

Original Research Article

Watering Regimes and Their Effects on Growth and Yield of Soybean (*Glycine max* L. Merrill) Varieties

Abstract

Climate change is causing a serious threat to agricultural sector as the major causes of environmental stress influencing plant growth and development. Water stress is one the major environmental stress. In order to evaluate the effects of two contrasting water stress (drought and waterlogging) on the growth and yield of soybean, a greenhouse experiment with 3 varieties of soybean and 5 watering regimes was conducted. Result showed that drought has more significant effect on soybean production than waterlogging. Water stress was observed to reduce plant height, root length, leaf area, number of leaves and number of pods produced in soybean. There is increase in chlorophyll A, chlorophyll B and proline which signify increase tolerance and resistance to water stress. Soil nitrogen fixed was reduced as water stress increases from waterlogging to drought. Findings shows that varieties of soybean were significant in all data obtained except root length. Result also concluded that watering regime of twice a week producing an average soil water content of 22.02% will be optimum for soybean production.

Keywords: Soybean, watering regimes, drought, waterlogging, chlorophyll content, proline, morphological traits

Introduction

Climate change has recently brought severe environmental factors to living organism. Environmental factors such as rainfall, temperature, soil salinity are becoming more extreme to plants as result of this climate change. Among these, water stress is the most significant. Water is an important compound to all living organisms due to its essential function for respiration and biochemical reactions in living organisms. Significance of water to plant might be negated in some cases causing water stress. Water stress including drought and waterlogging (flooding) is becoming a significant agricultural problem due to climate change (1). Plants which are sessile organism are mostly exposed to these two stresses. Responses of plant to stress occur through a number of ways such as anatomical, morphological or physiological responses. Water stress is a major setback to global food production and food security (2) as two – third of crop production in the world are cultivated under water stress (3). Drought is one of the major abiotic factors leading to high reduction in plant growth and development. It is the leading factor in limiting crop plant production. Lesk et al. (4) reported that it reduces plant yield by up to 50% in various part of the world. It is probably the most severe stress and major causes of significant losses in growth, productivity and yields of crop plants worldwide (5–7). It affects the physiological, biochemical and molecular processes in plants leading to growth inhibition, stomata closure, decrease in chlorophyll content, inhibition of photosynthesis and protein changes (8,9). Unfortunately, land area affected by drought worldwide has more than doubled from the early 1970's to the early 2000's (10). Drought severity is unpredictable and determined by rainfall amount, soil moisture holding capacity and crop evaporative demands (11). Water shortage is expected to increase due to global warming effects increasing evapotranspiration and drought intensity from 1 – 30% by 2100 (12,13). Waterlogging are natural water disturbances which have detrimental effects on terrestrial plants (14). Waterlogging mostly affects terrestrial plant roots as its aerobic respiration ceases due to waterlogging, reduces energy rich adenylates causing

decline in ion uptake and transport (15). It can cause oxygen stress (hypoxia) or total absence of oxygen (anoxia) in plants root (16). Excess water condition leads to high absorption, low transpiration rate causing build of high turgor pressure in cell elongation region causing maximum swelling of the cells resulting in leggy seedlings (17,18).

Glycine max (L.) Merrill (Soybean) is one of the underused crops in Africa including Nigeria. It is an economically legume crop cultivated worldwide. The crop is recently gaining attention due to its high combined vegetable protein (40%) and oil (20%) contents (19,20). Soybean, when processed in to flour, can be used in fortification of the common carbohydrates-based food in the region. The soybean leaves are an edible source of protein source in livestock feed and the roots when planted fixes nitrogen into the soil thereby repairing the soil through its nitrogen fixing capabilities and commonly used in crop rotation. Factors such as water availability affect its growth (21). Water stress is the most common and detrimental factor that significantly limits its production and yield (22,23) as it is sensitive to both waterlogging and flooding which reduce its growth and yield significantly (24). Soybean is sensitive to both water stresses and undergo morphological, physiological and biochemical changes which negatively affects its growth and yield (25). Global climate changes with persistent water stress are frightening reality to the sustainability of soybean production worldwide (26). Soybean production under water stress is dependent on the phenological stages of crop, duration and intensity of water stress (27).

Water availability, excess or scarcity, can mean a successful harvest, reduction or total failure in yield. Knowledge of the amount of water needed for optimum growth is therefore necessary for planting time and use of irrigation or drainage where necessary for optimum production. Watering regimes is an economical management strategy to improve time and irrigation water application/drainage as its contribution to irrigation/drainage profitability and water use efficiency (28). Plants use several morphological and physiological adaptive mechanism such as reduction in leaf sizes, hormonal changes or molecular adaptive mechanism to survive prolonged water stress (29). Differences in days of watering produces varying results in soil moisture content and provide a good adaptable way when irrigating soil as the procedure of soil moisture content calculation (30) has soil moisture content have been found tedious by small scale farmers. To overcome food and protein security threat, it is essential to identify best watering regimes for soybean cultivars. The study therefore investigates the best watering regime for optimum performance in soybean cultivation.

MATERIALS AND METHODS

Experimental Site:

The experiment was carried out at the green house of the Department of Botany, Faculty of Science, University of Ibadan, Ibadan, in order to control undesired input of water from external sources. Polythene bags were filled with sandy loamy soil gotten from the University of Ibadan nursery.

