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Response of Soybean to Transient Waterlogging Stress in Semi-arid Tropical Conditions

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Abstract

Global warming is an observed phenomenon characterized by an increase in average temperature by 1.4 - 4.4°C which is expected to result in 14 to 35 per cent increased rainfall by 2050 and 2100. Soybean is one of the major food crops and sensitive to waterlogging with yield reduction up to 83 per cent. Therefore, it is essential to have better understanding about the sensitivity of the soybean growth stages and waterlogging durations to device better management strategies. The study was conducted in pot under summer and *kharif* season with four levels of crop growth stages (S_1: 15 DAE; days after emergence, S_2: 30 DAE, S_3: 45 DAE and S_4: 60 DAE) and five levels of waterlogging durations (D_1: 2 DWL; days of waterlogging, D_2: 4 DWL, D_3: 6 DWL, D_4: 8 DWL and D_5: 10 DWL) replicated seven times under factorial complete randomized block design. Waterlogging at 45 DAE recorded higher reductions in plant height (4.82 cm during summer and 3.1 cm during *kharif*), number of leaves (10.53 in summer and 5.63 in *kharif*), SPAD (4.07 in summer and 4.34 in *kharif*), NDVI (0.16 in summer and 0.14 in *kharif*) and Seed yield (3.8 g plant^{-1} in summer and 0.9 g plant^{-1} in *kharif*). Likewise, 10 DWL recorded maximum reductions in number of leaves (8.05 in summer and 5.92 in *kharif*), SPAD (3.72 in summer and 4.58 in *kharif*) and increase in canopy temperature (1.50^{0}C in summer and 1.51^{0}C in *kharif*) and seed yield (3.5 g plant^{-1} in summer and 2.1 g plant^{-1} in *kharif*). Among the interactions $S_3 \times D_5$ observed with lower seed yield with 3.0 g plant^{-1} and 0.6 g plant^{-1}, respectively during summer and *kharif* season. The study reveals that, waterlogging for 10 days at 45 DAE is highly sensitive in terms of growth and seed yield.

Keywords : Semi-arid tropics, Soybean, Growth stages, Duration, Waterlogging stress

The climate change expected to increase the average temperature of the earth by 1.4°C to 4.4°C by 2100 which in turn increases the intensity by 6.2 mm day^{-1} to 7.3 mm day^{-1} and amount of rainfall by 14 to 35 per cent (Katzenberger *et al.*, 2022 and Lee *et al.*, 2023). This changed situation poses greater risk for agriculture. Under these changed situation there is a need to produce 60 per cent more agriculture produce than the current production to meet the food security of global population by 2050. Among the various changes climate induced abiotic stresses, waterlogging contributes about 65 per cent of financial damage to crops (Anonymous, 2018).

The United Nations Food and Agriculture Organization (FAO) reported that more than 1 billion people are now suffering from malnutrition. Water logging is one of the major abiotic stresses causing yield loss with flooding, all pores in the soil are filled with water which results in the onset of soil anoxic condition and reduces the oxygen diffusion rate by 10000 times lower than aerated soil. This adverse impact of waterlogging on terrestrial plant is consequence of slow diffusion of oxygen in water compared to soil (Yordanova and Popova, 2007).

Plant survival under waterlogged condition depends on establishment of an internal oxygen supply through the root system that can support aerobic respiration and detoxify chemically reduced soil phytotoxins (Armstrong, 1979). Excessive soil moisture leads to poor soil aeration, reduces leaf emergence rate, disorders root growth and destruction of root physiological function, thus resulting in alteration of plant hormone balance and nutrients shortage. Waterlogging enhances anaerobic respiration, leading to accumulation of a large number of harmful substances (H_2S, FeS) in the soil. The rhizosphere environment deteriorates resulting in the reduction of mineral ions and beneficial trace element absorption (Ren *et al*., 2016). With the waterlogging condition the nutrient recycling process is hampered and nutrient deficiency conditions become eminent especially nitrogen due to leaching and de-nitrification process in the soil and in addition, synthesis and translocation of growth regulators, photosynthesis and carbohydrate partitioning are also negatively affected.

