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Alleviation of waterlogging stress in soybean through application of potassium fertilizer

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ABSTRACT

Waterlogging (WL) causes a detrimental effect on soybean, and application of potassium (K) is presumed to ameliorate from the damage. An experiment was conducted to determine the effect of WL on the morpho-physiology of soybean, and to assess the role of K in ameliorating the adverse effects on the crop. Soybean genotype BD2334 was grown under control (without WL) and WL in the field. The K fertilizer was applied as K_0: no K fertilizer, K_B: full dose of K as basal, K_{B+BF}: 50% of K as basal + 50% before WL, K_{B+AF}: 50% of K as basal + 50% after the termination of WL. The WL condition was imposed for 7 days at the flowering stage of soybean. The WL exerted a detrimental effect on morpho-physiological parameters, yield and yield attributes, and nutrient uptake in soybean. The plants of K_{B+AF} treatment quickly recovered from the effects of WL stress, had improved photosynthesis (29.38 μ mol m^{-2} s^{-1}), higher pods $plant^{-1}$ (27.67), number of seeds $plant^{-1}$ (51.67) and healthier seeds (27.39 g per 100-seed) compared to the control treatment. Under WL conditions, BD2334 produced 1.06 t grain ha^{-1} with basal K application and the yield rose to 1.45 t ha^{-1} in the treatment K as 50% basal + 50% after WL termination (K_{B+AF}). Additionally, the grain nutrient absorption was enhanced by K as K_{B+AF} under WL conditions. The relative contribution of K management on grain yield was 17.62%, which reveals that it is possible to increase soybean yield by modifying K management under WL conditions.

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Introduction

Soybean (*Glycine max* L.) is an important legume and oilseed crop all over the continents. The seeds of soybean are reported to contain about 36% protein, 30% carbohydrates, 20% oil, and significant levels of vitamins, minerals, dietary fiber, folic acid, and isoflavones (Mannan and Mamun, 2018; Yasmin *et al*., 2022; Dola *et al*., 2022; Hossen *et al*., 2023). It is categorized more as an oil seed crop than a pulse. Both the chemical and food sectors use soybean products and by-products, which show its remarkable adaptability. As a result, soybeans have the potential to offer a cheap source of protein for both the production of animal feed and human consumption (Fatema *et al*., 2023). Additionally, using root nodule bacteria soybeans fix nitrogen from the atmosphere and increase soil fertility (Whippo *et al*., 2024). Moreover, soybean cake is used as an excellent livestock feed.

Soybean has been grown in Bangladesh since the Mennonite Central Committee began working to improve the nutrition of rural Bangladeshis in the broader Noakhali district in the early 1970s. The area under soybean cultivation has been expanded tragically from only 5000ha in 2005 to 62508ha in 2018-2019 (BBS, 2020). With a production of 162,000 Mt, this crop's cultivation has increased significantly to 82000 ha in the districts of Laksmipur, Noakhali, Barishal, Bhola, Chandpur, Patuakhali, Faridpur, and even northern Bangladesh (USDA, 2022). However, the global average yield of soybeans is significantly higher (2.79 t ha^{-1}) than the national average yield (1.54 t ha^{-1}) (FAO STAT, 2022).

Environmental factors influence both above and below-ground growth of plants (Madhu and Hatfield, 2016). Waterlogging (WL) is a critical environmental problem in the coastal region of Bangladesh. Heavy rainfall during monsoon causes severe localized WL in these regions causing widespread damage to crops like lowland rice, soybean, barley, maize, etc. In Bangladesh, soybean is mostly sown in January after harvesting Aman rice and harvest during April. During March to April, seasonal monsoon rains are intense and often continuous for several days. This causes temporary or prolonged WL, even in the absence of cyclones. Soybean fields are often affected by WL due to seasonal rainfall, especially in regions with poor drainage or heavy soils (like clayey or lowland areas). Soybean is highly sensitive to excess soil moisture. Its roots need oxygen (O_2), and waterlogging quickly reduces O_2 availability, leading to root damage and poor nodulation. Recently, due to a change in rainfall pattern the crop also suffers from excess soil moisture due to torrential rain. For example, heavy rains brought by cyclones NADA in 2016 and Amphan in 2020 severely harmed standing soybean fields. By selecting suitable soybean genotypes and adopting appropriate nutrient management the waterlogging damage can presumably be lowered. Hossain *et al*. (2019) identified BU Soybean-1 and Shohag as tolerant to WL for 4 days at flowering.

A previous study suggested that G00060, G00164, BD2334, and BD2336 were tolerant to WL for 7 days.