Plant materials:

Three varieties of soybean were collected from International Institute for Tropical Agriculture (IITA), Ibadan and are labelled as follows; Variety A - TGX 1987-10F, Variety B - TGX 1835-10E and Variety C - TGX 1987-62F. The soil was watered to field capacity and 3 seeds were planted into each of the pot. Germination and growth of seedlings were allowed for two weeks before imposition of water treatment after germinated seed were thinned to one stand per pot.

Experimental Treatments:

Water stress was simulated by variation in days of irrigation and waterlogging treatment always had soil over-saturated with water without submerging any parts of the plant. The soybean germinated seedlings were subjected to different watering regimes as follows: waterlogging treatment (Wat); once daily (1dy); twice a week (3dy); once a week (1wk) and once in two weeks (2wk). Plants were watered to field capacity on irrigation day until harvest.

Soil Moisture Content (SMC):

Small quantities of soil were taken from each watering regimes into an already weighed crucible and the weight is measured. This is taken as the wet weight (WW). The soil in the crucible was then oven dried at 80°C for 48hrs until a stable weight is obtained. The weight was measured again and taken as the dry weight (DW). SMC was then calculated as follows $SMC = \frac{WW - DW}{DW} \times 100$.

Morphological characters and yield:

Plant Height (PH), Root Length (RL), Leaf area (LA) = (Leaf Length × Leaf Breadth × Correlation factor (0.75) of third trifoliolate leaves) were measured with metre rule; Number of Leaves (NL), and Yield (Yd) was measured by counting the matured soybean pod produced by each treatment at the end of the experiment.

Chlorophyll Content:

Chlorophyll content was estimated and calculated using Arnon (31) method.

Proline Content:

Proline was estimated spectrophotometrically as concentration was determined by reference to a standard curve prepared using 0-1 mg L⁻¹ proline (sigma) and calculated on a dry weight basis (32).

Total Soil Nitrogen (TSN):

Soil collected from each treatment estimated using Bremmer (33) method and calculated using the following formula

$$\text{Total Soil Nitrogen (\%)} = \frac{(\text{Volume of NaOH} * \text{Normality of NaOH} * 14)}{\text{weight of sample in gram (0.5g)}} \quad (33).$$

Statistical Analysis:

Data were collected in triplicate and processed using Excel 2019 software and the data were expressed as average values ± standard error. SPSS 21.0 statistical analysis software (IBM Corp., Armonk, NY, USA) was used to perform the ANOVA analysis and used to compare treatments and interaction at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Effect of watering regimes on soil moisture content

Table 1: Table showing watering regimes on average soil moisture content

Wat	1dy	3dy	1wk	2wk	ANOVA (Watering Regime) at $\alpha = 0.05$
Soil Moisture Content (%)					
41.40 ± 0.48	37.32 ± 0.55	22.02 ± 2.32	15.06 ± 2.62	9.01 ± 1.94	44.995*

Soil moisture content is reflection of the watering regimes application. Good vegetative growth and yield are observed in plants with optimum soil moisture content. Average soil moisture content reduces from 41.40% in waterlogging treatment to 9.01% in once in two-week treatment in the study as shown in table 1. Decreased

soil moisture content under drought conditions has been reported in various agricultural system (34) and increase soil moisture content under waterlogging due to poor drainage (35). Increased leaf and soil evaporation during drought contributes to its low soil water content (37). Lee et al. (37) reported different growth responses in perennial herbaceous plants as soil moisture increased. Waterlogging reduces soybean yield by 17 to 43% and its vegetative growth by 50 to 56% (38).

Effects of watering regimes on soybean morphological characters and yield

Effects of water stress imposed in soybean are reflected in the morphological traits and yield of soybean. It reduces plant height from 146.33cm, 137.53cm and 156.20cm in daily application to 145.53cm, 132.13cm and 131.80cm in waterlogging treatment and 110.50cm, 104.73cm and 119.53cm in once in two weeks treatment in variety A, B and C respectively (Table 2). Results also indicated that the effect on watering regime is significant on plant height while variety effect was not significant as shown in the ANOVA analysis (Table 3). There is reduction in plant height under water stress (39,40). Previous study reported soybean seedling height decreased by 4.3% under drought stress (41). Drought stress reduces soybean plant height by limiting photosynthesis and nutrient uptake leading to hormonal imbalance and impaired plant growth (42). Similar effect is exhibited by waterlogging by restricting oxygen availability in plant root and leading to stunted growth (43). Anoxia and drought in plants reduces production and translocation of assimilants (44). Root length is an important morphological trait in plant under stress and perform important role in its survival during these periods (45). Results indicated that root length has the highest length under twice a week treatment with 31.60cm, 32.60cm and 29.40cm and reduced to 17.40cm, 16.40cm and 15.0cm in waterlogging treatment and 17.80cm, 21.20cm and 22.80cm in once in two-week water regime treatment in variety A, B and C respectively (Table 2). Results indicated that both water stresses significantly affect root length while variety was not found to be significant (Table 3). Manavalan et al. (46) and (47) reported a decrease in soybean root length under drought while (48) and (49) also reported similar results in soybean root length under waterlogging stress. (50) reported that excess water in soil induces root decay, affects root formation and growth of existing roots though root tolerance to anoxia varies among plant species (51). There is also reduction in root characters i.e. length, density and thickness as a result of low water supply. Drought stress increases the root length as the roots searched for water (52). In general, longer root growth has higher resistance ability to water stress condition (53).