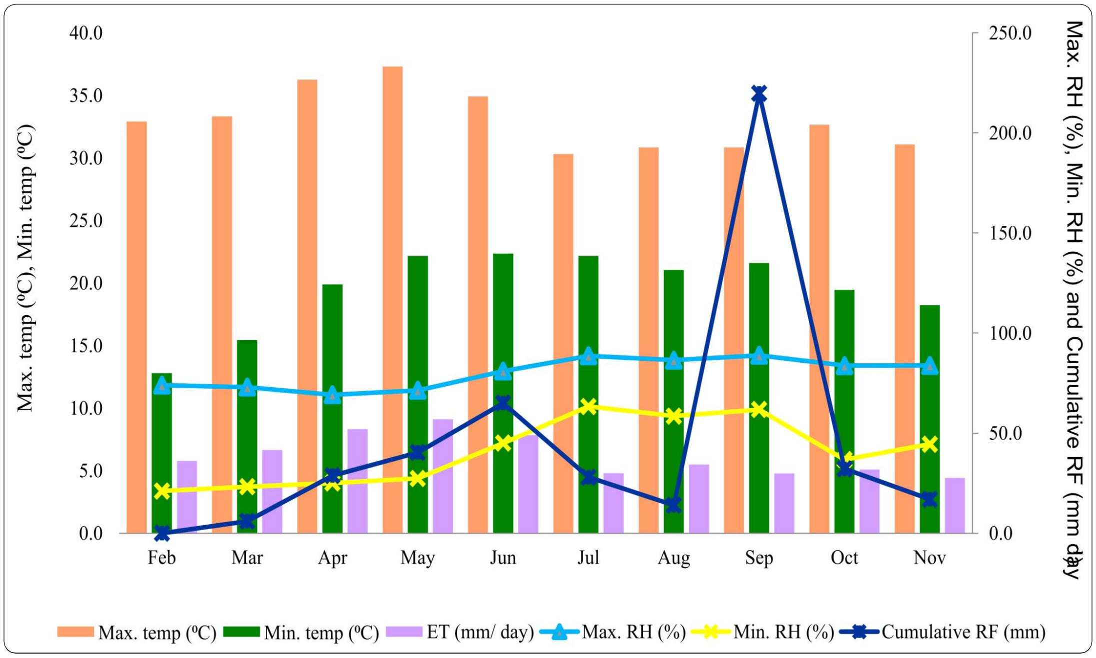
Soybean is the vital source of protein and oil for food, feed and a raw material for various industries with the grain production of about 341 m t worldwide. Waterlogging is one of the major reasons for reducing growth and production of soybean in many parts of the world as waterlogging affects about 16 per cent of total global cultivated area (Ploschuk *et al*., 2018). In India, 8.3 per cent of the total net sown area *i.e.,* 11.6 m ha is affected by the waterlogging stress (Chowdhury *et al*., 2018). Surface water stagnation due to rain water accumulation or over irrigation in the absence of a proper drainage system, high water table due to excessive seepage from upland areas or the irrigation water conveyance network system and irrigation induced by application of excess irrigation water are the three situations of waterlogging in India (Gopalakrishnan and Kulkarni, 2007). The changes in the rainfall pattern, distribution and increasing trend of extreme precipitation during the summer and monsoon seasons led to greater risk of flooding at regional scale. Majority of the soybean is cultivated in Maharashtra and Madhya Pradesh in *vertisols* which is subjected to waterlogging conditions.

Soybean is highly sensitive to waterlogging which disrupts respiration, biological nitrogen fixation and nutrient uptake leading to reduced growth, development and finally yields of the crop. The sensitivity of soybean to different durations of waterlogging by keeping stage constant and vice versa has been reported (Linkemer *et al.,* 1998; Bacanamwo & Purcell, 1999; Garcia *et al.,* 2020 and Fletcher *et al.,* 2023). The combinations of different durations of waterlogging at different crop growth stages have not been reported. Further, researchers have reported the impact of combined effect temperature and waterlogging on the growth and development of maize, rice and tomato (Wen *et al*., 2024; Zhen *et al*., 2020 and Shao *et al*., 2023). Such studies are lacking in soybean to study the impact of different durations of waterlogging at various crop growth stages on soybean growth and yield for the future climatic conditions as well as for present scenario are lacking. Given these considerations, the present study was formulated under pot conditions to evaluate the effects of varying waterlogging durations at different stages in two contrasting climatic conditions during both summer and *kharif* seasons.