Proper management and application of balanced inputs are essential for a productive crop establishment (Amin *et al.*, 2017). Potassium (K) is one of the vital inputs for legume crop production. It helps the soybean plants to cope with different stresses, diseases, and pests, and balanced uptake of other nutrients. It has a vital function in the plant's growth, development, and production processes (Minjian *et al.*, 2007), and also on the morphological and physiological characteristics of living plant cells (Pettigrew, 2008). Additionally, it facilitates the activation of enzymes during nodulation (Divito and Sadras, 2014) and has a prominent functionality in nitrogen and phosphorus uptake. Nutrient K also enhances the photosynthetic rate, carbohydrate production, translocation, and metabolism, which eventually increases the yield and quality of the grain. The time of K application is crucial for improving crop performance after the termination of flooding. Mamun *et al*. (2022) suggested that the application of 50% of K fertilizer after the recession of flooding improved grain yield of soybeans. However, how K is involved in the mechanism of WL tolerance and what role the K plays if applied before and after flooding is yet to be elucidated. Thus, the present study is planned to evaluate the effect of K management on ameliorating the adverse effects of WL on different physiological parameters, nutrient uptake and yield of soybeans.

Materials and Methods

Experimental location

The experiment was carried out in the Department of Agronomy's research field at Gazipur Agricultural University (GAU), Gazipur. The experimental site, situated in the Madhupur tract within Agro Ecological Zone 28, was 8.4 meters above mean sea level and fell within the sub-tropical climate zone. Its geographic coordinates were 24° 09′ North latitude and 90° 26′ East longitude. Under the Shallow Red Brown Terrace of the Argo-ecological zone (AEZ) Madhupur Tract (AEZ-28), the soil is a member of the Salna series. With a pH of 5.28, the sandy loam textural class consisted of 12.11% clay, 35.26% silt, and 53.63% sand (Table 1).

Preparation of land

A moldboard plough was initially used to open the experimental plot. A deep and cross plough, harrowing, and laddering were then used to prepare the ground. To obtain the desired tilth, the clods were broken up and the weeds and trash were cleared out of the field. Based on the fertilizer recommendation guide of the Bangladesh Agricultural Research Council (FRG, 2018), the basal doses of manure and fertilizers were administered.

Experimental design and layout

The treatments of this study comprised of two factors, Factor A: (K application) included K_0: 0 kg ha^{-1}, K_B: application of full dose of K as basal, K_{B+BF}: application of 50% of K as basal + 50% before flooding, and K_{B+AF}: application of 50% of K as basal + 50% after termination

Table 1. Physico-chemical properties of experimental soil

Soil properties	Unit	Value
Textural class	-	Sandy loam
Sand	%	53.63
Silt	%	35.26
Clay	%	12.11
pH	-	5.28
Organic carbon (OC)	%	1.68
Total nitrogen (N)	%	0.086
Available phosphorus (P)	µg g^{-1}	14.69
Exchangeable potassium (K)	meq 100g^{-1}	0.218
Available sulfur (S)	µg g^{-1}	14.10
Available zinc (Zn)	µg g^{-1}	0.857

of flooding; while Factor B (WL) were control and WL for 7 days during flowering stage (beginning of flower). This experiment was conducted during rabi season 2023 following a split-plot design with three replications. The unit plot size was 10 m^2 and plant spacing was 30 cm × 10 cm.

Seed sowing and crop establishment

In the last stages of land preparation, 54.94 kg urea ha^{-1}, 85 kg of triple super phosphate ha^{-1}, 72.28 kg of gypsum ha^{-1} and 4.17 kg of zinc sulphate ha^{-1} was applied in the plot. The muriate of potash (MOP) was applied according to treatment plan, using 101 kg MoP ha^{-1} (FRG, 2018).

Soybean genotype BD2334 was used as planting material, which was obtained from the Department of Agronomy, GAU, Gazipur. BD2334 is an advanced high-yielding soybean genotype which has a short life cycle (less than 100 days) with large sized seeds (28 g/100 seeds).

Before sowing the seeds were treated with 2.5 g kg^{-1} with vitavax-200. The manual sowing was done in lines on 5 February, 2023. To guarantee even emergence, the plots were irrigated right after seeding. After being sown, the seedlings appeared five days later.

Inter-cultural operations

When the first trifoliate leaf stage appeared, the plants were thinned to maintain required plant spacing. Necessary gap filling of the plants was done to maintain equal plant spacing in all plots. The crop was kept weed-free by mulching and weeding, and the soil crust was ground up for improved aeration and soil moisture conservation. Supplemental irrigation was used twice a week until the crop reached maturity to ensure that each plot had an adequate supply of water. To protect the plants from noxious insect pests Ripcord 10 EC @ 1 ml L^{-1} of water was sprayed once in a week up to maturity.

Treatments imposition

A polythene sheet was fixed surrounding the WL plots at a 30 cm deep into the ground, and extended 30 cm above the surface to retain water. Waterlogging was applied at the R1 stage (42 DAS, 19 March 2023). The plots were fully flooded up to 3 cm above ground level, which caused the WL stress. The WL treatments were kept up for the full 7 days (19 March 2023 to 26 March 2023). Water was then removed from the treated plots by draining them on 26 March 2023. In the control plots water was administered twice a week. Yellowing and lodging symptoms were visually evaluated daily during the course of the treatment (Akter *et al*., 2024).