Table 2 also shows that leaf area was reduced from 85.19cm², 110.27cm² and 74.68cm² in twice a week water regime to 63.96cm², 61.42cm² and 53.15cm² in waterlogging and 65.67cm², 70.61cm² and 49.57cm² in once in two weeks water treatment in variety A, B and C respectively. Watering regime treatment and varieties were significant on leaf area as indicated in Table 3. Previous research had shown reduction in leaf area in soybean under drought (54) and waterlogging (55) as leaf area is sensitive to water stress since there is increased ethylene production during stress causing leaf growth reduction (56). Decreased cell expansion and leaf growth inhibition under drought is described as a water saving mechanism (57,58). Reduced leaf area in drought has a direct consequence of limiting water losses by reducing stomatal and cuticular transpiration (59). Reduction in leaf area under drought results in decreasing intercepting radiation area resulting in decrease in transpiration (60). Thus, it can be substantiated that long and droopy leaves (*i.e.* with higher leaf angle) results into leaf rolling which is an adaptive response to water deficit in rice (61).

Number of leaves reduced from 9.20, 8.40 and 10.27 of leaves in twice a week water regime application to 7.60, 7.73 and 8.13 in waterlogging treatment and 7.47, 7.60 and 9.20 in once in two weeks water treatment (Table 2). Watering regime plays significant role in number of leaves while varieties was not significant (Table 3). Reduction in number of leaves observed in was more pronounced in drought than waterlogging (62). Results has shown reduction in **number of leaves** in soybean under drought condition (63). This results shows decrease leaf initiation and early senescence and can be drought tolerance mechanism or water conservation strategy under drought (12). Similar observation was reported in the number of leaves of *Conocarpus erectus* under drought (63). Number of leaves reduction which may be as a result of leaf shedding due to oxygen deficiency (64) was also reported under waterlogging (50).

Fruiting pod is the main yield of soybean plant producing the soybean seeds. Soybean pod yield was reduced under drought from 13, 11 and 12 pods produced under watering twice a week watering regime to 5, 6 and 7 in waterlogging and 3, 3 and 4 pods produced under once in two weeks water regime application in variety A, B and C respectively. Soybean growth and development is affected under waterlogging and drought watering regimes which then reduces the yield as stress increases. Stress factor particularly drought negatively causes sharp decrease of plant yield (65). Yield is reduced under drought stress as reported by previous researches(66,67). Drought leads to reduction in flower initiation, pod set, pod number per plant and pod size (68). Waterlogging causes impaired pollen viability, increased flower abortion and inhibited reproductive development (69,70).

All morphological traits are affected by the waterlogging and drought factor as seen in table 3 with soybean varieties significant on leaf area only. Good morphological characters and yield result were generally obtained in twice a week treatment with a soil moisture content of 38% across all varieties. In all soybean varieties studied, morphological characters showed a decrease with increase water stress with waterlogging performing better than drought. Decrease in morphological characters and pod might be due to decrease in cell elongation resulting from the inhibiting effect of water stress on growth promoting hormone leading to decrease in cell turgor and eventually leading to suppression in plant photosynthetic efficiency due to closing of stomata and inhibition of Rubisco enzyme (8).

Table 2: Morphological traits and yield of soybean varieties in response to different watering regime

	Wat	1dy	3dy	1wk	2wk
Varieties	Plant Height (cm)				
A	145.53 ± 19.65	146.33 ± 18.63	145.47 ± 15.32	134.87 ± 16.14	110.50 ± 14.02
B	132.13 ± 15.41	137.53 ± 16.68	134.60 ± 15.37	128.00 ± 13.79	104.73 ± 14.56
C	131.80 ± 16.33	156.20 ± 19.16	154.20 ± 20.21	146.20 ± 21.04	119.53 ± 16.40
Varieties	Root Length (cm)				
A	17.40 ± 1.60	29.60 ± 3.46	31.60 ± 1.50	24.60 ± 0.51	17.80 ± 1.85
B	16.40 ± 2.42	29.40 ± 2.16	32.60 ± 2.38	25.00 ± 1.22	21.20 ± 2.18
C	15.40 ± 2.42	28.40 ± 1.60	29.40 ± 2.84	26.60 ± 2.20	22.80 ± 2.60
Varieties	Leaf Area (cm²)				
A	63.96 ± 2.64	76.65 ± 7.86	85.19 ± 7.05	66.78 ± 6.93	65.67 ± 7.03
B	61.42 ± 6.50	87.27 ± 9.60	110.27 ± 8.01	105.05 ± 8.82	70.61 ± 7.59

C	53.15 ± 4.12	73.19 ± 8.61	74.67 ± 10.63	63.05 ± 7.44	49.57 ± 4.75
Varieties	Number of Leaves				
A	7.60 ± 0.97	8.00 ± 1.04	9.20 ± 1.27	8.20 ± 1.23	7.47 ± 1.03
B	7.73 ± 1.05	7.67 ± 1.15	8.40 ± 1.16	7.67 ± 1.07	7.40 ± 1.19
C	8.13 ± 1.11	9.13 ± 1.06	10.27 ± 1.59	9.20 ± 1.27	8.47 ± 1.18
Varieties	Number of Fruiting Pods				
A	5 ± 0	7 ± 1	13 ± 1	7 ± 1	3 ± 1
B	6 ± 1	8 ± 0	11 ± 0	9 ± 0	3 ± 1
C	7 ± 0	9 ± 2	12 ± 2	8 ± 1	4 ± 1

Wat - Waterlogging, 1dy - Daily watering, 3dy - Twice a week, 1wk - Once a week, 2wk - Once in two weeks