Material and Methods

Climatic Data during Crop Growth Period

The study response of soybean to transient waterlogging stress was conducted at ICAR-National Institute of Abiotic Stress Management, Baramati, Maharashtra, India (18° 09' 30.62'' N; 74° 30' 03.08'' E; mean sea level: 570 m). The study location lies in semi-arid tropics with 570 mm of average annual rainfall. The 70 per cent of the rainfall received in during monsoon while another 21 per cent received during post-monsoon period. The average monthly climatic conditions during summer (February-May) and *kharif* (July-November) is presented in Fig. 1. The mean maximum temperature was 34.9°C and



*Max temp-maximum temperature (°C), Min temp-minimum temperature (°C), Max RH-maximum relative humidity (%), Min RH-minimum relative humidity (%), RF-Rainfall (mm)

Fig. 1 : Climatic parameters during summer (February-June) and *kharif* season (July-November)

31.1°C during summer and *kharif* season, respectively. Meanwhile, the minimum temperature was 18.5°C and 20.5°C.

Likewise, the maximum and minimum relative humidity was found to be 73.7 and 28.4 per cent during summer whereas, during *kharif* season maximum relative humidity was 86.3 per cent and minimum relative humidity was 55.0 per cent. The cumulative rainfall was 140.2 mm during summer and 311 mm during *kharif* season. Notably, the average evapotranspiration rate was higher during summer (7.5 mm day^{-1}) compared to *kharif* (4.9 mm day^{-1}).

Experimental Details

The study was conducted for two seasons during summer-2023 and *kharif*-2023 with factorial randomized complete block design with two factors which replicated seven times. The first factor comprised of four stages of waterlogging (S_1: 15 DAE; Days after emergence, S_2: 30 DAE, S_3: 45 DAE and S_4: 60 DAE) and second factor consists of five durations of waterlogging (D_1: 2 DWL; Days of waterlogging, D_2: 4 DWL, D_3: 6 DWL, D_4: 8 DWL, and D_{10}: 10 DWL). Each pot was filled with 14 kg of soil. The soil was black clayey soil with low in available nitrogen, medium available phosphorous and potassium (Table 1). The Recommended dose of fertilizers (25:50:25 kg $N:P_2O_5:K_2O$ ha^{-1}) applied to each pot. The nutrients were supplied through urea, Diammonium Phosphate and Potassium chloride and thoroughly mixed with the soil before sowing. The pots were dibbled manually with four seeds of NRC-136 (procured from Indian Institute of Soybean Research, Indore, Madhya Pradesh) and irrigated regularly at 60 per cent field capacity for better germination and crop growth. The thinning was performed seven days after emergence, maintaining two healthy plants per pot. Once the crop attains at particular stage, the pots were artificially imposed with waterlogging (~ 3 cm above soil surface) in a cement tank with a capacity of 38.08 m^3 (5.43 m × 5.48 m × 1.28 m). The observations *i.e.*, plant height, number of leaves, SPAD, NDVI and Canopy temperatures were recorded 10 days after removal from the waterlogging stress and each treatment was compared

TABLE 1

Initial characteristics of soil

Particulars	Value obtained	Method employed	Reference
I. Physical properties			
Coarse sand (%)	9.10	International pipette method	(Piper, 2002)
Fine sand (%)	10.22		
Silt (%)	10.41		
Clay (%)	71.27		
Textural class	Clayey		
Colour	Black	Munsell colour chart	(Nickerson, 1969)
Bulk density (Mg m^{-3})	1.2	Core sampler	(Black, 1967)
II. Chemical properties			
Soil pH (1:2.5 soil: water ratio)	8.02	Potentiometric method	(Piper, 2002)
Electrical conductivity (1:2.5 soil: water extract) (dS m^{-1})	0.176	Conductometric method	(Piper, 2002)
Organic carbon (g kg^{-1})	5.20	Walkley and Black's wet Oxidation method	(Jackson, 1973)
Available nitrogen (kg ha^{-1})	157.2	Alkaline potassium permanganate method	(Sahrawat and Burford, 1982)
Available phosphorus (kg ha^{-1})	12.12	Olsen's method by spectrophotometer using $NaHCO_3$ as extractant	(Jackson, 1973)
Available potassium (kg ha^{-1})	310.50	Neutral Normal Ammonium Acetate method using Flame photometer	(Jackson, 1973)

with the respective control plant observation and presented as reduction in values from their respective control plant observations. The NDVI values were recorded by Green Seeker® as to indicate the N level in plant leaves (Parameshnaik *et al*., 2024). Similarly, SPAD values were recorded as described by Vinutha *et al*. (2024) and Canopy temperature is recorded with the help of infrared gun.