Data collection

SPAD values

The SPAD value was taken to determine the leaf greenness with time under WL and control condition. After being exposed to WL stress for 24 hours, the soybean leaves turned from green to yellow. A chlorophyll meter (SPAD-502, Minolta, Japan) was used to obtain SPAD value. The values were recorded every day starting one day after removal of flood and continued up to 9^{th} days. Fully expanded leaf from the top of each treatment was selected randomly and SPAD values were recorded from 11. 0 am to 1.0 pm. Three SPAD readings were taken plant^{-1} and mean were calculated.

Determination of pigment content

A double beam spectrophotometer was used to determine Chl at 60 DAS on an FW basis that extracted with 80% acetone. The Chl was determined according to Talukder *et al*. (2022) and Ahsan *et al*. (2023).

Chl *a* (mg g^{-1} FW) = $[12.7(D_{663})\text{-}2.69(D_{646})] \times [V/1000 \times W]$

Chl *b* (mg g^{-1} FW) = $[22.9\ (D_{646})\text{-}4.68(D_{663})] \times [V/1000 \times W]$

Total Chl (mg g^{-1} FW) = $[20.2(D_{646}) + 8.02(D_{663})] \times [V/1000 \times W]$

Where, D (663, 646) = Optical density of the Chl extract at a wavelength of 663 and 646 nm, respectively. V = Final volume (mL) of the 80% acetone with Chl extract and W = Weight of fresh leaf sample in g.

Measurement of photosynthetic traits

Photosynthetic traits such as photosynthesis (Pn), transpiration (Tr), stomatal conductance (Gs), and leaf temperature were measured at 62 DAS (8 April 2023, 14 days after removal of flood) at full sunshine during this experimentation. The measurement was taken using a portable Pn system (Li-COR-LI-6400) assembled with an infra-red gas analyzer (Li-COR-LI-6250).

Harvesting

When the crop reached maturity, when the pods turned into brown and became hard, harvesting took place (98 DAS on 16 May 2023). One plant was chosen at random from a single row for each sampling. The first and end rows of the plot were discarded during sampling in order to prevent the border effect. A meter scale (100 cm) was used to measure the height of plants. The plants were chopped off at the base. Plant height was calculated by averaging its measurements from the base to the tip of the main stem. A pod was considered filled if it contained at least one seed; an empty pod was considered unfilled. The seeds were manually counted once they were extracted from the pods. Next, the mean value was noted according to treatment. For each treatment, the weight of 100 seeds was recorded. Seeds were threshed and dried after a 1.8 m^2 patch was harvested in order to get grain and straw yield. After measuring the grain weight, the moisture content was corrected to 14%. Straw was measured and dried plant stems were weighed. The grain sample was pulverized using a Wiley Mill and dried at 700C for 72 hours. The total N content of the ground sample was measured using the micro Kjeldahl method after it was digested in concentrated H_2SO_4 (Yoshida *et al*., 1976). After digesting a 0.2 g powdered sample with 6 ml of 5:2 HNO_3: $HClO_4$, the concentrations of P and K were measured. Total nutrient uptake was determined by the following formulae:

$$\text{Nutrient uptake by grain (kg ha}^{-1}) = \frac{\text{Nutrient in grain (\%)} \times \text{grain yield (kg ha}^{-1})}{100}$$

Nutrient translocation coefficient (NTC) was determined as Mamun *et al*. (2020). Higher NTC indicates relatively higher N translocate from grain to straw. The NTC was determined by the following formulae:

$$\text{Nutrient translocation coefficient (NTC)} = \frac{\text{Nutrient accumulation in grain (kg ha}^{-1})}{\text{Nutrient accumulation in straw (kg ha}^{-1})}$$

$$\text{Protein content in grain (\%)} = \text{N (\%)} \times 6.25$$

Statistical analysis

The statistical package CropStat (version 7.2) was used to compile and apply analysis of variance (ANOVA) to the acquired data of various parameters. Using the Duncan's multiple range test at the 5% level of significance, the treatment means were compared (Gomez and Gomez, 1984). Graphs were prepared using Excel software. The correlation graphs were prepared using R (version 4.2.2).

Results and Discussion

SPAD values

The SPAD value was used in this study to determine the leaf greenness with time under WL and control condition (Fig. 1). After exposure to WL stress for 24 hours, the soybean leaves turned from green to yellow. The result showed that the SPAD values generally reduced, especially during the 7-day WL treatment. When comparing the leaves of WL to the control plants, the SPAD reading revealed a lower value. The change in leaf color was caused by a considerable drop in Chl concentration in soybean leaves under WL. This demonstrated that soybeans were sensitive and reacted rapidly to the WL. Nine SPAD readings were obtained, beginning one day after recession of WL condition and continuing until the ninth day. After the recession of flood, a noticeable change in leaf color from yellow to green was observed daily.