Table 3: ANOVA for soybean morphological traits and yield at p = 0.05

Effect	Df	Plant Height	Root Length	Leaf Area	Number of Leaves	Number of Fruiting Pod
Wat. Reg	4	2.04*	23.45*	8.87*	1.62*	28.56*
Varieties	2	0.89*	0.13	13.50*	1.34*	0.61*
Wat. Reg x Varieties	8	0.11	0.59	1.50*	0.49	0.64

Effects of watering regime on chlorophyll contents

Table 4: Effects of watering regime on chlorophyll A and chlorophyll B in soybean varieties

	Wat	1dy	3dy	1wk	2wk	ANOVA (Watering Regime) at p = 0.05
Varieties	Chlorophyll A Content (mg/g)					
A	7.64	16.19	17.01	18.47	21.97	
B	3.98	10.50	10.71	15.73	16.39	212.73*
C	5.38	15.84	15.30	16.33	18.03	
Varieties	Chlorophyll B Content (mg/g)					
A	5.29	9.26	8.76	9.42	10.98	
B	2.80	5.77	6.51	6.62	8.38	25.54*
C	4.37	8.80	6.36	7.23	9.43	

Wat - Waterlogging, 1dy - Daily watering, 3dy - Twice a week, 1wk - Once a week, 2wk - Once in two weeks

Water stress causes biochemical and physiological changes in plants thereby affecting plant growth and development. Chlorophyll a is highest at once in two weeks watering regime application with 21.31, 16.39 and 18.03 and lowest under waterlogging treatment with 7.31, 3.98 and 5.05 for variety A, B and C respectively. Chlorophyll b is observed highest also at once in two weeks water regime with 10.18, 8.37 and 9.43 and lowest at waterlogging regime with 5.98, 2.80 and 4.37 for variety A, B and C respectively (Table 4). Variable responses with both increase and decrease were reported on chlorophyll level of plants subjected to droughts and waterlogging stress (65) depending on duration and severity of stress with majority of results indicating decline in chlorophyll content (59). Majority Results obtained indicted increase in chlorophyll level of soybean varieties with increase in drought stress. This might be attributed to intermittent subjecting the

soybean to water stress and rehydration making the soybean adjust the chlorophyll level as a means of survival. (71) reported that increasing level of chlorophyll under water stress is a survival mechanism developed in plant (72,73). Increase in chlorophyll in onion under drought stress has also been reported (74).

Effects of watering regimes on proline in soybean varieties

Table 5: Effects of Watering Regime on Proline in soybean

	Wat	1dy	3dy	1wk	2wk	ANOVA (Watering Regime) at p = 0.05
Varieties	Proline Content (µg/g)					
A	948.40	419.20	386.33	1607.20	6558.80	
B	671.40	457.60	402.20	1269.60	6675.60	5677.736*
C	585.20	723.60	577.40	1748.60	6557.20	

Wat - Waterlogging, 1dy - Daily watering, 3dy - Twice a week, 1wk - Once a week, 2wk - Once in two weeks

Adverse environmental stress conditions tend to adjust plant structural conditions and prevent excessive water loss and maintain cell turgidity (75). All soybean varieties studied increased in proline accumulation as water stress increases in soybean. The highest was observed under excessive drought water regime at once in two weeks water regime treatment with 6558.8, 6675.6 and 6557.2 and lowest in daily water regime in varieties A, B, and C respectively and lowest at daily watering regime with 419.2, 457.6 and 505.2 in varieties A, B and C respectively (Table 5). Similar results of proline accumulation under stress have been reported in groundnut (76,77) and chickpea (78). Water stress induces the plants to produce proline to maintain cell turgor pressure (79). Accumulation of proline is a metabolic response of plants under abiotic stress. Increase in its accumulation indicates reduction in negative effects of water stress as it works as osmotic adjustor to stress effect and promote higher cells resistance cells under adverse conditions (80). Proline, an essential amino acid, is a common amino acid accumulated during biotic and abiotic stresses and reported under drought stress (79,81). It is considered as neutral osmolyte and stabilises enzymes and protects cellular structures (82,83). Proline also possesses antioxidant activity and contribute to cellular homeostasis thereby cushioning water stress effects on plants and provides energy source for the stress-recovery process (84,85).

Effects of watering regimes on Total Soil Nitrogen fixation of soybean

Table 6: Effects of watering regime on fixed total soil nitrogen

	Wat	1dy	3dy	1wk	2wk	ANOVA (Watering Regime) at p = 0.05
Varieties	Soil Nitrogen Content (g/kg)					
A	1.47	2.17	1.64	2.80	2.95	
B	1.58	1.79	2.26	2.69	3.27	3.97*
C	1.80	1.86	1.68	3.15	3.25	

Wat - Waterlogging, 1dy - Daily watering, 3dy - Twice a week, 1wk - Once a week, 2wk - Once in two weeks

Soil nitrogen fixed from effect of watering regime on soybean in the soil increased from an initial concentration of 0.9g/kg present in the soil before the start of the experiment to concentration varying from an increase of 1.47g/kg, 1.58g/kg and 1.80g/kg in waterlogging regime which has the lowest values to 2.96g/kg, 3.27g/kg and 3.25g/kg in once in two week water regime application in variety A, B, and C respectively. Nitrogen content fixed was not significant among the variety and treatment. Waterlogging in most cases reduces availability of nitrogen to plants (86) by causing reduction in stomatal conductance due to increase in abscisic acid accumulation (87) thereby reducing root hydraulic conductance (88). Formation and growth of root nodules can be affected by factors affecting plant development such as stress.

