was significantly higher in control plants than the ABA deficient mutants. Stomatal conductance was higher in ABA deficient mutants than control plants while RWC was higher in control plants than ABA deficient mutants. This means in control plants ABA was closing the stomata to maintain the leaf water status. In a study by Ismail, et al. [47] on pepper, it was found that stomatal conductance and leaf growth decreased with an increase in ABA concentration in water-stressed plants. Topçu, et al. [97] found that DI-50 treatment had significantly higher ABA concentration than the full irrigation in tomato. These studies suggest that increased ABA concentration closes the stomata and helps to maintain leaf water status, which is crucial for normal functioning of the plant under water stress conditions.

However, due to stomatal closure effect of ABA, rate of CO$_2$ assimilation reduces in response to reduced CO$_2$ intake. It is also evident that ABA can reduce the photosynthesis activity independent of the stomatal closure effect. The ABA inhibits photosynthesis activity by inhibiting the activity of ribulose 1,5-bisphosphate carboxylase (RuBPCase) [132]. Hence, increased ABA concentration under stress can have negative impact on photosynthesis and ultimately yield of crop. This further supports that measurements of ABA can fairly be used to detect the water stress in plants. However, ABA measurements can be used only for research activities (screening of drought tolerant cultivars or determining the response of plants to new irrigation practices) while they cannot be practicable for irrigation scheduling due to complexity of methods for determining the ABA content. Aside from ABA, a number of other hormones and their interactions regulate stomatal conductance under the water stress conditions. Auxins and cytokinins, inhibit the ABA-mediated mechanisms responsible for stomatal control, while isoleucine jasmonates, brassinosteroids, and salicylic and jasmonic acids promote the effects of ABA [133]. Ethylene triggers the stomatal closure through ethylene-induced H$_2$O$_2$ synthesis. The H$_2$O$_2$ is a key molecule in ABA-induced stomatal closure [134]. Ethylene also stimulates senescence. Thus, these phytohormones have a very complex mode of action, which renders their use as water stress indicators hardly possible [135].
2.7. Osmotic Adjustments

Osmotic adjustment is a mechanism of plant adaptation to water stress. Osmotic adjustment is the process of accumulation of osmotically active and metabolically neutral solutes, such as amino acids (primarily proline and glycine), organic acids, sugars, betaine and polyamines [136]. Accumulation of solutes results in lower osmotic potential, which is crucial for maintaining the water status and physiological activity of plant cells under water stress [137]. For example, cell expansion takes place only due to influx of water directed by the lower osmotic potential, which is result of net accumulation of solutes by the expanding cell [138]. Additionally, osmotic adjustments also help in detoxification of ROS, maintaining structural integrity of membrane, stabilization of proteins or enzymes, maintaining stomatal conductance, leaf water status, photosynthesis rate and plant growth under stress conditions [59,139–142].

Nahar and Ullah [143] found an increase in proline, glucose, sucrose, fructose, malic acid, citric acid and ascorbic acid in tomato plants under increased water stress conditions. A similar trend was observed by Sarker, et al. [144] in eggplant with respect to proline content. The proline content increased from 0.45 mg g\(^{-1}\) of fresh weight at transplanting to 3.98 mg g\(^{-1}\) and 51.55 mg g\(^{-1}\) of fresh weight at 56 days after transplanting, in well-watered and highly water-stressed plants, respectively. Crusciol, et al. [145] also reported an increase in proline content in potato plants under water-stressed conditions. Sahin, et al. [55] found an increase in proline content with an increased level of water stress in cabbage. The above studies indicate that osmotic adjustments are responsive to water stress. Hence, measuring the amount of a particular accumulated solute can help to determine the degree of water stress in the plant.

Accumulating solutes are specific for some crop species, while some of these are common for a number of crop species. For example, glycine betaine is specific for sugar beet and spinach [142], whereas proline is a feature of a wide range of crop species [146]. Therefore, such metabolites can work as non-specific and species-specific indicators of water stress. However, measurements of accumulating of metabolites can be used only for research activities (screening of drought tolerant cultivars or determining the response of plants to new irrigation practices) while they cannot be practicable for irrigation scheduling due to complexity of methods for determining the metabolite content. Under severe water stress conditions, when soil water is highly unavailable, osmotic adjustments are unable to cope up with the detrimental effects of the water stress. In such circumstances, osmotic adjustments can be detrimental to plants because accumulation of solutes exhausts too many resources of the plant [147,148].

2.8. Electrolyte Leakage

Electrolyte leakage is another relevant plant-based approach for assessing the level of water stress in plants. It is an indirect measurement of the integrity and stability of cell membrane under stress conditions [149–152]. More electrolyte leakage means less stable cell membrane. Cell membrane plays a critical role of barrier and its disintegration can cause cell death [153]. Under stress conditions, ROS activated outward potassium currents mediate the efflux of K\(^+\) and so-called counter ions (Cl\(^-\), HPO\(_4^{2-}\), NO\(_3^-\), citrate\(^{3-}\), malate\(^{2-}\)) move in order to balance the efflux of positively charged K\(^+\) ions. Major part of electrolyte leakage consists of leakage of K\(^+\). Electrolyte leakage is crucial for roots where leakage of K\(^+\) leads to irreversible loss of K\(^+\) from plants under water stress conditions. The K is the key element for enzyme activity, protein synthesis, energy transfer, osmoregulation, stomatal adjustments, photosynthesis activity, phloem transport, and cation–anion balance [154]. Hence, loss of K through electrolyte leakage is detrimental to the normal functioning of the plant. Electrolyte leakage also occurs due to damage to lipid bilayer by oxidative degradation and mechanical defects [155]. Electrolyte leakage has also been shown to be associated with leaf senescence [52]. Hence, electrolyte leakage can be used to estimate the cell membrane injury, and to obtain crucial information about the cell metabolic activities.
Electrolyte leakage is the percentage of stress-induced leakage of electrolytes to the total cellular electrolytes [% electrolyte leakage = (Electrolyte leakage)stress/total cellular electrolytes]. Electrolyte leakage can be measured by following the procedures outlined by [52,156–160].

Electrolyte leakage has been used extensively to quantify various stresses, including biotic stress [161–165], heavy metal accumulation [166–168], salinity stress [169–172], thermal stress [173] and several other stresses in a wide range of crops. In Table 5, various studies on the effect of water stress on electrolyte leakage in different vegetable crops are summarized. Most of the studies demonstrated an increase in electrolyte leakage with increased water stress. In addition, electrolyte leakage results are consistent with the yield results for most of the vegetable crops. Both the high sensitivity of electrolyte leakage to water stress and its consistency with yield results encourage its use to quantify the water stress in vegetable crops. However, electrolyte leakage can be used only for research activities (screening of drought tolerant cultivars or determining the response of plants to new irrigation practices) while it will not be practicable for irrigation scheduling due to complexity of methods for measuring the electrolyte leakage.

Table 5. Effect of water stress on electrolyte leakage and yield of various vegetable crops.

| Crop     | Irrigation Treatment | Electrolyte Leakage                                                                 | Yield                                      | References            |
|----------|----------------------|--------------------------------------------------------------------------------------|--------------------------------------------|-----------------------|
| Cucumber | FI and DI-50         | Electrolyte leakage increased significantly in DI-50                                | Yield decreased significantly in DI-50     | Kirnak and Demirtas [52] |
|          |                      | Electrolyte leakage increased significantly with the increased levels of water deficit | Shoot weight decreased significantly with the increased levels of water deficit | Sahin, et al. [55]    |
| Cabbage  | FI, DI-80 and DI-60  | Electrolyte leakage was significantly different among irrigation treatments except between FI and DI-80 | Yield decreased significantly with increased deficiency of water | Kirnak, et al. [156]  |
| Eggplant | FI, DI-80, DI-60 and DI-40 | Electrolyte leakage was significantly different among irrigation treatments except between FI and DI-80 | The yield was significantly different among irrigation treatments except between FI and DI-90 | Kirnak, et al. [157]  |
| Eggplant | FI (daily irrigating based on A pan evaporation), DI-90 (irrigating at 4 days interval), DI-80 (8 days) and DI-70 (12 days) | Electrolyte leakage was significantly different among irrigation treatments except between FI and DI-90 |                          | El-Mageed, et al. [158] |
| Squash   | FI, DI-80 and DI-60  | Electrolyte leakage increased significantly with increased water stress              | Yield decreased significantly with increased water stress | Abdelhady, et al. [159] |
| Tomato   | FI, DI-80 and DI-60  | Electrolyte leakage was significantly higher in DI-60 compared to FI and DI-80        | Yield decreased significantly with increased water stress |                      |
| Tomato   | Withholding water for 10 days at 20 and 30 days after sowing | Electrolyte leakage was more at 30 days compared to 20 days after sowing             | –                                          | Hayat, et al. [160]    |
| Cabbage  | FI, DI-75 and DI-50. | Electrolyte leakage increased significantly with increased deficiency of water       | Yield decreased significantly with increased deficiency of water | Metwaly and El-Shatoury [174] |
| Pepper   | C (Irrigating at 60% of field capacity (FC)), irrigating at 45% and 35% of FC | Electrolyte leakage increased with increased water stress                             | Yield decreased significantly with increased water stress | Ullah, et al. [175]   |

Note: FI: irrigation amount equal to total water requirement of the crop, DI: deficit irrigation, DI-X: irrigation amount equal to X% of FI, PRD: partial root zone drying and PRD-X: irrigation amount equal to X% of FI applied to one half of root zone.