The SPAD values in K_0 varied from 25.07 to 38.83 in the WL condition and from 39 to 45 in the control. It showed that the first day following the flood recession saw the largest decrease in the SPAD value, while the ninth day following the flood recession saw the lowest drop (Fig. 1). Similarly, when a complete dose of K was applied as basal (K_B), the SPAD of WL plots ranged from 26.18 to 37.77. In this instance, the 7th day following the flood recession showed the largest reduction, whilst the 8th and 9th days showed the lowest. However, the SPAD values ranged from 25.07 to 43.20 in the WL plot during application of 50% of K as basal + 50% before WL (K_{B+BF}). In this case the highest reduction was observed in 1st day after the recession of flood, while no difference was observed at 9th day. Moreover, the SPAD values ranged from 23.93 to 40.97 in the WL plot during application of 50% of K as basal + 50% after the termination of WL (K_{B+AF}). In this case the highest reduction was observed in the 1st day after the recession of flood, while no difference was observed at 9th day. The results implied that K prevented the

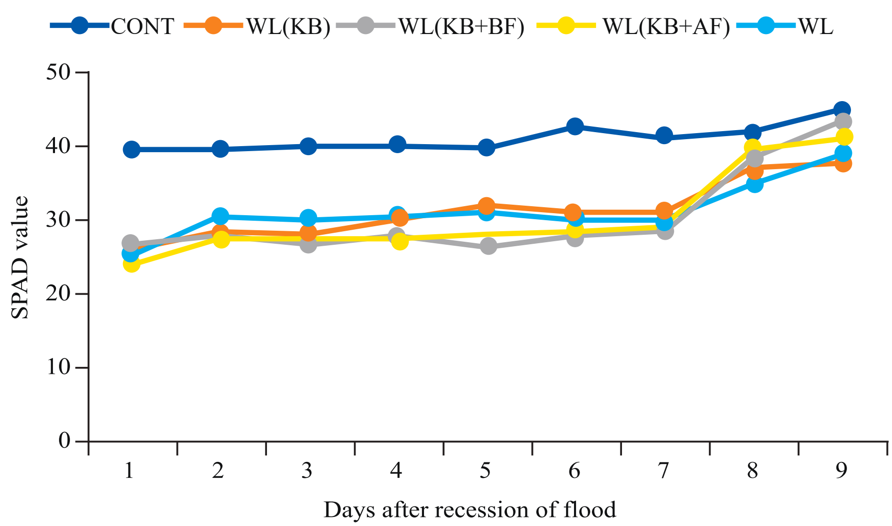

Fig. 1. Effect of WL and K application on SPAD values after the recession of flood. WL = Waterlogging, CONT = Control, $K_{(0)}$ = Control (no K fertilizer), $K_{(B)}$ = Application of full dose of K as basal, $K_{(B+BF)}$ = Application of 50 % of K as basal + 50 % before flooding, $K_{(B+AF)}$ = Application of 50 % of K as basal + 50 % after the termination of flooding.

decrease in SPAD values under WL conditions by improving the plant's physiological resilience and reducing stress-induced Chl degradation. It is plausible that by keeping the roots healthier, K helped the plant to maintain overall vigor. This, in turn, slowed down the degradation of Chl, which was the pigment responsible for the green color of leaves as measured by the SPAD meter. WL caused roots to become stressed, leading to a buildup of fermentation products and lipid peroxidation. The nutrient K probably helped to maintain root function, which limits the accumulation of fermentation products and peroxidation that damage photosynthetic tissues. By mitigating these negative effects of WL, K application as $K_{B+AF,}$ helped the plant maintaining a higher level of Chl, which was measured by the SPAD meter. Rocío *et al*. (2018) found a gradual drop in SPAD values of adult leaves one week after WL application, followed by declines in SPAD values of young leaves toward the end of the stress. It was also consistent with findings that leaf Chl content was reduced during WL stress (Manzur *et al*., 2009).

Pigments content in soybean leaves

The interaction of WL × K exerted a significant effect on leaf pigment content of soybean (Figs.2a to c). Though WL stress showed a negative effect, but K had positive effect on leaf chlorophyll (Chl) content of soybean. The highest Chl *a* concentration (3.2 mg g^{-1} fresh weight, FW) was measured under K_B, which was statistically similar with that of K_{B+BF} (3.0 mg g^{-1} FW) andK_{B+AF} (3.0 mg g^{-1} FW) under control condition (Fig. 2a). Under WL stress condition, however, the Chl *a* content of soybean leaf measured from K_{B+BF} (2.6 mg g^{-1} FW), K_B (2.57 mg g^{-1} FW) and K_{B+AF} (2.48 mg g^{-1} FW) applied plots were statistically identical. In the case of Chl *b* content, the highest concentration was measured from K_{B+BF} (1.1 mg g^{-1} FW) which was statistical similar with K_B (1.0 mg g^{-1} FW) and K_{B+AF} (1.0 mg g^{-1} FW) under no stress condition (Fig. 2b). Like Chl *a* content, K_B (0.98 mg g^{-1} FW), K_{B+BF} (0.96 mg g^{-1} FW) and K_{B+AF} (0.87 mg g^{-1} FW) showed statistically identical concentration of Chl *b* in the case of flooding stress. Regarding total Chl content, the highest concentration was measured from K_B (4.2 mg g^{-1} FW), which was statistical similar with K_{B+BF} (4.1 mg g^{-1} FW) and K_{B+AF} (4.0 mg g^{-1} FW) under no stress condition (Fig. 2c). Like Chl *b* content, K_B (3.55 mg g^{-1} FW), K_{B+BF} (3.56 mg g^{-1} FW) and K_{B+AF} (3.35 mg g^{-1} FW) showed statistically identical concentration of total Chl under WL stress.