CONCLUSION

Soybean is a significant worldwide oilseed and vegetable oils from its seed, source of cheap leafy biomass for the livestock industry which also remedy the soil by fixing nitrogen. Its production is adversely affected by environmental stress among which it is more sensitive to water stress. It becomes necessary to irrigate or drain where necessary when it is exposed to stress to produce higher yield in pod, nitrogen fixation and higher biomass. Local farmers tend to not understand water content but easy to recommend days of watering. Soybean is affected by water stress with drought effect more significant than waterlogging. The study helps to understand adaptive mechanism of soybean varieties under varying water stress and can be used to identify useful traits for soybean breeding. From the study, it can be observed that watering regimes of twice a week and once a week to field capacity will be optimum soybean production considering the agricultural and economic value of production. Further study is necessary to replicate and confirm results under field conditions.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

References

1. Trenberth KE, Fasullo JT, Shepherd TG. Attribution of climate extreme events. Vol. 5, Nature Climate Change. Nature Publishing Group; 2015. p. 725–30.
2. Liu CY, Wu QS. Responses of plant growth, root morphology, chlorophyll and indoleacetic acid to phosphorus stress in trifoliate orange. Biotechnology. 2017;16(1):40–4.
3. Mekonnen MM, Hoekstra AY. Sustainability: Four billion people facing severe water scarcity. Sci Adv. 2016 Feb 1;2(2).
4. Lesk C, Rowhani P, Ramankutty N. Influence of extreme weather disasters on global crop production. Nature. 2016 Jan 6;529(7584):84–7.
5. Ludlow MM, Muchow RC. A critical evaluation of traits for improving crop yields in water-limited environments. Vol. 43, Advances in Agronomy. 1990.
6. Riaz A, Younis A, Hameed M, Kiran S. Morphological and biochemical responses of turf grasses to water deficit conditions. Vol. 42, Pak. J. Bot. 2010.

7. Hamayun M, Sohn EY, Afzal Khan S, Shinwari ZK, Latif Khan A, Lee IJ. Silicon alleviates the adverse effects of salinity and drought stress on growth and endogenous plant growth hormones of soybean (*Glycine max* L.). Vol. 42, Pak. J. Bot. 2010.
8. Lawlor DW, Cornic G. Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. *Plant Cell Environ.* 2002;25(2):275–94.
9. Zhu JK. Salt and drought stress signal transduction in plants. Vol. 53, *Annual Review of Plant Biology.* 2002. p. 247–73.
10. Dai A. Drought under global warming: A review. Vol. 2, *Wiley Interdisciplinary Reviews: Climate Change.* Wiley-Blackwell; 2011. p. 45–65.
11. Wery J, Silim SN, Knights EJ, Malhotra RS, Cousin S, Lepse R. Screening techniques and sources of tolerance to extremes of moisture and air temperature in cool season food legumes. *Euphytica.* 1994;
12. Zhao WL, Siddiq Z, Fu PL, Zhang JL, Cao KF. Stable stomatal number per minor vein length indicates the coordination between leaf water supply and demand in three leguminous species. *Sci Rep.* 2017 Dec 1;7(1).
13. Odjugo PAO. The impact of climate change on water resources: global and Nigerian analysis. *FUTY Journal of the Environment.* 2009;4(1).
14. Colmer TD, Voisenek LACJ. Flooding tolerance: Suites of plant traits in variable environments. *Functional Plant Biology.* 2009;36(8):665–81.
15. Huang S, Greenway H, Colmer TD. Responses by coleoptiles of intact rice seedlings to anoxia: K⁺ net uptake from the external solution and translocation from the caryopses. *Ann Bot.* 2003 Jan 1;91(SPEC. ISS. JAN.):271–8.
16. Maurenza D, Marengo RA, Fernandez MT. Efeito da inundação de longa duração sob o crescimento de *Pouteria glomerata* (Sapotaceae), uma arbórea da várzea da Amazônia Central. Vol. 39. 2009.
17. Gray WM. Hormonal regulation of plant growth and development. Vol. 2, *PLoS Biology.* 2004.
18. Hsiao TC, Xu LK. 350 WD Special Issue. Vol. 51, *Journal of Experimental Botany.* 2000.
19. Banaszkiwicz T. Nutritional Value of Soybean Meal [Internet]. 200AD. Available from: www.intechopen.com
20. Michelfelder AJ. “Soy: a complete source of protein.” . *Am Fam Physician.* 2009;79(1):43–7.
21. Staniak M, Szpunar-Krok E, Kocira A. Responses of Soybean to Selected Abiotic Stresses—Photoperiod, Temperature and Water. Vol. 13, *Agriculture (Switzerland).* MDPI; 2023.
22. Casagrande F, Darbon JM. Effects of structurally related flavonoids on cell cycle progression of human melanoma cells: regulation of cyclin-dependent kinases CDK2 and CDK111 Abbreviations: CDK, cyclin-dependent kinase; CKI, CDK inhibitor; PI 3-kinase, phosphatidylinositol 3-kinase; PKC, protein kinase C; DTT, dithiothreitol; RIPA, radioimmunoprecipitation assay buffer. *Biochem Pharmacol* [Internet]. 2001;61(10):1205–15. Available from: <https://www.sciencedirect.com/science/article/pii/S0006295201005834>