It is evident that electrolyte leakage also occurs due to damage to lipid bilayer by oxidative degradation (by ROS) and mechanical defects [155]. Some plants undergo osmotic adjustments under water stress, and it is known that osmotic adjustments have the potential to prevent the oxidative damage to lipid bilayer by scavenging the ROS [59,139–142]. Thus, osmotic adjustments can help to maintain the structural integrity of the membrane and to prevent the leakage of electrolytes under water stress. Hence, electrolyte leakage may be insensitive to water stress in drought tolerant crop species.
2.9. Sap Flow

Another important plant-based water stress quantification approach is through the measurement of the sap flow. Sap is the water present in the tracheary cells of the xylem tissue. Sap flow represents the transpiration flow as the ascent of sap within the xylem tissue. Under water-stressed conditions, transpiration rate decreases due to stomatal closure which subsequently affects the sap flow. Therefore, sap flow rate can be used to determine plant water stress [176].

Sap flow rate has been used in a limited number of studies on vegetable crops to assess the level of water stress. Yang, et al. [177] found a significant decline in the sap flow rate in DI-65 (DI-65 = 65\% of FI) compared to FI at flowering and fruit setting stages of tomato. Qiu, et al. [178] reported that stem sap flow rate decreased by 22.1\% and 42.8\% in DI-65 and DI-50 treatments, respectively, compared to full irrigation in tomato. Grey [179] observed that the sap flow decreased significantly after 3 days of imposing of the water stress in tomato. A fairly good correlation between sap flow and reference crop evapotranspiration (ET\textsubscript{0}) on a daily basis was also observed. Results of all these studies suggest that sap flow rate is responsive to water stress and advocate that it can be fairly used to determine the water stress level in plants.

The invention of heat-balance thermal-sensors and heat pulse sensors for measuring the sap-flow rate in the stems of plants have provided an alternative approach for irrigation scheduling. Many researchers have used the sap-flow rate for irrigation scheduling in various crops [180–186] with varying degrees of success.

Sap flow data cannot be used unequivocally because sap flow is affected by both internal and external factors. Internal factors refer to factors affecting plant water transport, i.e., hydraulic conductivity of roots and stem, canopy structure, stomatal aperture. External factors include soil moisture status, solar radiation and VPD. Sap flow has a positive linear relationship with solar radiation, air temperature and VPD. Sap flow rate at a particular soil moisture level is highly sensitive to solar radiation followed by VPD and then by air temperature [177]. Hence, under simultaneously varying environmental and soil moisture conditions, it becomes difficult to discern that decreased sap flow rate is due to low soil water availability or due to increased evaporative demand of the atmosphere [187,188]. In such situations, irrigation scheduling based on sap flow rate can result in under or over-irrigation of crop. For irrigation scheduling, sap flow method requires calibration of sap flow sensors for each crop species and also requires different thresholds for different crop species [15]. Due to the capability of sap flow rate measuring sensors to automatically record the data, sap flow rate is suitable for automated irrigation scheduling, but it is a little challenging to find out the appropriate threshold for a particular crop.

2.10. Stem Diameter Variation

Another approach to determine the plant water status in vegetable crops is by measuring the variations in stem diameter. Stem diameter varies in response to back and forth movement of water between the xylem and phloem. Early in the morning, root water uptake is not sufficient to cope up with increased atmospheric demand due to increased solar radiation. Hence, with the start of transpiration, a tension occurs in the xylem forcing the water stored in phloem during the night to come to the xylem to be lost through transpiration. Again, during the nighttime, re-hydration of phloem occurs [189,190]. Shrinking-expanding of stem occurs in response to changing water potential in xylem [189,191,192]. More daily shrinkage of stem under water-stressed conditions hinders the growth of stem [193,194]. Hence, variations in stem diameter are responsive to changes in water availability and can be used to access the level of water stress in plants.

A number of indices have been developed to measure stem diameter variations (SDVs) including, stem growth rate (SGR), maximum daily stem shrinkage (MDS), daily minimum stem diameter (MNSD) and daily maximum stem diameter (MXSD) [194–197]. However, it is evident that SGR and MDS are the most commonly used indices [185,197–201].
SDVs have been used in a large number of studies on fruit trees, however, it has limited usage in vegetable crops. Gallardo, et al. [202] observed that MDS was sensitive to water stress during the fruiting stages in melon and tomato. In another study on tomato by Gallardo, et al. [197], SGR was found to be the most sensitive to water stress during the early growth stages, while MDS at late growth stages. Cohen, et al. [203] and Katerji, et al. [204] also reported that the sensitivity of SDV indices to water stress was affected by the phenological stage of the pepper plant. Gallardo, et al. [197] mentioned that SDV indices were less sensitive to water stress under low VPD conditions and were highly sensitive during the high VPD conditions. These studies on different vegetable crops indicate that SDV derived indices can serve as a helpful tool to detect the water stress in vegetable crops under high evaporative demand conditions.

For irrigation scheduling, use of SDV indices is a little challenging. Expertise in interpreting SDV data is required. In addition, SDV indices are highly affected by the seasonal growth rate, plant size and age, fruit load and some other factors besides water stress. These limitations have restricted the implementation of SDV indices for automated irrigation scheduling [205]. However, despite these limitations for irrigation scheduling, SDV indices can still be helpful to detect the water stress in plants because of its high sensitivity to water stress.

2.11. Leaf Expansion

Most of the above-mentioned plant-based water stress indicators have some disadvantages that they cannot be used generally for most of the vegetable crops. The leaf expansion rate is also shown to be responsive to water stress. The Leaf expansion rate changes in response to the change in leaf temperature, photon flux density, evaporative demand and soil water content [206]. Generally, loss in leaf turgor under water stress results in reduced cell expansion. Reduced cell expansion inhibits leaf elongation. However, in some studies, reduced leaf elongation has been observed even in turgid leaves. In a study by Ismail, et al. [47] on pepper, leaf elongation rate started to decline after the second day of withholding of irrigation, while the decline in leaf turgor was apparent only after 5 days of withholding irrigation. In this case, the leaf elongation rate decreased to maintain the leaf water status. This means cell expansion is not totally dependent on the cell turgor. The Cell expansion also depends on the other metabolic and physical processes such as nutrient and metabolite deposition, which affect the cell wall extensibility, water uptake and cell wall yielding (extend irreversibly) [48–50]. These metabolic and physical processes are responsive to water stress, suggesting that leaf expansion rate can fairly be used for water stress detection. Moreover, it has been reported that leaf expansion reduces earlier than photosynthesis rate per unit leaf area under water stress [206]. From this discussion, it can be said that leaf expansion rate can also be used to access water stress level in the plants. Leaf area growth represents the light interception capacity of the plant and is a relevant parameter for determining the plant growth and yield [207]. To the best of our knowledge, there are no studies on vegetable crops in which leaf expansion rate has been used for irrigation scheduling.