RESULTS AND DISCUSSION

Growth Response of Soybean to Waterlogging under different Climates

The response of soybean to different waterlogging durations and stages was found significant under both the climatic conditions (Table 2). Among the crop growth stages waterlogging, 45 DAE; days after emergence was found with significantly higher reductions in plant height (4.82 cm in summer and 3.10 cm in *kharif*) and number of leaf (10.53 in summer and 5.63 in *kharif*). The significantly higher reduction in plant height and number of leaves is primarily due to the coincidence of waterlogging with the peak crop growth stages resulting in reductions in higher growth attributes. Likewise, durations of waterlogging showed reductions in growth attributes with increase in waterlogging duration's growth attributes *i.e.*, plant height and number of leaves reduced. The higher reductions in plant height (3.75 cm in summer and 3.25 cm in *kharif*) and number of leaves (8.05 in summer and 5.92 in *kharif*) was observed at 10 DWL. Increasing waterlogging durations results in rapid utilization of oxygen resulting in reduction in redox potential and creates anaerobic conditions. Anaerobic condition results in reduced root growth resulting in reductions in crop growth attributes. These results are in line with the finding of Gangana Gowdra *et al*. (2025) in soybean, Senthamil *et al*. (2025a) and Basavaraj *et al*. (2024) in cowpea. Notably, the interaction of waterlogging

TABLE 2

Reductions in growth response of soybean to waterlogging stress at different crop growth stages and durations under different climatic conditions

Treatments	Plant height (cm)		No. of leaves	
	Summer - 2023	*kharif* - 2023	Summer - 2023	*kharif* - 2023
Stages of waterlogging (S)				
S_1	1.43	2.06	1.43	1.23
S_2	2.83	2.77	6.90	4.40
S_3	4.82	3.10	10.53	5.63
S_4	1.18	1.61	3.27	4.17
S.Em. ±	0.05	0.04	0.13	0.08
CD (P=0.05)	0.15	0.12	0.37	0.22
Durations of waterlogging (D)				
D_1	1.58	1.41	2.99	1.79
D_2	1.95	1.96	4.35	2.38
D_3	2.60	2.44	5.39	4.17
D_4	2.95	2.87	6.88	5.04
D_5	3.75	3.25	8.05	5.92
S.Em. ±	0.06	0.05	0.14	0.09
CD (P=0.05)	0.17	0.13	0.41	0.24
Interactions (S × D)				
S_1D_1	0.72	0.80	0.31	0.50
S_1D_2	1.08	1.30	0.51	0.67
S_1D_3	1.44	1.93	1.10	1.33
S_1D_4	1.48	2.87	2.09	1.50
S_1D_5	2.42	3.40	3.13	2.17
S_2D_1	1.64	2.00	3.97	0.50
S_2D_2	1.80	2.58	5.22	2.17
S_2D_3	3.00	2.62	5.67	4.67
S_2D_4	3.51	3.22	8.67	6.67
S_2D_5	4.20	3.45	10.97	8.00
S_3D_1	3.34	1.53	5.00	3.33
S_3D_2	3.98	2.50	8.67	3.33
S_3D_3	4.92	3.70	11.44	6.00
S_3D_4	5.50	3.73	13.11	7.00
S_3D_5	6.37	4.03	14.44	8.50
S_4D_1	0.62	1.30	2.67	2.83
S_4D_2	0.93	1.43	3.00	3.33
S_4D_3	1.05	1.50	3.33	4.67
S_4D_4	1.32	1.67	3.67	5.00
S_4D_5	2.00	2.13	3.67	5.00
S.Em. ±	0.12	0.09	0.29	0.17
CD (P=0.05)	0.35	0.26	0.82	0.49

*S_1: 15 DAE; Days after emergence; S_2: 30 DAE; S_3: 45 DAE; S_4: 60 DAE; D_1: 2 DWL; Days of waterlogging, D_2: 4 DWL, D_3: 6 DWL; D_4: 8 DWL; D_5: 10 DWL

stages and durations found significantly affected by waterlogging where, the higher reductions in plant height (6.37 cm in summer and 4.03 cm in *kharif* season) and number of leaves (14.44 in summer and 8.50 in *kharif*) was found at 45 DAE × 10 DWL meanwhile, the least reduction was observed at 15 DAE × 2 DWL. The significantly higher reductions is highly attributable to the greater reduction in root attributes and probably due to higher accumulation of ethylene under waterlogging reduces the biosynthesis of auxin resulting in lower growth attributes.