23. Candogan BN, Sincik M, Buyukcangaz H, Demirtas C, Goksoy AT, Yazgan S. Yield, quality and crop water stress index relationships for deficit-irrigated soybean [*Glycine max* (L.) Merr.] in sub-humid climatic conditions. *Agric Water Manag.* 2013 Feb;118:113–21.
24. Adegoye GA, Olorunwa OJ, Alsajri FA, Walne CH, Wijewardana C, Kethireddy SR, et al. Waterlogging Effects on Soybean Physiology and Hyperspectral Reflectance during the Reproductive Stage. *Agriculture (Switzerland)*. 2023 Apr 1;13(4).
25. Souza GM, Catuchi TA, Bertolli SC, Soratto RP. Soybean Under Water Deficit: Physiological and Yield Responses. In: Board JE, editor. *A Comprehensive Survey of International Soybean Research* [Internet]. Rijeka: IntechOpen; 2013. Available from: <https://doi.org/10.5772/54269>
26. Foyer CH, Lam HM, Nguyen HT, Siddique KHM, Varshney RK, Colmer TD, et al. Neglecting legumes has compromised human health and sustainable food production. *Nat Plants*. 2016;2(8).
27. Doss BD, Thurlow DL. Irrigation, Row Width, and Plant Population in Relation to Growth Characteristics of Two Soybean Varieties. *Agronomy Journal* 1974 Vol. 66: 620 – 623
28. Alordzinu KE, Jiu hao L, Appiah SA, Aasmi AAL, Blege PK, Afful EA. Water stress affects the physio-morphological development of tomato growth. *Afr J Agric Res.* 2021;17(5):733–42.
29. Yavas I, Jamal MA, Din KU, Ali S, Hussain S, Farooq M. Drought-Induced Changes in Leaf Morphology and Anatomy: Overview, Implications and Perspectives. Vol. 33, *Polish Journal of Environmental Studies*. HARD Publishing Company; 2024. p. 1517–30.
30. Schattman RE, Jean H, Faulkner JW, Maden R, McKeag L, Nelson KC, et al. Effects of irrigation scheduling approaches on soil moisture and vegetable production in the Northeastern U.S.A. *Agric Water Manag.* 2023 Sep 1;287.
31. Arnon DI. Copper enzymes in isolated chloroplasts. Polyphenoloxidase in *Beta vulgaris*. *Plant Physiol.* 1949;24:1–15.
32. Bates L. S. Rapid determination of free proline for water-stress studies. *Plant Soil.* 1973 Nov 16;39:205–7.
33. Bremner JM. Determination of nitrogen in soil by the Kjeldahl method. Vol. 55, *J. Agric. Sci.* 1960.
34. Zia R, Nawaz MS, Siddique MJ, Hakim S, Imran A. Plant survival under drought stress: Implications, adaptive responses, and integrated rhizosphere management strategy for stress mitigation. Vol. 242, *Microbiological Research*. Elsevier GmbH; 2021.
35. Kaur G, Singh G, Motavalli PP, Nelson KA, Orlowski JM, Golden BR. Impacts and management strategies for crop production in waterlogged or flooded soils: A review. Vol. 112, *Agronomy Journal*. John Wiley and Sons Inc.; 2020. p. 1475–501.
36. Seleiman MF, Al-Suhaibani N, Ali N, Akmal M, Alotaibi M, Refay Y, et al. plants Drought Stress Impacts on Plants and Different Approaches to Alleviate Its Adverse Effects. 2021; Available from: <https://doi.org/10.3390/plants10020259>

37. Lee EP, Han YS, Lee SI, Cho KT, Park JH, You YH. Effect of nutrient and moisture on the growth and reproduction of *Epilobium hirsutum* L., an endangered plant. *J Ecol Environ*. 2017 Oct 3;41(1).
38. Oosterhuis DM SHHR and WS. Physiological response of two soybean (*Glycine max* L. Merr) cultivars to short-term flooding. *Env Exp Bot* . 1990;30:85–92.
39. Nemeskéri E, Helyes L. Physiological responses of selected vegetable crop species to water stress. Vol. 9, *Agronomy*. MDPI AG; 2019.
40. Jaleel CA, Manivannan P, Lakshmanan GMA, Sridharan R, Panneerselvam R. NaCl as a physiological modulator of proline metabolism and antioxidant potential in *Phyllanthus amarus*. *C R Biol*. 2007 Nov;330(11):806–13.
41. Navari-Izzo F, Vangioni N, Quartacci MF. Lipids of soybean and sunflower seedlings grown under drought conditions. Vol. 29, *Phytochemistry*. 1990.
42. Sinclair TR, Vadez V. The future of grain legumes in cropping systems. Vol. 63, *Crop and Pasture Science*. 2012. p. 501–12.
43. Kaur G, Asthir B. Proline: a key player in plant abiotic stress tolerance. *Biologia plantarum*. 2015 vol. 59: 609 - 619.
44. Khalid Muhammad Fasih and Zakir I and KRI and IS and SS and ZN and AS and AM and AT and HS. Effect of Water Stress (Drought and Waterlogging) on Medicinal Plants. In: Husen Azamal and Iqbal M, editor. *Medicinal Plants: Their Response to Abiotic Stress* [Internet]. Singapore: Springer Nature Singapore; 2023. p. 169–82. Available from: https://doi.org/10.1007/978-981-19-5611-9_6
45. Hoogenboom G, Huck MG, Peterson CM. Root Growth Rate of Soybean as Affected by Drought Stress. *Agronomy Journal*. 1987;79;607 - 614
46. Manavalan LP, Guttikonda SK, Phan Tran LS, Nguyen HT. Physiological and molecular approaches to improve drought resistance in soybean. Vol. 50, *Plant and Cell Physiology*. 2009. p. 1260–76.
47. de Sousa LF, de Menezes-Silva PE, Lourenço LL, Galmés J, Guimarães AC, da Silva AF, et al. Improving water use efficiency by changing hydraulic and stomatal characteristics in soybean exposed to drought: the involvement of nitric oxide. *Physiol Plant*. 2020 Mar 1;168(3):576–89.
48. Voesenek LACJ, Bailey-Serres J. Flooding tolerance: O₂ sensing and survival strategies. Vol. 16, *Current Opinion in Plant Biology*. 2013. p. 647–53.
49. Das A, Rangappa K, Basavaraj S, Dey U, Haloi M, Layek J, et al. Conservation tillage and nutrient management practices in summer rice (*Oryza sativa* L.) favoured root growth and phenotypic plasticity of succeeding winter pea (*Pisum sativum*L.) under eastern Himalayas, India. *Heliyon*. 2021 May 1;7(5).
50. Kozlowski TT, Pallardy SG. *Growth control in woody plants*. Elsevier; 1997.
51. Drew MC. Hypoxia and anoxia oxygen deficiency and root metabolism: Injury and Acclimation Under Hypoxia and Anoxia [Internet]. Vol. 48, *Annu. Rev. Plant Physiol. Plant Mol. Biol*. 1997. Available from: www.annualreviews.org