3. Conclusions

This article has briefly highlighted the relative efficacy of different plant-based water stress indicators to detect and measure the water stress, their consistency with yield results of a crop as affected by different water-deficit levels, and also for their potential to be used in irrigation scheduling in vegetable crops. Plant-based water stress indicators have an advantage over the soil-based approaches as they can sense water stress due to the cumulative effect of low soil moisture availability and increased atmospheric water demand. Most of the water stress indicators mentioned above are responsive to water stress. They can be successfully used to detect and measure the water stress level in crop subjected to different water-deficit levels. In most studies mentioned in this review, water stress indicator results were consistent with the yield results. Therefore, the water stress measurements taken at earlier growth stages can be used to estimate the yield. Threshold values of these water stress indicators can be used to determine the threshold water stress level to which crop can be exposed.
without having a detrimental effect on crop growth and yield. In this way, these water stress indicators can be useful for understanding the response and adaptation of plants to new water-conserving irrigation practices. Moreover, plant-based water stress indicators can be quite helpful in screening the drought-tolerant cultivars. However, these water stress indicators are incapable of discerning the cause of water stress (increased evaporative demand or declined soil moisture status), which makes them unsuitable for irrigation scheduling in vegetable crops grown under highly fluctuating environmental conditions. They can lead to under or over-irrigation under varying environmental conditions. Therefore, plant-based water stress indicators can be used only for locations where there are very little fluctuations in environmental conditions. Threshold values of plant-based water stress indicators for irrigation scheduling vary for crop species and genotypes (isohydric or anisohydric, drought susceptible or tolerant) as well as for varying environmental conditions. Intensive research is required to determine the threshold values for each crop species by taking into account the effect of environmental variations on existing level of water stress so that plant-based water stress indicators can be successfully implemented for irrigation scheduling in each vegetable crop species. Similarly, for precise water stress detection by plant-based methods, more research is required to determine the relative efficacy of different plant-based water stress indicators by involving a number of water stress indicators at a time for each crop species. In addition, it is important to consider the effect of varying environmental conditions on effectiveness of each water stress indicator to detect water stress precisely.