Application of K as K_{B+AF} led to a significant reduction in the negative impacts on a plant's physiological processes, including Chl content. It is known that K regulates stomatal opening and closing for maintaining proper leaf turgor and water balance. Adequate water status prevents Chl degradation under WL stress, thus preserving higher Chl content. However, K activates many enzymes involved in photosynthetic carbon fixation and Chl synthesis, which increases the rate of Chl formation and its stability within chloroplasts. K helps in the synthesis

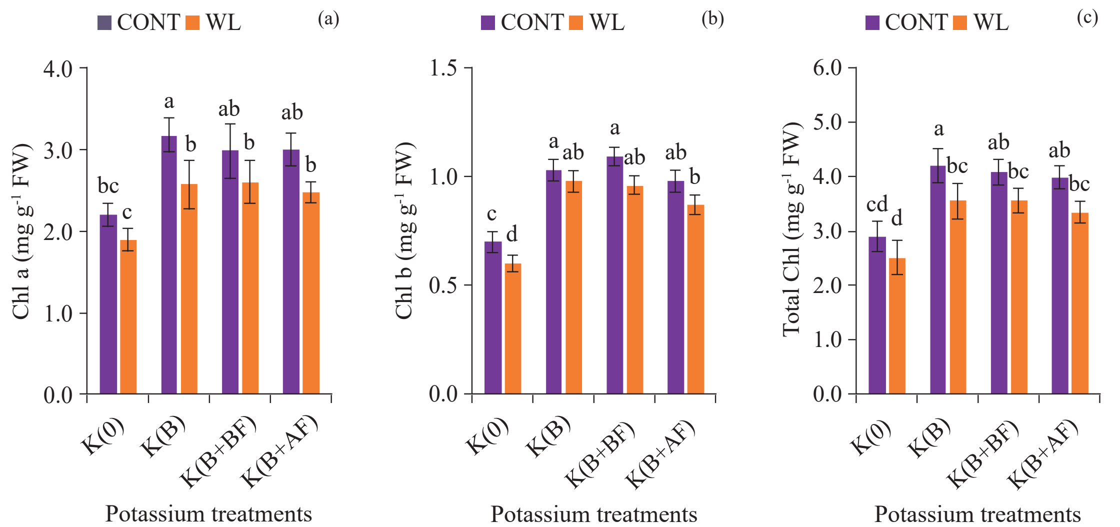

Fig. 2. Effect of WL and K application on pigment content of soybean leaf after the recession of flood. WL = Waterlogging, CONT = Control, $K_{(0)}$ = Control (no K fertilizer), $K_{(B)}$ = Application of full dose of K as basal, $K_{(B+BF)}$ = Application of 50 % of K as basal + 50 % before flooding, $K_{(B+AF)}$ = Application of 50 % of K as basal + 50 % after the termination of flooding. Bars with different letters are vary significantly, as determined by ANOVA followed by Duncan's multiple range test ($P < 0.05$). Small bars on bar graphs indicate mean ± standard error.

of antioxidant enzymes that protect Chl from oxidative damage caused by reactive oxygen species, maintaining higher Chl concentration. Further, K promotes the translocation of photosynthates (sugars) from source to sink tissues. This ensures a steady energy supply for chloroplast development and Chl maintenance (Khatoon *et al*., 2022). K deficiency accelerates leaf aging, leading to Chl breakdown.

Adequate K as K_{B+AF} delayed senescence by maintaining membrane integrity and enzyme function, resulting in greener, longer-living leaves. K enhances Chl content by improving Mg uptake, activating Chl-synthesizing enzymes, maintaining water balance, protecting against oxidative stress, and delaying leaf senescence. Previous studies showed that WL for 10 days at 30 days after reproductive stage reduced Chl concentration by 51% (de Marcos Lapaz *et al*., 2020), while WL at 30 days after sowing for 8 eight days decreased Chl concentration by 34% (Pereira *et al*., 2020).

Gas exchange of soybean

The interaction of WL × K exerted a significant effect on gas exchange parameters of soybean (Figs.3a to d). Though WL stress showed a negative effect, but K had positive effect on photosynthesis (Pn), stomatal conductance (Gs), transpiration rate (Tr) and leaf temperature (LT) of soybean. The highest Pn rate (30 µ mol m^{-2} s^{-1}) was measured under control, which was statistically similar with that of WL (29.38 µ mol m^{-2} s^{-1}) condition during following K management practice ac K_{B+AF} (Fig. 3a). The Pn rate of BD2334 was 27.0 and 28.0 µ mol m^{-2} s^{-1} in the case of K_B and K_{B+BF} management practice under control condition, which were statistically similar with that of under WL condition in the same management practice. In the case of Gs, the highest value was measured from K_{B+AF} (0.72 m mol m^{-2} s^{-1}) under WL condition, which was statistical similar with that of K_B (0.71 30 m mol m^{-2} s^{-1}) under same growing condition (Fig. 3b). Like Pn, K_B (0.50 m mol m^{-2} s^{-1}) under control and K_{B+BF} (0.52