52. Khan MN, Komatsu S. Proteomic analysis of soybean root including hypocotyl during recovery from drought stress. *J Proteomics*. 2016 Jul 20;144:39–50.
53. Leishman MR, Westoby M. The Role of Seed Size in Seedling Establishment in Dry Soil Conditions- Experimental Evidence from Semi-Arid Species. Vol. 82, Source: *Journal of Ecology*. 1994.
54. Kumar A, V RK, Singh C, V SK, Agarwal DK, Pal G, et al. Bioprospecting nutraceuticals from soybean (*Glycine max*) seed coats and cotyledons [Internet]. Vol. 89, *Indian Journal of Agricultural Sciences*. 2019. Available from: www.statista.com
55. Kaur G, Asthir B. Molecular responses to drought stress in plants. Vol. 61, *Biologia Plantarum*. Springer Netherlands; 2017. p. 201–9.
56. Salazar C, Hernández C, Pino MT. Plant water stress: Associations between ethylene and abscisic acid response. Vol. 75, *Chilean Journal of Agricultural Research*. Instituto de Investigaciones Agropecuarias, INIA; 2015. p. 71–9.
57. Gunes A, Inal A, Sahin O, Taskin MB, Atakol O, Yilmaz N. Variations in mineral element concentrations of poultry manure biochar obtained at different pyrolysis temperatures, and their effects on crop growth and mineral nutrition. *Soil Use Manag*. 2015 Dec 1;31(4):429–37.
58. Farooq M, Rizwan M, Nawaz A, Rehman A, Ahmad R. Application of natural plant extracts improves the tolerance against combined terminal heat and drought stresses in bread wheat. *J Agron Crop Sci*. 2017 Dec 1;203(6):528–38.
59. Blum A. Drought resistance, water-use efficiency, and yield potential - Are they compatible, dissonant, or mutually exclusive? In: *Australian Journal of Agricultural Research*. 2005. p. 1159–68.
60. Randhawa MS, Maqsood M, Shehzad MA, Chattha MU, Chattha MB, Nawaz F, et al. Light interception, radiation use efficiency and biomass accumulation response of maize to integrated nutrient management under drought stress conditions. *Turkish Journal of Field Crops*. 2017;22(1):134–42.
61. Singh P., Vijaya, D., Srinivas, K., and Wani S. P. Potential Productivity, Yield Gap, and Water Balance of Soybean-Chickpea Sequential Systematic Selected Benchmark Sites in India Executive summary. ICRISAT. 2002
62. Maqsood M, Ali SNA. Effects of drought on growth, development, radiation use efficiency and yield of finger millet (*Eleusine coracana*) [Internet]. Vol. 39, *Pak. J. Bot*. 2007. Available from: www.gov.lk
63. El-Juhany LI, Aref IM. Growth and dry matter partitioning of *Leucaena leucocephala* (Lam. de Wit.) trees as affected by water stress. *Alexandria Journal of Agricultural Research*. 1999. 44:237 - 260
64. Luo Z, Liu H, Li W, Zhao Q, Dai J, Tian L, et al. Effects of reduced nitrogen rate on cotton yield and nitrogen use efficiency as mediated by application mode or plant density. *Field Crops Res*. 2018 Apr 1;218:150–7.
65. Pan XY, Wang GX, Yang HM, Wei XP. Effect of water deficits on within-plot variability in growth and grain yield of spring wheat in northwest China. *Field Crops Res*. 2003 Jan 1;80:195–205.