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References

1. Garces-Restrepo, C.; Vermillion, D.; Muoz, G. Irrigation Management Transfer. Worldwide Efforts and Results; Food and Agriculture Organization: Rome, Italy, 2007.
2. Chai, Q.; Gan, Y.; Zhao, C.; Xu, H.-L.; Waskom, R.M.; Niu, Y.; Siddique, K.H. Regulated deficit irrigation for crop production under drought stress. A review. Agron. Sustain. Dev. 2016, 36, 3. [CrossRef]
3. Evans, R.G.; Sadler, E.J. Methods and technologies to improve efficiency of water use. Water Resour. Res. 2008, 44. [CrossRef]
4. Kang, Y.; Khan, S.; Ma, X. Climate change impacts on crop yield, crop water productivity and food security—A review. Prog. Nat. Sci. 2009, 19, 1665–1674. [CrossRef]
5. Solomon, S.; Qin, D.; Manning, M.; Averyt, K.; Marquis, M.; Tignor, M.M. Climate Change 2007: The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC; Cambridge University Press: Cambridge, UK, 2007; Volume 4.
6. McGuire, V.L. Water-Level and Recoverable Water in Storage Changes, High Plains Aquifer, Predevelopment to 2015 and 2013–15; 2328-0328; US Geological Survey: Reston, VA, USA, 2017.
7. Neupane, J.; Guo, W. Agronomic Basis and Strategies for Precision Water Management: A Review. Agronomy 2019, 9, 87. [CrossRef]
8. Pereira, L.S.; Oweis, T.; Zairi, A. Irrigation management under water scarcity. Agric. Water Manag. 2002, 57, 175–206. [CrossRef]
9. Costa, J.M.; Ortúñol, M.F.; Chaves, M.M. Deficit irrigation as a strategy to save water: Physiology and potential application to horticulture. J. Integr. Plant Biol. 2007, 49, 1421–1434. [CrossRef]
10. Wakchaure, G.; Minhas, P.; Meena, K.K.; Singh, N.P.; Hegade, P.M.; Sorty, A.M. Growth, bulb yield, water productivity and quality of onion (Allium cepa L.) as affected by deficit irrigation regimes and exogenous application of plant bio–regulators. Agric. Water Manag. 2018, 199, 1–10. [CrossRef]
11. Mohawesh, O. Utilizing deficit irrigation to enhance growth performance and water-use efficiency of eggplant in arid environments. J. Agric. Sci. Technol. 2018, 18, 265–276.
12. Liu, F.; Shahnazari, A.; Andersen, M.N.; Jacobsen, S.-E.; Jensen, C.R. Effects of deficit irrigation (DI) and partial root drying (PRD) on gas exchange, biomass partitioning, and water use efficiency in potato. Sci. Hortic. 2006, 109, 113–117. [CrossRef]
13. Ihuoma, S.O.; Madramootoo, C.A. Recent advances in crop water stress detection. Comput. Electron. Agric. 2017, 141, 267–275. [CrossRef]
14. Pereira, L.S. Higher performance through combined improvements in irrigation methods and scheduling: A discussion. Agric. Water Manag. 1999, 40, 153–169. [CrossRef]
15. Jones, H.G. Irrigation scheduling: Advantages and pitfalls of plant-based methods. J. Exp. Bot. 2004, 55, 2427–2436. [CrossRef] [PubMed]
16. Wang, X.; Zhao, C.; Guo, N.; Li, Y.; Jian, S.; Yu, K. Determining the canopy water stress for spring wheat using canopy hyperspectral reflectance data in loess plateau semiarid regions. Spectrosc. Lett. 2015, 48, 492–498. [CrossRef]
17. Dias, J.S. Nutritional quality and health benefits of vegetables: A review. Food Nutr. Sci. 2012, 3, 1354–1374. [CrossRef]
18. Kumar, P.; Rouphael, Y.; Cardarelli, M.; Colla, G. Vegetable grafting as a tool to improve drought resistance and water use efficiency. Front. Plant Sci. 2017, 8, 1130. [CrossRef]
19. Lott, D.E.; Hammond, V.E. Water Wise Vegetable and Fruit Production. In NebGuide; University of Nebraska-Lincoln Extension, Institute of Agriculture and Natural Resources: Lincoln, NE, USA, 2013.
20. Kumar, R.; Solanki, S.S.; Singh, M. Breeding for drought tolerance in vegetables. Veg. Sci. 2012, 39, 1–15.
21. Sorensen, E.J. WSU Drought Advisory: Vegetable Crops; Washington State University Extension, Washington State University: Pullman, WA, USA, 2005.
22. Singh, M.; Saini, R.K.; Singh, S.; Sharma, S.P. Potential of Integrating Biochar and Deficit Irrigation Strategies for Sustaining Vegetable Production in Water-limited Regions: A Review. HortScience 2019, 54, 1872–1878. [CrossRef]
23. Jones, H.G. Physiological aspects of the control of water status in horticultural crops. HortScience 1990, 25, 19–26. [CrossRef]
24. Robbins, N.E.; Dinneny, J.R. The divining root: Moisture-driven responses of roots at the micro-and macro-scale. J. Exp. Bot. 2015, 66, 2145–2154. [CrossRef]
25. Jones, H.G. Estimation of an effective soil water potential at the root surface of transpiring plants. Plant Cell Environ. 1983, 6, 671–674.
26. Bates, L.; Hall, A. Stomatal closure with soil water depletion not associated with changes in bulk leaf water status. Oecologia 1981, 50, 62–65. [CrossRef] [PubMed]
27. Limpus, S. Isohydric and Anisohydric Characterisation of Vegetable Crops. The Classification of Vegetables by Their Physiological Responses to Water Stress; Queensland Government, Department of Primary Industries and Fisheries: Brisbane, QLD, Australia, 2009.
28. Buckley, T.N. The control of stomata by water balance. New Phytol. 2005, 168, 275–292. [CrossRef] [PubMed]
29. Jones, H.; Tardieu, F. Modelling water relations of horticultural crops: A review. Sci. Hortic. 1998, 74, 21–46. [CrossRef]
30. Jones, H. Irrigation scheduling-comparison of soil, plant and atmosphere monitoring approaches. In Proceedings of the V International Symposium on Irrigation of Horticultural Crops; ISHS Acta Horticulturae 792; International Society for Horticultural Science: Leuven, Belgium, 2008; pp. 391–403.
31. Jones, H.G. Monitoring plant and soil water status: Established and novel methods revisited and their relevance to studies of drought tolerance. J. Exp. Bot. 2006, 58, 119–130. [CrossRef]
32. Tardieu, F.; Davies, W. Integration of hydraulic and chemical signalling in the control of stomatal conductance and water status of droughted plants. Plant Cell Environ. 1993, 16, 341–349. [CrossRef]
33. Pazzagli, P.T.; Weiner, J.; Liu, F. Effects of CO2 elevation and irrigation regimes on leaf gas exchange, plant water relations, and water use efficiency of two tomato cultivars. Agric. Water Manag. 2016, 169, 26–33. [CrossRef]
34. Kochler, M.; Kage, H.; Stützel, H. Modelling the effects of soil water limitations on transpiration and stomatal regulation of cauliflower. Eur. J. Agron. 2007, 26, 375–383. [CrossRef]
35. Zhang, Q.; Wu, S.; Chen, C.; Shu, L.-Z.; Zhou, X.-J.; Zhu, S.-N. Regulation of nitrogen forms on growth of eggplant under partial root-zone irrigation. Agric. Water Manag. 2014, 142, 56–65. [CrossRef]
36. Gallardo, M.; Jackson, L.; Thompson, R. Shoot and root physiological responses to localized zones of soil moisture in cultivated and wild lettuce (Lactuca spp.). Plant Cell Environ. 1996, 19, 1169–1178. [CrossRef]
37. Schultz, H.R. Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown Vitis vinifera L. cultivars during drought. Plant Cell Environ. 2003, 26, 1393–1405. [CrossRef]
38. Zegbe-Dominguez, J.; Behboudian, M.; Lang, A.; Clothier, B. Water relations, growth, and yield of processing tomatoes under partial rootzone drying. J. Veg. Crop Prod. 2004, 9, 31–40. [CrossRef]
39. Liu, F.; Jensen, C.R.; Shahanzari, A.; Andersen, M.N.; Jacobsen, S.-E. ABA regulated stomatal control and photosynthetic water use efficiency of potato (Solanum tuberosum L.) during progressive soil drying. Plant Sci. 2005, 168, 831–836. [CrossRef]
40. Dorji, K.; Behboudian, M.; Zegbe-Dominguez, J. Water relations, growth, yield, and fruit quality of hot pepper under deficit irrigation and partial rootzone drying. Sci. Hortic. 2005, 104, 137–149. [CrossRef]
41. Sezen, S.M.; Yazar, A.; Tekin, S. Physiological response of red pepper to different irrigation regimes under drip irrigation in the Mediterranean region of Turkey. Sci. Hortic. 2019, 245, 280–288. [CrossRef]
42. Zhang, D.; Du, Q.; Zhang, Z.; Jiao, X.; Song, X.; Li, J. Vapour pressure deficit control in relation to water transport and water productivity in greenhouse tomato production during summer. Sci. Rep. 2017, 7, 43461. [CrossRef]
43. Rogiers, S.Y.; Greer, D.H.; Hatfield, J.M.; Clarke, S.J.; Hutchinson, P.A.; Somers, A. Stomatal response of an anisohydric grapevine cultivar to evaporative demand, available soil moisture and abscisic acid. Tree Physiol. 2011, 32, 249–261. [CrossRef]
44. Chalmers, D. A physiological examination of regulated deficit irrigation. N. Z. J. Agric. Sci. 1989, 23, 44–48.
45. Passioura, J. Root signals control leaf expansion in wheat seedlings growing in drying soil. Funct. Plant Biol. 1988, 15, 687–693. [CrossRef]
46. Zhang, J.; Davies, W. Does ABA in the xylem control the rate of leaf growth in soil-dried maize and sunflower plants? J. Exp. Bot. 1990, 41, 1125–1132. [CrossRef]
47. Ismail, M.R.; Davies, W.; Awad, M.H. Leaf growth and stomatal sensitivity to ABA in droughted pepper plants. Sci. Hortic. 2002, 96, 313–327. [CrossRef]
48. Boyer, J.S. Water transport. Annu. Rev. Plant Physiol. 1985, 36, 473–516. [CrossRef]
49. Cosgrove, D. Biophysical control of plant cell growth. Annu. Rev. Plant Physiol. 1986, 37, 377–405. [CrossRef]
50. Shackel, K.A.; Matthews, M.A.; Morrison, J.C. Dynamic relation between expansion and cellular turgor in growing grape (Vitis vinifera L.) leaves. Plant Physiol. 1987, 84, 1166–1171. [CrossRef]
51. Bahadur, A.; Lama, T.; Chaurasia, S. Gas exchange, chlorophyll fluorescence, biomass production, water use and yield response of tomato (Solanum lycopersicum) grown under deficit irrigation and varying nitrogen levels. Indian J. Agric. Sci. 2015, 85, 224–228.
52. Kirmak, H.; Demirtas, M.N. Effects of different irrigation regimes and mulches on yield and macronutrition levels of drip-irrigated cucumber under open field conditions. J. Plant Nutr. 2006, 29, 1675–1690. [CrossRef]
53. Kirmak, H.; Doğan, E.; Bilgel, L.; Beraktağolu, K. Effect of preharvest deficit irrigation on second crop watermelon grown in an extremely hot climate. J. Irrig. Eng. 2009, 135, 141–148. [CrossRef]
54. El-Mageed, T.A.A.; Semida, W.M. Effect of deficit irrigation and growing seasons on plant water status, fruit yield and water use efficiency of squash under saline soil. Sci. Hortic. 2015, 186, 89–100. [CrossRef]
55. Sahin, U.; Ekinci, M.; Ors, S.; Turan, M.; Yildiz, S.; Yildirim, E. Effects of individual and combined effects of salinity and drought on physiological, nutritional and biochemical properties of cabbage (Brassica oleracea var. capitata). Sci. Hortic. 2018, 240, 196–204. [CrossRef]
56. Xu, C.; Leskovar, D.I. Effects of A. nodosum seaweed extracts on spinach growth, physiology and nutrition value under drought stress. Sci. Hortic. 2015, 183, 39–47. [CrossRef]
57. Boyer, J.S.; James, R.A.; Munns, R.; Condon, T.A.; Passioura, J.B. Osmotic adjustment leads to anomalously low estimates of relative water content in wheat and barley. Funct. Plant Biol. 2008, 35, 1172–1182. [CrossRef]
58. Basu, S.; Ramegowda, V.; Kumar, A.; Pereira, A. Plant adaptation to drought stress version 1; referees: 3. F1000Research 2016, 5, 1554. [CrossRef]
59. Farooq, M.; Wahid, A.; Kobayashi, N.; Fujita, D.; Basra, S. Plant drought stress: Effects, mechanisms and management. In Sustainable Agriculture; Springer: Dordrecht, The Netherlands, 2009; pp. 153–188.
60. Pandey, V.; Shukla, A. Acclimation and tolerance strategies of rice under drought stress. Rice Sci. 2015, 22, 147–161. [CrossRef]
61. Kingston-Smith, A.; Foyer, C. Bundle sheath proteins are more sensitive to oxidative damage than those of the mesophyll in maize leaves exposed to paraquat or low temperatures. *J. Exp. Bot.* **2000**, *51*, 123–130. [CrossRef]

62. Amirjani, M.R.; Mahdiyeh, M. Antioxidative and biochemical responses of wheat to drought stress. *J. Agric. Biol. Sci.* **2013**, *8*, 291–301.

63. Kabiri, R.; Nasibi, F.; Farahbakhsh, H. Effect of exogenous salicylic acid on some physiological parameters and alleviation of drought stress in *Nigella sativa* plant under hydroponic culture. *Plant Prot. Sci.* **2014**, *50*, 43–51. [CrossRef]

64. Guo, P.; Li, M. Studies on photosynthetic characteristics in rice hybrid progenies and their parents I. chlorophyll content, chlorophyll-protein complex and chlorophyll fluorescence kinetics. *J. Trop. Subtrop. Bot.* **1996**, *4*, 60–65.