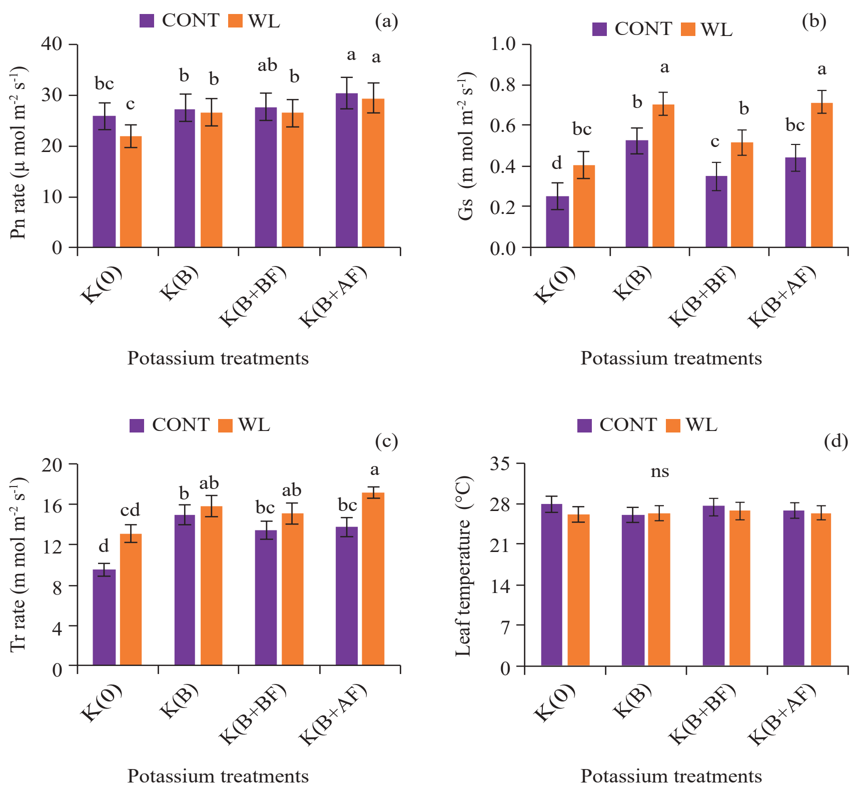

Fig. 3. Effect of WL and K application on gas exchange of soybean leaf after the recession of flood. WL = Waterlogging, CONT = Control, $K_{(0)}$ = Control (no K fertilizer), $K_{(B)}$ = Application of full dose of K as basal, $K_{(B+BF)}$ = Application of 50 % of K as basal + 50 % before flooding, $K_{(B+AF)}$ = Application of 50 % of K as basal + 50 % after the termination of flooding. Bars with different letters are vary significantly, as determined by ANOVA followed by Duncan's multiple range test ($P < 0.05$). Small bars on bar graphs indicate mean ± standard error, ns = not significant.

m mol m^{-2} s^{-1}) under WL condition showed statistically identical Gs. Regarding Tr, the highest rate was recorded from K_{B+AF} (17.21 m mol m^{-2} s^{-1}), which was statistical similar with K_B (15.80 m mol m^{-2} s^{-1}) and K_{B+BF} (15.08 m mol m^{-2} s^{-1}) under stress condition (Fig. 3c). In the control environment, K_B (15 m mol m^{-2} s^{-1}), K_{B+BF} (13 m mol m^{-2} s^{-1}) and K_{B+AF} (14 m mol m^{-2} s^{-1}) showed statistically identical Tr. The LT of soybean did not vary due to interaction of WL × K (Fig. 3d). Pn increased with K application as K_{B+AF} because K activates enzymes involved in Pn, particularly *Rubisco* and *PEP carboxylase*, enhancing CO_2 fixation. However, K improves Chl content and stability, allowing more efficient light energy capture. Further, K enhances ATP synthesis since K is essential for energy transfer in chloroplasts. Higher CO_2 assimilation increases Pn rate. On the other hand, K regulates stomatal opening and closing by controlling osmotic balance in guard cells. When K^+ enters guard cells, osmotic potential decreases, water enters into the guard cell, stomata open and gas exchange increases. Under stress, optimal K allows dynamic stomatal regulation like stomata stay open enough for CO_2 uptake but prevent excessive water loss. Therefore, K balanced Gs ensures sustained photosynthesis without severe dehydration. Again, proper K nutrition maintains leaf turgor and xylem hydraulic conductance, supporting steady Tr.

Under stress, K helps stomata close efficiently, reducing unnecessary transpiration losses (Rawat *et al.*, 2022). Controlled Tr maintains cooling and nutrient flow without excessive water loss. Therefore, through regulated Tr, K maintains evaporative cooling of leaves. However, numerically higher LT was observed in the case of K_0 in both conditions. Different plant processes such as photosynthesis, accumulation of dry matter, plant growth, and formation of flowers and pods are marked as disturbed under the WL conditions (Hasanuzzaman *et al.*, 2016).