66. Mak M, Babla M, Xu SC, O’Carrigan A, Liu XH, Gong YM, et al. Leaf mesophyll K⁺, H⁺ and Ca²⁺ fluxes are involved in drought-induced decrease in photosynthesis and stomatal closure in soybean. *Environ Exp Bot*. 2014 Feb;98:1–12.
67. Li X, Xu Y, Tsuji I. Soybean and Prostate Cancer. In: *Soybean - Bio-Active Compounds*. InTech; 2013.
68. Farooq M, Wahid A, Lee DJ. Exogenously applied polyamines increase drought tolerance of rice by improving leaf water status, photosynthesis and membrane properties. *Acta Physiol Plant* [Internet]. 2009;31(5):937–45. Available from: <https://doi.org/10.1007/s11738-009-0307-2>
69. Pang B, Zhang K, Kisekka I, Bean S, Zhang M, Wang D. Evaluating effects of deficit irrigation strategies on grain sorghum attributes and biofuel production. *J Cereal Sci*. 2018 Jan 1;79:13–20.
70. QI D liang, HU T tian, SONG X. Effects of nitrogen application rates and irrigation regimes on grain yield and water use efficiency of maize under alternate partial root-zone irrigation. *J Integr Agric*. 2020 Nov 1;19(11):2792–806.
71. Farooq M. and Hussain M and WA and SKHM. Drought Stress in Plants: An Overview. In: Aroca R, editor. *Plant Responses to Drought Stress: From Morphological to Molecular Features* [Internet]. Berlin, Heidelberg: Springer Berlin Heidelberg; 2012. p. 1–33. Available from: https://doi.org/10.1007/978-3-642-32653-0_1
72. Yang X, Lu M, Wang Y, Wang Y, Liu Z, Chen S. Response mechanism of plants to drought stress. Vol. 7, *Horticulturae*. MDPI AG; 2021.
73. Rustioni L, Bianchi D. Drought increases chlorophyll content in stems of *Vitis* interspecific hybrids. *Theor Exp Plant Physiol*. 2021 Mar 1;33(1):69–78.
74. Chowdhury MK, Hasan MA, Bahadur MM, Islam R, Hakim A, Iqbal MA, et al. Evaluation of Drought Tolerance of Some Wheat (*Triticum aestivum* L.) Genotypes through Phenology, Growth, and Physiological Indices. 2021;11:1792. Available from: <https://doi.org/10.3390/agronomy>
75. Kaur G, Asthir B. Molecular responses to drought stress in plants. Vol. 61, *Biologia Plantarum*. Springer Netherlands; 2017. p. 201–9.
76. Ranganayakulu GS, Sudhakar C, Reddy PS. Effect of water stress on proline metabolism and leaf relative water content in two high yielding genotypes of groundnut (*Arachis hypogaea* l.) with contrasting drought tolerance. *Journal of Experimental Biology and Agricultural Sciences* [Internet]. 2015;3:97–103. Available from: <https://api.semanticscholar.org/CorpusID:58941989>
77. Kundy AC, Mayes S, Msanya B, Ndakidemi P, Massawe F. Building Resilient Crop Production Systems for Drought-Prone Areas—A Case for Bambara Groundnut (*Vigna subterranea* L. Verdc) and Groundnut (*Arachis hypogaea* L.). *Agronomy*. 2023 Feb 1;13(2).
78. Mafakheri A, Siosemardeh A, Bahramnejad B, Struik PC, Sohrabi E. Effect of drought stress on yield, proline and chlorophyll contents in three chickpea cultivars. Vol. 4, *AJCS*. 2010.
79. Hayat S, Hayat Q, Alyemeni MN, Wani AS, Pichtel J, Ahmad A. Role of proline under changing environments: A review. Vol. 7, *Plant Signaling and Behavior*. 2012.

80. Jaleel CA, Manivannan P, Lakshmanan GMA, Sridharan R, Panneerselvam R. NaCl as a physiological modulator of proline metabolism and antioxidant potential in *Phyllanthus amarus*. *C R Biol*. 2007 Nov;330(11):806–13.
81. Verbruggen N, Hermans C. Proline accumulation in plants: A review. Vol. 35, *Amino Acids*. 2008. p. 753–9.
82. Delauney AJ, Verma DPS. Proline biosynthesis and osmoregulation in plants. *Plant Journal*. 1993;4(2):215–23.
83. Kavi Kishor' PB, Hong Z, Miao3 CH, Hu4 CAA, Pal D, Verma S. Overexpression of A1-Pyrroline-5-Carboxylate Synthetase Increases Proline Production and Confers Osmotolerance in Transgenic Plants' [Internet]. Vol. 1, *Plant Physiol*. 1995. Available from: www.plantphysiol.org
84. Szabados L, Savaouré A. Proline: a multifunctional amino acid. Vol. 15, *Trends in Plant Science*. 2010. p. 89–97.
85. Hoque MA, Banu MNA, Nakamura Y, Shimoishi Y, Murata Y. Proline and glycinebetaine enhance antioxidant defense and methylglyoxal detoxification systems and reduce NaCl-induced damage in cultured tobacco cells. *J Plant Physiol*. 2008 May 26;165(8):813–24.
86. Shabala S, Shabala L, Barcelo J, Poschenrieder C. Membrane transporters mediating root signalling and adaptive responses to oxygen deprivation and soil flooding. Vol. 37, *Plant Cell and Environment*. 2014. p. 12216–33.
87. Aroca R, Ruiz-Lozano JM, Zamarreño ángel M, Paz JA, García-Mina JM, Pozo MJ, et al. Arbuscular mycorrhizal symbiosis influences strigolactone production under salinity and alleviates salt stress in lettuce plants. *J Plant Physiol*. 2013 Jan 1;170(1):47–55.
88. Vandeleur R, Niemietz C, Tilbrook J, Tyerman SD. Roles of aquaporins in root responses to irrigation. *Plant and soil*. 2005: 274: 141 – 161