65. López-Jurado, J.; Balao, F.; Mateos-Naranjo, E. Deciphering the ecophysiological traits involved during water stress acclimation and recovery of the threatened wild carnation, *Dianthus inoxianus*. *Plant Physiol. Biochem.* **2016**, *109*, 397–405. [CrossRef]

66. Powles, S.B. Photo inhibition of photosynthesis induced by visible light. *Annu. Rev. Plant Physiol.* **1964**, *35*, 15–44. [CrossRef]

67. Aro, E.-M.; Virgin, I.; Andersson, B. Photo inhibition of photosystem II. Inactivation, protein damage and turnover. *Biochim. Biophys. Acta BBA Bioenerg.* **1993**, *1143*, 113–134. [CrossRef]

68. Murata, N.; Takahashi, S.; Nishiyama, Y.; Allakhverdiev, S.I. Photo inhibition of photosystem II under environmental stress. *Biochim. Biophys. Acta BBA Bioenerg.* **2007**, *1767*, 414–421. [CrossRef]

69. Murata, N.; Allakhverdiev, S.I.; Nishiyama, Y. The mechanism of photo inhibition in vivo: Re-evaluation of the roles of catalase, α-tocopherol, non-photochemical quenching, and electron transport. *Biochim. Biophys. Acta BBA Bioenerg.* **2012**, *1817*, 1127–1133. [CrossRef]

70. Demmig-Adams, B.; Cohu, C.M.; Muller, O.; Adams, W.W. Modulation of photosynthetic energy conversion efficiency in nature: From seconds to seasons. *Photosynth. Res.* **2012**, *113*, 75–88. [CrossRef]

71. Murchie, E.H.; Lawson, T. Chlorophyll fluorescence analysis: A guide to good practice and understanding some new applications. *J. Exp. Bot.* **2013**, *64*, 3983–3998. [CrossRef]

72. Demmig-Adams, B.; Adams III, W.W. Photoprotection in an ecological context: The remarkable complexity of thermal energy dissipation. *New Phytol.* **2006**, *172*, 11–21. [CrossRef]

73. Fracheboud, Y.; Jompuk, C.; Ribaut, J.; Stamp, P.; Leipner, J. Genetic analysis of cold-tolerance of *Arabidopsis thaliana* wild-type (Columbia) and ABA-deficient mutant (aba2). *Environ. Exp. Bot.* **2013**, *86*, 44–51. [CrossRef]

74. Yuan, X.; Yang, Z.; Li, Y.; Liu, Q.; Han, W. Effects of different levels of water stress on leaf photosynthetic characteristics and antioxidant enzyme activities of greenhouse tomato. *Photosynthetica* **2016**, *54*, 28–39. [CrossRef]

75. Jefferies, R. Effects of drought on chlorophyll fluorescence in potato (*Solanum tuberosum* L.). I. Plant water status and the kinetics of chlorophyll fluorescence. *Potato Res.* **1992**, *35*, 25–34. [CrossRef]

76. Shangguan, Z.; Shao, M.; Dyckmans, J. Effects of nitrogen nutrition and water deficit on net photosynthetic rate and chlorophyll fluorescence in winter wheat. *J. Plant Physiol.* **2000**, *156*, 46–51. [CrossRef]

77. Guang-Cheng, S.; Rui-qi, G.; Na, L.; Shuang-en, Y.; Weng-Gang, X. Photosynthetic, chlorophyll fluorescence and growth changes in hot pepper under deficit irrigation and partial root zone drying. *Afr. J. Agric. Res.* **2011**, *6*, 4671–4679.

78. Haisel, D.; Pospísilová, J.; Synková, H.; Schnablová, R.; Baťková, P. Effects of abscisic acid or benzyladenine on pigment contents, chlorophyll fluorescence, and chloroplast ultrastructure during water stress and after rehydration. *Photosynthetica* **2006**, *44*, 606–614. [CrossRef]

79. Ozfidan, C.; Turkan, I.; Sekmen, A.H.; Seckin, B. Time course analysis of ABA and non-ionic osmotic stress-induced changes in water status, chlorophyll fluorescence and osmotic adjustment in *Arabidopsis thaliana* wild-type (Columbia) and ABA-deficient mutant (aba2). *Environ. Exp. Bot.* **2013**, *86*, 44–51. [CrossRef]

80. Yuan, X.; Yang, Z.; Li, Y.; Liu, Q.; Han, W. Effects of different levels of water stress on leaf photosynthetic characteristics and antioxidant enzyme activities of greenhouse tomato. *Photosynthetica* **2016**, *54*, 28–39. [CrossRef]

81. Jefferies, R. Effects of drought on chlorophyll fluorescence in potato (*Solanum tuberosum* L.). II. Relations between plant growth and measurements of fluorescence. *Potato Res.* **1992**, *35*, 35–40. [CrossRef]
82. Mo, Y.; Yang, R.; Liu, L.; Gu, X.; Yang, X.; Wang, Y.; Zhang, X.; Li, H. Growth, photosynthesis and adaptive responses of wild and domesticated watermelon genotypes to drought stress and subsequent re-watering. *Plant Growth Regul.* **2016**, *79*, 229–241. [CrossRef]

83. Li, Q.M.; Liu, B.B.; Wu, Y.; Zou, Z.R. Interactive effects of drought stresses and elevated CO2 concentration on photochemistry efficiency of cucumber seedlings. *J. Integr. Plant Biol.* **2008**, *50*, 1307–1317. [CrossRef]

84. Pietragalla, J.; Pask, A. Stomatal conductance. In *Physiological Breeding II: A Field Guide to Wheat Phenotyping*; Pask, A., Pietragalla, J., Mullan, D., Reynolds, M., Eds.; International Maize and Wheat Improvement Center CIMMYT: Texcoco de Mora, Mexico, 2012; pp. 15–17.

85. Eaton, F.M.; Belden, G.O. Leaf Temperatures of Cucumbers and Their Relation to Transpiration, Varietal Differences and Yields; United States Department of Agriculture: Washington, DC, USA, 1929.

86. Ehrler, W.L. Cotton leaf temperatures as related to soil water depletion and meteorological factors 1. *Agron. J.* **1973**, *65*, 404–409. [CrossRef]

87. Gates, D.M. Leaf temperature and transpiration1. *Agron. J.* **1964**, *56*, 273–277. [CrossRef]

88. Wallace, R.H.; Clum, H.H. Leaf temperatures. *Am. J. Bot.* **1938**, *25*, 83–97. [CrossRef]

89. Liu, F.; Jensen, C.R.; Andersen, M.N. Hydraulic and chemical signals in the control of leaf expansion and xylem embolism under soil drought in the Vosges mountains: Whole-tree hydraulic conductance, xylem embolism and water loss regulation. *Ann. For. Sci.* **1996**, *53*, 113–121. [CrossRef]

90. Savic, S.; Liu, F.; Stikic, R.; Jacobsen, S.-E.; Jensen, C.R.; Jovanovic, Z. Comparative effects of partial rootzone drying and deficit irrigation on growth and physiology of tomato plants. *Arch. Biol. Sci.* **2009**, *61*, 801–810. [CrossRef]

91. Hnilíčka, F.; Koudela, M.; Martinková, J.; Svozilová, V. Effects of deficit irrigation and straw mulching on gas exchange of cucumber plants (Cucumis sativus L.). *Acta Univ. Agric. Silvic. Meddel. Brun.* **2013**, *60*, 43–50.

92. Hashem, M.S.; El-Abedin, T.Z.; Al-Ghobari, H.M. Assessing effects of deficit irrigation techniques on water productivity of tomato for subsurface drip irrigation system. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 156–167. [CrossRef]

93. Xu, C.; Leskovar, D. Growth, physiology and yield responses of cabbage to deficit irrigation. *Hortic. Sci.* **2014**, *41*, 138–146. [CrossRef]

94. Testi, L.; Goldhamer, D.; Iniesta, F.; Salinas, M. Crop water stress index is a sensitive water stress indicator in pistachio trees. *Irrig. Sci.* **2008**, *26*, 395–405. [CrossRef]

95. Labate, C.A.; Adcock, M.D.; Leegood, R.C. Effects of temperature on the regulation of photosynthetic carbon assimilation in leaves of maize and barley. *Planta* **1990**, *181*, 547–554. [CrossRef]

96. Camejo, D.; Rodríguez, P.; Morales, M.A.; Dell’Amico, J.M.; Torrecillas, A.; Alarcón, J.J. High temperature effects on photosynthetic activity of two tomato cultivars with different heat susceptibility. *J. Plant Physiol.* **2005**, *162*, 281–289. [CrossRef]

97. Idso, S.; Jackson, R.; Pinter Jr, P.; Reginato, R.; Hatfield, J. Normalizing the stress-degree-day parameter for environmental variability. *Agric. Meteorol.* **1981**, *24*, 45–55. [CrossRef]
106. Walker, G.; Hatfield, J. Stress Measurement Using Foliage Temperatures. *Agron. J.* 1983, 75, 623–629. [CrossRef]

107. Smith, R.; Barrs, H.; Steiner, J.; Stapper, M. Relationship between wheat yield and foliage temperature: Theory and its application to infrared measurements. *Agric. For. Meteorol.* 1985, 36, 129–143. [CrossRef]

108. Çolak, Y.B.; Yazar, A.; Çolak, I.; Akça, H.; Duraktekin, G. Evaluation of crop water stress index (CWSI) for eggplant under varying irrigation regimes using surface and subsurface drip systems. *Agric. Agric. Sci. Procedia* 2015, 4, 372–382. [CrossRef]

109. Erdem, Y.; Arin, L.; Erdem, T.; Polat, S.; Deveci, M.; Okursoy, H.; Gültas, H.T. Crop water stress index for assessing irrigation scheduling of drip irrigated broccoli (*Brassica oleracea* L. var. italica). *Agric. Water Manag.* 2010, 98, 148–156. [CrossRef]

110. Orta, A.H.; Erdem, Y.; Erdem, T. Crop water stress index for watermelon. *Sci. Hortic.* 2003, 98, 121–130. [CrossRef]

111. Şimşek, M.; Kaçıra, M.; Tonkaz, T. The effects of different drip irrigation regimes on watermelon (*Citrullus lanatus* (Thunb.)) yield and yield components under semi-arid climatic conditions. *Aust. J. Agric. Res.* 2004, 55, 1149–1157.