Physiological Response of Soybean to Water logging under different Climates

The effects of different waterlogging durations and growth stages on soybean were statistically significant under both climatic conditions (Table 3). Physiological attributes of soybean were found to be lower during 45 DAE with higher reductions in SPAD (4.07 in summer and 4.34 in *kharif*), NDVI (0.16 in summer and 0.14 in *kharif*) and canopy temperature (1.13°C in summer and 1.19°C in *kharif*). Meanwhile, the lower reductions of SPAD and NDVI were observed at 15 DAE whereas, a lower canopy temperature was observed at 30 DAE. The significantly higher reductions in physiological attributes is likely due to lower antioxidants compared to 15 and 30 DAE resulting in higher reductions in NDVI and SPAD because of reactive oxygen species (ROS). Similarly, waterlogging durations had significant influence on the physiology of soybean with higher reductions in SPAD (3.72 in summer and 4.58 in *kharif*), NDVI (0.11 in summer and 0.12 in *kharif*) and canopy temperature (1.50°C in summer and 1.51°C in *kharif*) at 10 DWL. The higher reductions in physiological attributes are likely due to lower PSII activities and antioxidants as well as higher reductions in growth and root attributes (Gangana Gowdra *et al*., 2025). Likewise, the interaction of waterlogging stages and d urations showed significantly higher variations in physiological attributes. The higher reductions in SPAD (6.82 in summer and 8.18 in *kharif*) and NDVI (0.20 in summer and 0.18 in *kharif*) was observed at 45 DAE × 10 DWL. Meanwhile, the higher reduction in canopy temperature was observed at 15 DAE × 10 DWL (1.81°C) during summer whereas, during *kharif* the higher canopy temperature was observed at 60 DAE × 10 DWL (1.67°C) followed by 15 DAE × 10 DWL (1.23°C). The higher reduction in physiological attributes is highly attributable to the higher susceptibility of young plants to waterlogging stress. These findings are in line with the findings of Senthamil *et al*. (2025a, b) and Basavaraj *et al*. (2024) in cowpea.