Plant height and pod production of soybean

The plant height of soybean did not change statistically as a result of interaction between WL × K application, but pod production plant^{-1} (Table 2). However, in all K management methods, the BD2334 had numerically taller plants under control than WL condition. Moreover, BD2334 produced numerically taller plants (29.67 cm) under control when K_{B+BF} management practice was followed, while the shorter plants were found under K_0 practice under both control (26.33 cm plants) and WL (26.00 cm plants) condition. Under WL situation, BD2334 gave tall stature plants (29.00 cm plants) under the application of K_{B+AF}. The WL-induced decrease in plant height was also noted in soybeans (Mamun *et al.*, 2022). Kim *et al.* (2018) reported that the reduction in plant height under WL conditions was probably due toO_2 deficiency, anaerobic conditions, less root activity, and inhibition of synthesis and transport of photosynthetic assimilates.

When K_{B+BF} management approach was used, the soybean genotype BD2334 produced the highest number of pods (42.67 plant^{-1}) under control; this was statistically identical to that of K_B (40.00 pods plant^{-1}) (Table 2). Conversely, when K_{B+BF} and K_{B+AF} management practices were used, BD2334 produced 27.0 and 27.67 pods plant^{-1} under WL conditions. Under K_0 management approach, the genotype produced the fewest pods plant^{-1} under both control (23 pods plant^{-1}) and WL (21.33 pods plant^{-1}) circumstances. The K element has a viable function in the development, growth, and production process of plants (Minjian *et al.,* 2007).

One of the key characteristics of soybeans that contributes to yield is the quantity of pods plant^{-1}. According to this study, WL in soybeans decreased pod production. Plant nutrient K acts as a key regulator in almost all physiological and biochemical processes of plant growth and reproduction. K activates many enzymes involved in photosynthesis and carbohydrate metabolism. With more efficient CO_2 fixation and sugar transport, plants have greater energy and assimilates to support cell division and elongation. Therefore, K increases internodal length and overall plant height. Adequate K promotes cell expansion, especially in stems and young tissues, leading to taller plants. Again, K regulates carbohydrate translocation from leaves to reproductive organs. Flowers receive more energy for development, resulting in better flower retention and reduced flower abortion resulting more flowers develop into pods. Further, K maintains stigma receptivity and pollen viability by ensuring balanced water relations and enzymatic activity in reproductive tissues, leading to more fertilized ovules and higher pod set (Rehman and Yun, 2006). K enhances pod formation by maintaining water balance and enzyme stability, K supports continuous reproductive development. Under WL circumstances, growth and pod formation were disrupted (Ahmed *et al*., 2020; Sathi *et al*., 2022). On the other hand, using K fertilizer after the flood

Table 2. Effect of WL and K application on plant height and pod production of soybean.

Mode of K application	Plant height (cm)		Pod production (no. plant^{-1})	
	CONT	WL	CONT	WL
$K_{(0)}$	26.33 ± 2.40	26.00± 0.33	23.00 ± 4.04 c	21.33 ± 2.37 c
$K_{(B)}$	29.00± 1.45	28.67± 0.58	40.00 ± 0.58 a	21.00 ± 3.61 c
$K_{(B+BF)}$	29.67± 1.01	28.33± 1.53	42.67 ± 0.01 a	27.00 ± 2.14 b
$K_{(B+AF)}$	29.00± 0.88	29.00± 1.01	28.00 ± 2.60 b	27.67 ± 2.01 b
CV (%)	8.0		16.7	

WL = Waterlogging, CONT = Control, $K_{(0)}$ = Control (no K fertilizer), $K_{(B)}$ = Application of full dose of K as basal, $K_{(B+BF)}$ = Application of 50 % of K as basal + 50 % before flooding, $K_{(B+AF)}$ = Application of 50 % of K as basal + 50 % after the termination of flooding. Values with different letters are vary significantly, as determined by ANOVA followed by Duncan's multiple range test ($P < 0.05$).

recession promotes the growth of additional pods plant^{-1}. This result was comparable to that of Hossen *et al*. (2023).

Seed production and pod wall weight of soybean

The interaction of WL × K application exhibited a significant effect on seed and pod wall production plant^{-1} (Table 3). The tested soybean genotype produced significantly higher number of seeds plant^{-1} under control than WL condition in all K management approaches. BD2334 produced the highest number of seeds during practicing K_{B+BF} management approach (86.33 seeds plant^{-1}), which was statistically identical with that of K_B (85.33 seeds plant^{-1}) in control plot (Table 3). The K_{B+AF} management practice produced the maximum number of seeds (51.67 seeds plant^{-1}), which was statistically similar with that of K_{B+BF} (46.67 seeds plant^{-1}) under WL condition. Under K_0 management approach, the genotype produced the fewest seeds plant^{-1} under both control (54.67 seeds plant^{-1}) and WL (39.67 seeds plant^{-1}) circumstances. The number of seeds plant^{-1} is an important yield contributing attribute of soybean. In this study, the production of seeds plant^{-1} reduced due to WL in soybeans. Growth and pod formation were disturbed under WL conditions (Islam *et al*., 2014). This finding was similar to Vyas *et al*. (2007). However, the application of K before flood was beneficial for soybean seeds production in control, while application of K after flood water recession was helpful for seed setting in soybean in WL condition.