112. Sezen, S.M.; Yazar, A.; Daşgan, Y.; Yucel, S.; Akyıldız, A.; Tekin, S.; Akhoundnejad, Y. Evaluation of crop water stress index (CWSI) for red pepper with drip and furrow irrigation under varying irrigation regimes. *Agric. Water Manag.* 2014, 143, 59–70. [CrossRef]

113. Aladenola, O.; Madramootoo, C. Response of greenhouse-grown bell pepper (*Capsicum annuum* L.) to variable irrigation. *Can. J. Plant Sci.* 2014, 94, 303–310. [CrossRef]

114. Obreza, T.; Pitts, D.; McGovern, R.; Spreen, T. Deficit irrigation of micro-irrigated tomato affects yield, fruit quality, and disease severity. *J. Prod. Agric.* 1996, 9, 270–275. [CrossRef]

115. Şimşek, M.; Tonkaz, T.; Kaçıra, M.; Çömlekçıoğlu, N.; Doğan, Z. The effects of different irrigation regimes on cucumber (*Cucumis sativus* L.) yield and yield characteristics under open field conditions. *Agric. Water Manag.* 2005, 73, 173–191.

116. Erdem, Y.; Erdem, T.; ORTA, A.H.; Okursoy, H. Irrigation scheduling for watermelon with crop water stress index (CWSI). *J. Cent. Eur. Agric.* 2005, 6, 449–460.

117. Idso, S.B. Non-water-stressed baselines: A key to measuring and interpreting plant water stress. *Agric. Meteorol.* 1982, 27, 59–70. [CrossRef]

118. Alderfasi, A.A.; Nielsen, D.C. Use of crop water stress index for monitoring water status and scheduling irrigation in wheat. *Agric. Water Manag.* 2001, 47, 69–75. [CrossRef]

119. Hatfield, J.; Wanjura, D.; Barker, G. Canopy temperature response to water stress under partial canopy. *Trans. Asae* 1985, 28, 1607–1611. [CrossRef]

120. Gardner, B.; Nielsen, D.; Shock, C. Infrared thermometry and the crop water stress index. I. History, theory, and baselines. *J. Prod. Agric.* 1992, 5, 462–466. [CrossRef]

121. Osakabe, Y.; Osakabe, K.; Shinozaki, K.; Tran, L.-S. Response of plants to water stress. *Front. Plant Sci.* 2014, 5. [CrossRef]

122. Wright, S. The relationship between leaf water potential ψ*leaf* and the levels of abscisic acid and ethylene in excised wheat leaves. *Planta* 1977, 134, 183–189. [CrossRef] [PubMed]

123. Miller, G.; Khalilian, A.; Adelberg, J.W.; Farahani, H.J.; Hassell, R.L.; Wells, C.E. Grafted watermelon root length density and distribution under different soil moisture treatments. *HortScience* 2013, 48, 1021–1026. [CrossRef]

124. Cutler, A.J.; Krochko, J.E. Formation and breakdown of ABA. *Trends Plant Sci.* 1999, 4, 472–478. [CrossRef]

125. Fambrini, M.; Vernieri, P.; Toncelli, M.L.; Rossi, V.D.; Pugliesi, C. Characterization of a wiltly sunflower (*Helianthus annuus* L.) mutant: III. Phenotypic interaction in reciprocal grafts from wiltly mutant and wild-type plants. *J. Exp. Bot.* 1995, 46, 525–530. [CrossRef]

126. Holbrook, N.M.; Shashidhar, V.; James, R.A.; Munns, R. Stomatal control in tomato with ABA-deficient roots: Response of grafted plants to soil drying. *J. Exp. Bot.* 2002, 53, 1503–1514.

127. Jones, H.; Sharp, C.; Higgs, K. Growth and water relations of wiltly mutants of tomato (*Lycopersicon esculentum* Mill.). *J. Exp. Bot.* 1987, 38, 1848–1856. [CrossRef]

128. Bhargava, S.; Sawant, K. Drought stress adaptation: Metabolic adjustment and regulation of gene expression. *Plant Breed.* 2013, 132, 21–32. [CrossRef]
129. Suzuki, N.; Miller, G.; Salazar, C.; Mondal, H.A.; Shulaev, E.; Cortes, D.F.; Shuman, J.L.; Luo, X.; Shah, J.; Schlauch, K.; et al. Temporal-Spatial Interaction between Reactive Oxygen Species and Abscisic Acid regulates rapid systemic acclimation in plants. *Plant Cell* 2013, 25, 3553–3569. [CrossRef]

130. Neill, S.; Horgan, R. Abscisic acid production and water relations in wilting tomato mutants subjected to water deficiency. *J. Exp. Bot.* 2004, 55, 2365–2384. [CrossRef]

131. Yuan, G.-F.; Jia, C.-G.; Li, Z.; Sun, B.; Zhang, L.-P.; Liu, N.; Wang, Q.-M. Effect of brassinosteroids on drought resistance and abscisic acid concentration in tomato under water stress. *Sci. Hort.* 2010, 126, 103–108. [CrossRef]

132. Seemann, J.R.; Sharkey, T.D. The effect of abscisic acid and other inhibitors on photosynthetic capacity and the biochemistry of CO2 assimilation. *Plant Physiol.* 1987, 84, 696–700. [CrossRef] [PubMed]

133. Wilkinson, S.; Davies, W.J. Drought, ozone, ABA and ethylene: New insights from cell to plant to community. *Plant Cell Environ.* 2011, 33, 510–525. [CrossRef] [PubMed]

134. Desikan, R.; Last, K.; Harrett-Williams, R.; Tagliavia, C.; Harter, K.; Hooley, R.; Hancock, J.T.; Neill, S.J. Ethylene-induced stomatal closure in Arabidopsis occurs via AtrbohF-mediated hydrogen peroxide synthesis. *Plant J.* 2006, 47, 907–916. [CrossRef]

135. Osmolovskaya, N.; Shumilina, J.; Kim, A.; Didio, A.; Grishina, T.; Bilova, T.; Keltisieva, O.A.; Zhukov, V.; Tikhonovich, I.; Tarakhovskaya, E. Methodology of drought stress research: Experimental setup and physiological characterization. *Int. J. Mol. Sci.* 2018, 19, 4089. [CrossRef] [PubMed]

136. Paudel, G.; Bilova, T.; Schmidt, R.; Greifenhagen, U.; Berger, R.; Tarakhovskaya, E.; Stöckhardt, S.; Balcke, G.; Humbek, K.; Brandt, W. Changes in Arabidopsis thaliana advanced glycated proteome induced by the polyethylene glycol-related osmotic stress. *J. Exp. Bot.* 2016, 67, 6283–6295. [CrossRef]

137. Sanders, G.J.; Arndt, S.K. Osmotic adjustment under drought conditions. In *Plant Responses to Drought Stress*. Springer: Berlin/Heidelberg, Germany, 2012; pp. 199–229.