Yield Response of Soybean to Waterlogging under different Climate

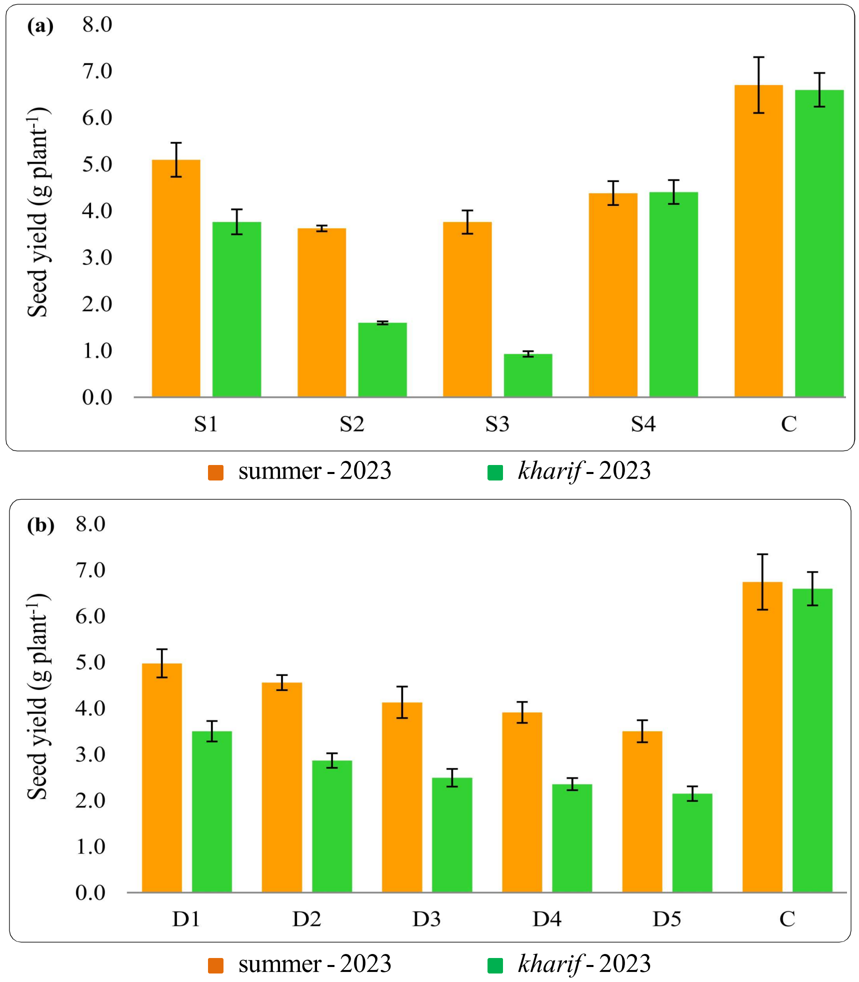
The effect of waterlogging on the seed yield of soybean was found significant. Among the stages, waterlogging at 30 DAE resulted in maximum reduction seed yield (3.6 g plant^{-1}) followed by 45 DAE (3.8 g plant^{-1}) during summer season. Whereas, seed yield during *kharif* season was significantly reduced at 45 DAE (0.9 g plant^{-1}) (Fig. 2a). The major reason behind higher reductions in seed yield is highly attributable to coincidence of peak flowering stages of respective season with waterlogging as the crop cycle is comparatively lower during summer (94 days) compared to *kharif* season (104 days). Likewise, increased durations of waterlogging resulted in lower seed yield. The maximum reduction in seed yield was observed at 10 DWL (3.5 g plant^{-1} in summer and 2.1 g plant^{-1}) (Fig. 2b). Increasing waterlogging durations resulted in lower root, shoot and physiology resulting in lower seed yield. The interactions of waterlogging stages and durations showed significant variations in seed yield with lower seed yield at 45 DAE × 10 DWL with 3.1 g plant^{-1} and 1.1 g plant^{-1}, respectively during summer and *kharif* season (Fig. 3). The significantly lower reductions in highly due to lower number of pods formed because of flower dropping under waterlogging (Gangana Gowdra *et al*., 2025).

TABLE 3

Reductions in physiological response of soybean to waterlogging stress at different crop growth stages and durations under different climatic conditions

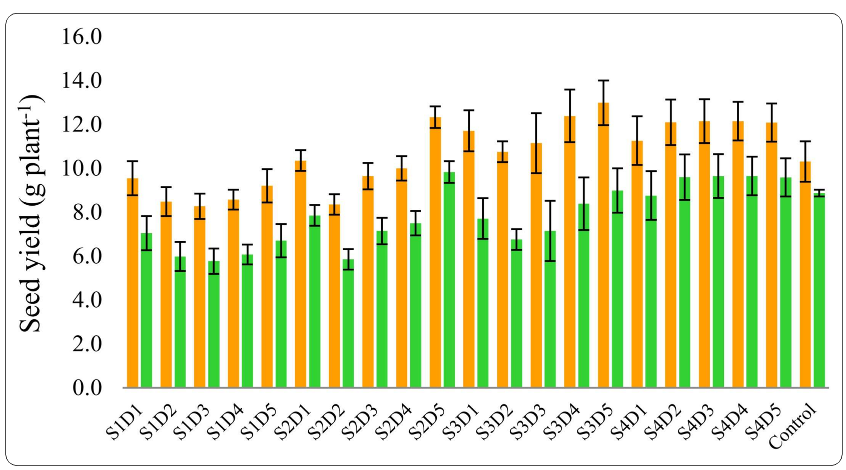
Treatments	SPAD		NDVI		CT (°C)	
	Summer -2023	*Kharif* -2023	Summer -2023	*Kharif* -2023	Summer -2023	*Kharif* -2023
Stages of waterlogging (S)						
S_1	1.48	1.68	0.07	0.09	0.90	0.58
S_2	2.88	3.65	0.13	0.11	0.71	0.45
S_3	4.07	4.34	0.16	0.14	1.13	1.19
S_4	1.17	1.64	0.03	0.04	1.08	1.10
S.Em. ±	0.05	0.06	0.002	0.002	0.02	0.018
CD (P=0.05)	0.14	0.16	0.006	0.005	0.05	0.050
Durations of waterlogging (D)						
D_1	1.58	1.27	0.07	0.04	0.40	0.27
D_2	1.33	2.00	0.09	0.09	0.70	0.58
D_3	2.27	2.69	0.10	0.11	0.97	0.78
D_4	3.10	3.60	0.10	0.11	1.21	1.03
D_5	3.72	4.58	0.11	0.12	1.50	1.51
S.Em. ±	0.06	0.06	0.002	0.002	0.02	0.020
CD (P=0.05)	0.16	0.18	0.006	0.006	0.05	0.056
Interactions (S × D)						
S_1D_1	0.12	0.83	0.03	0.04	0.21	0.07
S_1D_2	0.20	0.97	0.06	0.09	0.24	0.13
S_1D_3	1.56	1.43	0.06	0.10	1.01	0.67
S_1D_4	2.43	2.23	0.09	0.10	1.23	0.80
S_1D_5	3.07	2.95	0.11	0.10	1.81	1.23
S_2D_1	1.49	1.48	0.11	0.01	0.44	0.03
S_2D_2	1.90	3.02	0.15	0.13	0.48	0.33
S_2D_3	2.16	4.30	0.11	0.14	0.64	0.37
S_2D_4	3.93	4.15	0.12	0.14	0.80	0.47
S_2D_5	4.92	5.30	0.14	0.15	1.18	1.03
S_3D_1	2.54	1.67	0.09	0.09	0.68	0.03
S_3D_2	2.88	2.53	0.12	0.10	0.84	1.03
S_3D_3	3.41	3.17	0.19	0.15	1.08	1.20
S_3D_4	4.69	6.13	0.19	0.16	1.44	1.60
S_3D_5	6.82	8.18	0.20	0.18	1.58	2.10
S_4D_1	2.16	1.08	0.06	0.03	0.25	0.93
S_4D_2	0.32	1.47	0.04	0.03	1.23	0.80
S_4D_3	1.97	1.87	0.02	0.05	1.16	0.87
S_4D_4	1.33	1.87	0.01	0.05	1.36	1.23
S_4D_5	0.07	1.90	0.01	0.06	1.43	1.67
S.Em. ±	0.11	0.13	0.005	0.004	0.04	0.039
CD (P=0.05)	0.32	0.36	0.013	0.011	0.10	0.112

*S_1: 15 DAE; Days after emergence, S_2: 30 DAE, S_3: 45 DAE, S_4: 60 DAE, D_1: 2 DWL; Days of waterlogging, D_2: 4 DWL, D_3: 6 DWL, D_4: 8 DWL, D_5: 10 DWL, SPAD: Soil plant analysis device, NDVI: Normalized differential vegetation index, CT: Canopy temperature



*S_1: 15 DAE; Days after emergence, S_2: 30 DAE, S_3: 45 DAE, S_4: 60 DAE, D_1: 2 DWL; Days of waterlogging, D_2: 4 DWL, D_3: 6 DWL, D_4: 8 DWL, D_5: 10 DWL

Fig. 2 : Effect of waterlogging stress (a) at various crop growth stages and (b) waterlogging durations on summer and *kharif* seasons



*S_1: 15 DAE; Days after emergence, S_2: 30 DAE, S_3: 45 DAE, S_4: 60 DAE, D_1: 2 DWL; Days of waterlogging, D_2: 4 DWL, D_3: 6 DWL, D_4: 8 DWL, D_5: 10 DWL

Fig. 3 : Interaction effect of waterlogging stages and durations on the seed yield of soybean under summer and *kharif* season

The present study indicates the sensitivity of soybean to varied waterlogging stages for different intensity of waterlogging durations. The study revealed that, flower initiation to pod development stages (S_2 and S_3) stages were found highly sensitive to waterlogging in terms of waterlogging. The higher reductions in growth and physiological attributes were recorded at S_3 (45 DAE). Furthermore, extended durations of waterlogging *i.e.*, 10 days resulted in significant reduction in number of leaves, NDVI and seed yield. The current study complies with the present (*kharif*) and future situation (summer) under waterlogging conditions. The result helps policy makers to estimate the yield losses and helps agricultural scientists in devising the mitigation strategies.

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