138. Girma, F.S.; Krieg, D.R. Osmotic adjustment in sorghum: I. Mechanisms of diurnal osmotic potential changes. *Plant Physiol.* 1992, 99, 577–582. [CrossRef]

139. Chaves, M.M.; Oliveira, M.M. Mechanisms underlying plant resilience to water deficits: Prospects for water-saving agriculture. *J. Exp. Bot.* 2004, 55, 2365–2384. [CrossRef]

140. Oosterhuis, D.M.; Wullschleger, S.D. Osmotic adjustment in cotton (Gossypium hirsutum L.) leaves and roots in response to water stress. *Plant Physiol.* 1987, 84, 1154–1157. [CrossRef]

141. Yuan, G.-F.; Jia, C.-G.; Li, Z.; Sun, B.; Zhang, L.-P.; Liu, N.; Wang, Q.-M. Effect of brassinosteroids on drought resistance and abscisic acid concentration in tomato under water stress. *Sci. Hort.* 2010, 126, 103–108. [CrossRef]

142. Ashraf, M.; Foolad, M. Roles of glycine betaine and proline in improving plant abiotic stress resistance. *Environ. Exp. Bot.* 2007, 59, 206–216. [CrossRef] [PubMed]

143. Nahar, K.; Ullah, S.M. Drought Stress Effects on Plant Water Relations, Growth, Fruit Quality and Osmotic Adjustment of Tomato (Solanum lycopersicum) under Subtropical Condition. *Asian J. Agric. Hortic. Res.* 2013, 25, 3945–25 of 28. [CrossRef] [PubMed]

144. Sarker, B.C.; Hara, M.; Uemura, M. Proline synthesis, physiological responses and biomass yield of eggplants during and after repetitive soil moisture stress. *Sci. Hort.* 2009, 119, 949–954. [CrossRef] [PubMed]

145. Crusciol, C.A.; Pulz, A.L.; Lemos, L.B.; Soratto, R.P.; Lima, G.P. Effects of silicon and drought stress on tuber yield and leaf biochemical characteristics in potato. *Crop Sci.* 2009, 49, 949–954. [CrossRef] [PubMed]

146. Giri, J. Glycinebetaine and abiotic stress tolerance in plants. *Plant Signal. Behav.* 2011, 6, 1746–1751. [CrossRef] [PubMed]

147. Kramer, P.J.; Boyer, J.S. *Water Relations of Plants and Soils*; Academic Press: Cambridge, MA, USA, 1995.

148. Templer, S.E.; Ammon, A.; Pscheidt, D.; Ciobotea, O.; Schuy, C.; McCollum, C.; Sonnewald, U.; Hanemann, A.; Förster, J.; Ordon, F.; et al. Metabolite profiling of barley flag leaves under drought and combined heat and drought stress reveals metabolic QTLs for metabolites associated with antioxidant defense. *J. Exp. Bot.* 2017, 68, 1697–1713. [CrossRef]

149. Levitt, J. *Responses of Plants to Environmental Stresses*; Academic Press: Cambridge, MA, USA, 1987; Volume 2.

150. Blum, A.; Ebercon, A. Cell membrane stability as a measure of drought and heat tolerance in wheat 1. *Crop Sci.* 1981, 21, 43–47. [CrossRef]

151. Bajji, M.; Kinet, J.-M.; Lutts, S. Osmotic and ionic effects of NaCl on germination, early seedling growth, and ion content of Atriplex halimus (Chenopodiaceae). *Can. J. Bot.* 2002, 80, 297–304. [CrossRef]
152. Bajji, M.; Kinet, J.-M.; Lutts, S. The use of the electrolyte leakage method for assessing cell membrane stability as a water stress tolerance test in durum wheat. Plant Growth Regul. 2002, 36, 61–70. [CrossRef]

153. McNeil, P.L.; Steinhardt, R.A. Loss, restoration, and maintenance of plasma membrane integrity. J. Cell Biol. 1997, 137, 1–4. [CrossRef]

154. Wang, M.; Zheng, Q.; Shen, Q.; Guo, S. The critical role of potassium in plant stress response. Int. J. Mol. Sci. 2013, 14, 7370–7390. [CrossRef] [PubMed]

155. Demidchik, V.; Stralsdova, D.; Medvedev, S.S.; Pozhvanov, G.A.; Sokolik, A.; Yurin, V. Stress-induced electrolyte leakage: The role of K+-permeable channels and involvement in programmed cell death and metabolic adjustment. J. Exp. Bot. 2014, 65, 1259–1270. [CrossRef] [PubMed]

156. Kirnak, H.; Kaya, C.; Tas, I.; Higgs, D. The influence of water deficit on vegetative growth, physiology, fruit yield and quality in eggplants. Bulg. J. Plant Physiol 2001, 27, 34–46.

157. Kirnak, H.; Tas, I.; Kaya, C.; Higgs, D. Effects of deficit irrigation on growth, yield and fruit quality of eggplant under semi-arid conditions. Aust. J. Agric. Res. 2002, 53, 1367–1373. [CrossRef]

158. El-Mageed, T.A.; Semida, W.; Mohamed, G.; Rady, M. Combined effect of foliar-applied salicylic acid and deficit irrigation on physiological-anatomical responses, and yield of squash plants under saline soil. South Afr. J. Bot. 2016, 106, 8–16. [CrossRef]

159. Abdelhady, S.A.; El-Azm, N.; El-Kafafi, E.-S.H. Effect of deficit irrigation levels and NPK fertilization rates on tomato growth, yield and fruits quality. Middle East J. 2017, 6, 587–604.

160. Hayat, S.; Hasan, S.A.; Fariduddin, Q.; Ahmad, A. Growth of tomato (Lycopersicon esculentum) in response to salicylic acid under water stress. J. Plant Interact. 2008, 3, 297–304. [CrossRef]

161. Atkinson, M.M.; Huang, J.-S.; Knopp, J.A. The hypersensitive reaction of tobacco to Pseudomonas syringae pv. pisi: Activation of a plasmalemma K+/H+ exchange mechanism. Plant Physiol. 1985, 79, 843–847. [CrossRef]

162. Atkinson, M.M.; Keppler, L.D.; Orlandi, E.W.; Baker, C.J.; Mischke, C.F. Involvement of plasma membrane calcium influx in bacterial induction of the K+/H+ and hypersensitive responses in tobacco. Plant Physiol. 1990, 92, 215–221. [CrossRef]

163. Ebel, J.; Mithöfer, A. Early events in the elicitation of plant defence. Planta 1998, 206, 335–348. [CrossRef]

164. Blatt, M.R.; Grabov, A.; Brearley, J.; Hammond-Kosack, K.; Jones, J.D. K+ channels of Cf-9 transgenic tobacco guard cells as targets for Cladosporium fulvum Avr9 elicitor-dependent signal transduction. Plant J. 1999, 19, 453–462. [CrossRef] [PubMed]

165. Maffei, M.E.; Mithöfer, A.; Boland, W. Before gene expression: Early events in plant–insect interaction. Trends Plant Sci. 2007, 12, 310–316. [CrossRef] [PubMed]

166. De Vos, C.; Schat, H.; De Waal, M.; Vooios, R.; Ernst, W. Increased resistance to copper-induced damage of the root cell plasmalemma in copper tolerant Silene cucubalus. Physiol. Plant. 1991, 82, 523–528. [CrossRef]

167. Murphy, A.; Taiz, L. Correlation between potassium efflux and copper sensitivity in 10 Arabidopsis ecotypes. New Phytol. 1997, 136, 211–222. [CrossRef]

168. Demidchik, V.; Shabala, S.N.; Coutts, K.B.; Tester, M.A.; Davies, J.M. Free oxygen radicals regulate plasma membrane Ca2+- and K+-permeable channels in plant root cells. J. Cell Sci. 2003, 116, 81–88. [CrossRef]

169. Nassery, H. The effect of salt and osmotic stress on the retention of potassium by excised barley and bean roots. New Phytol. 1975, 75, 63–67. [CrossRef]

170. Maathuis, F.J.; Amtmann, A. K+ nutrition and Na+ toxicity: The basis of cellular K+/Na+ ratios. Ann. Bot. 1999, 84, 123–133. [CrossRef]

171. Shabala, S.; Demidchik, V.; Shabala, L.; Cuin, T.A.; Smith, S.J.; Miller, A.J.; Davies, J.M.; Newman, I.A. Extracellular Ca2+ ameliorates NaCl-induced K+ loss from Arabidopsis root and leaf cells by controlling plasma membrane K+-permeable channels. Plant Physiol. 2006, 141, 1653–1665. [CrossRef]

172. Demidchik, V. Reactive oxygen species, oxidative stress and plant ion channels. In Ion Channels and Plant Stress Responses; Springer: Berlin/Heidelberg, Germany, 2010; pp. 207–232.

173. Liu, X.; Huang, B. Heat stress injury in relation to membrane lipid peroxidation in creeping bentgrass. Crop Sci. 2000, 40, 503–510. [CrossRef]

174. Metwaly, E.; El-Shatoury, R. An Attempt to Alleviation of Irrigation Water Deficit Stress in Cabbage (Brassica oleracea Var. Capitata L.) by Exogenous Foliar Application with some Antioxidant. J. Plant Prod. 2017, 8, 1315–1322. [CrossRef]
Ullah, U.; Ashraf, M.; Shahzad, S.M.; Siddiqui, A.R.; Piracha, M.A.; Suleman, M. Growth behavior of tomato (Solanum lycopersicum L.) under drought stress in the presence of silicon and plant growth promoting rhizobacteria. Soil Environ. 2016, 35, 65–75.

Hillel, D.; Hattfield, J.L. Encyclopedia of Soils in the Environment; Elsevier: Amsterdam, The Netherlands, 2005; Volume 3.

Yang, H.; Shukla, M.K.; Mao, X.; Kang, S.; Du, T. Interactive regimes of reduced irrigation and salt stress depressed tomato water use efficiency at leaf and plant scales by affecting leaf physiology and stem sap flow. Front. Plant Sci. 2019, 10, 160. [CrossRef] [PubMed]

Qiu, R.; Du, T.; Kang, S.; Chen, R.; Wu, L. Influence of water and nitrogen stress on stem sap flow of tomato grown in a solar greenhouse. J. Am. Soc. Hortic. Sci. 2015, 140, 111–119. [CrossRef]

Grey, S.N. Monitoring the Simultaneous Response of Various Water Status Indicators for Use in the Irrigation Scheduling and Drought Stress Detection of a Greenhouse Tomato Crop. Master’s Thesis, University of Zimbabwe, Harare, Zimbabwe, 2012.

Eastham, J.; Gray, S.A. A preliminary evaluation of the suitability of sap flow sensors for use in scheduling vineyard irrigation. Am. J. Enol. Vitic. 1998, 49, 171–176.

Ginestar, C.; Eastham, J.; Gray, S.; Iland, P. Use of sap-flow sensors to schedule vineyard irrigation. II. Effects of post-veraison water deficits on composition of Shiraz grapes. Am. J. Enol. Vitic. 1998, 49, 421–428.

Améglio, T.; Archer, P.; Cohen, M.; Valancogne, C.; Daudet, F.-a.; Dayau, S.; Cruiziat, P. Significance and limits in the use of predawn leaf water potential for tree irrigation. Plant Soil 1999, 207, 155–167. [CrossRef]

Fernández, J.; Palomo, M.; Díaz-Espejo, A.; Clothier, B.; Green, S.; Girón, I.; Moreno, F. Heat-pulse measurements of sap flow in olives for automating irrigation: Tests, root flow and diagnostics of water stress. Agric. Water Manag. 2001, 51, 99–123. [CrossRef]

Giorio, P.; Giorio, G. Sap flow of several olive trees estimated with the heat-pulse technique by continuous monitoring of a single gauge. Environ. Exp. Bot. 2003, 49, 9–20. [CrossRef]

Remorini, D.; Massai, R. Comparison of water status indicators for young peach trees. Irrig. Sci. 2003, 22, 39–46. [CrossRef]

Ehret, D.; Lau, A.; Bittman, S.; Lin, W.; Shelford, T. Automated monitoring of greenhouse crops. Agronomie 2001, 21, 403–414. [CrossRef]

De Swaef, T.; Steppe, K.; Lemeur, R. Determining reference values for stem water potential and maximum daily trunk shrinkage in young apple trees based on plant responses to water deficit. Agric. Water Manag. 2009, 96, 541–550. [CrossRef]

Liu, H.; Sun, J.; Duan, A.; Liu, Z.; Liang, Y. Experiments on variation of tomato sap flow under drip irrigation conditions in greenhouse. Trans. Chin. Soc. Agric. Eng. 2010, 26, 77–82.

Molz, F.J.; Klepper, B. On the Mechanism of Water-Stress-Induced Stem Deformation 1. Agron. J. 1973, 65, 304–306. [CrossRef]

Kozlowski, T. Water supply and leaf shedding. Soil Water Meas. Plant Responses Breed. Drought Resist. 1976, 4, 191–231.

Dobbs, R.; Scott, D. Distribution of diurnal fluctuations in stem circumference of Douglas-fir. Can. J. For. Res. 1971, I, 80–83. [CrossRef]

Jarvis, P. Water transfer in plants. In Heat and Mass Transfer in the Biosphere; Scripta Book Co.: Washington, DC, USA, 1975; pp. 369–394.

Klepper, B.; Taylor, H.; Huck, M.; Fiscus, E. Water Relations and Growth of Cotton in Drying Soil1. Agron. J. 1973, 65, 307–310. [CrossRef]

Goldhamer, D.A.; Fereres, E. Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrig. Sci. 2001, 20, 115–125. [CrossRef]

Goldhamer, D.A.; Fereres, E.; Mata, M.; Girona, J.; Cohen, M. Sensitivity of continuous and discrete plant and soil water status monitoring in peach trees subjected to deficit irrigation. J. Am. Soc. Hortic. Sci. 1999, 124, 437–444. [CrossRef]

Moriani, A.; Fereres, E. Plant indicators for scheduling irrigation of young olive trees. Irrig. Sci. 2002, 21, 83–90.

Gallardo, M.; Thompson, R.; Valdez, L.; Fernández, M. Use of stem diameter variations to detect plant water stress in tomato. Irrig. Sci. 2006, 24, 241–255. [CrossRef]
198. Fereres, E.; Goldhamer, D. Suitability of stem diameter variations and water potential as indicators for irrigation scheduling of almond trees. *J. Hortic. Sci. Biotechnol.* 2003, 78, 139–144. [CrossRef]
199. Goldhamer, D.; Fereres, E. Irrigation scheduling of almond trees with trunk diameter sensors. *Irrig. Sci.* 2004, 23, 11–19. [CrossRef]
200. Intrigliolo, D.; Castel, J. Continuous measurement of plant and soil water status for irrigation scheduling in plum. *Irrig. Sci.* 2004, 23, 93–102. [CrossRef]
201. Moriana, A.; Fereres, E. Establishing reference values of trunk diameter fluctuations and stem water potential for irrigation scheduling of olive trees. In *Proceedings of the IV International Symposium on Irrigation of Horticultural Crops*; ISHS Acta Horticulturae 664; International Society for Horticultural Science: Leuven, Belgium, 2004; pp. 407–412.
202. Gallardo, M.; Thompson, R.; Valdez, L.; Pérez, C. Response of stem diameter to water stress in greenhouse-grown vegetable crops. In *Proceedings of the IV International Symposium on Irrigation of Horticultural Crops*; ISHS Acta Horticulturae 664; International Society for Horticultural Science: Leuven, Belgium, 2004; pp. 253–260.
203. Cohen, M.; Save, R.; Biel, C.; Marfà, O. Simultaneous measurements of water stress with LVDT sensors and electrotensimeters: Application in pepper plants grown in two types of perlites. In *Proceedings of the II International Symposium On Sensors in Horticulture*; ISHS Acta Horticulturae 421; International Society for Horticultural Science: Leuven, Belgium, 1998; pp. 193–200.
204. Katerji, N.; Hamdy, A.; Raad, A.; Mastrorilli, M. *Consequences of Water Stress Applied at Different Growth Stages in the Production of Pepper Plants*; Food and Agriculture Organization: Rome, Italy, 1991.
205. Fernández, J.; Cuevas, M. Irrigation scheduling from stem diameter variations: A review. *Agric. For. Meteorol.* 2010, 150, 135–151. [CrossRef]
206. Tardieu, F.; Granier, C.; Muller, B. Modelling leaf expansion in a fluctuating environment: Are changes in specific leaf area a consequence of changes in expansion rate? *New Phytol.* 1999, 143, 33–43. [CrossRef]
207. Weraduwage, S.M.; Chen, J.; Anozie, F.C.; Morales, A.; Weise, S.E.; Sharkey, T.D. The relationship between leaf area growth and biomass accumulation in Arabidopsis thaliana. *Front. Plant Sci.* 2015, 6, 167. [CrossRef]

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