When K_{B+BF} management approach was used, the soybean genotype BD2334 produced the highest dry matter of pod wall (11.80g plant^{-1}) under control; this was statistically identical to that of K_B (11.0g plant^{-1}) (Table 3). Conversely, when K_{B+AF} management practices were used, BD2334 produced 7.71g pod wall plant^{-1}, which was statistically higher than other K management practices under WL conditions. Under K_0 management

Table 3. Effect of WL and K application on seed production and pod wall weight of soybean.

Mode of K application	Seed production (no. plant^{-1})		Pod wall weight (g plant^{-1})	
	CONT	WL	CONT	WL
$K_{(0)}$	46.33 ± 3.74 c	39.67 ± 3.31 d	6.72 ± 0.89 c	4.46 ± 1.03 d
$K_{(B)}$	85.33 ± 1.45 a	41.67 ± 4.32 cd	11.09 ± 0.50 a	5.63 ± 0.55 cd
$K_{(B+BF)}$	86.33 ± 1.33 a	46.67 ± 1.45 c	11.80 ± 0.69 a	5.75 ± 2.52 cd
$K_{(B+AF)}$	54.67 ± 1.45 b	51.67 ± 3.74 bc	7.30 ± 0.07 b	7.71 ± 1.35 b
CV (%)	15.0		15.8	

WL = Waterlogging, CONT = Control, $K_{(0)}$ = Control (no K fertilizer), $K_{(B)}$ = Application of full dose of K as basal, $K_{(B+BF)}$ = Application of 50 % of K as basal + 50 % before flooding, $K_{(B+AF)}$ = Application of 50 % of K as basal + 50 % after the termination of flooding. Values with different letters are vary significantly, as determined by ANOVA followed by Duncan's multiple range test ($P < 0.05$).

approach, the genotype produced the fewest pod wall dry matter plant^{-1} under both control (6.72g plant^{-1}) and WL (4.46g plant^{-1}) circumstances. The BD2334 produced higher number of pods plant^{-1} during the application of K_{B+BF}under control, while K_{B+AF} under WL condition. Thus, the pod wall dry matter was also higher in both treatments.

100-seed weight and grain yield of soybean

The 100-seed weight of soybean did not vary significantly due to the interaction of WL × K application (Table 4). However, the tested soybean genotype produced heavier seeds when K fertilizer was applied as K_{B+BF} and K_{B+AF} under control and WL conditions, respectively. On the other hand, smaller seeds were found in the case of K_0 management practice in both growing conditions. Individual seed weight is a genetically controlled characteristic of plants. However, split application of K fertilizer increased the 100-grain weight of soybean varieties under both control and WL conditions. This indicated that the split application of K improved the production of seed through the use of another nutrient element by soybean plants. Ahmed *et al*. (2009) reported that the test weight of maize and soybean increased by 8 and 4%, respectively, due to a higher amount of K application. The application of K at a higher rate increased Pn and accumulation of a greater amount of photosynthate to grain, as split application of K after recession of flood water favors roots to absorb more minerals from the soil. On the other hand, K also helps to increase Pn and production of more photo assimilates that are ultimately stored in the seed. Thus, the 100-seed weight of BD2334 increased when K was applied after removal of flood.

The interaction of WL × K application showed a significant effect on grain yield ha^{-1} (Table 4). The tested soybean genotype produced significantly higher grain under control than WL condition in all K management approaches. BD2334 produced the highest grain yield during practicing K_B management approach (2.24 t ha^{-1}), which was statistically identical with that of K_{B+BF} (2.17 t ha^{-1}) in control plot (Table 5). The K_{B+AF} management practice produced the maximum grain yield (1.45 t ha^{-1}), which was statistically similar with that of K_{B+BF} (1.26 t ha^{-1}) under WL condition. Under K_0 management approach, the genotype produced the fewest grain ha^{-1} under both control (1.16 t ha^{-1}) and WL (1.03 t ha^{-1}) circumstances.

Under the WL conditions, grain yield was drastically reduced. The reduction of yield contributing characters under WL resulted in lower yield. The yield components of soybean were also affected by WL, as reported by Mamun *et al*. (2023), resulting in lower yield (Amin *et al*., 2017). However, the split application of K improved grain yield in the case of BD2334 under both growing conditions. In this experiment, it was observed that the application of K before flood was beneficial for soybean grain production in control, while application of K after flood water recession was helpful for seed yield in soybean during WL condition. BD2334

Table 4. Effect of WL and K application on 100-seed weight and grain yield of soybean.

Mode of K application	100-seed weight (g)		Grain yield (t ha^{-1})	
	CONT	WL	CONT	WL
$K_{(0)}$	25.17± 1.27	24.74± 2.91	1.16 ± 0.50 c	1.03 ± 0.08 c
$K_{(B)}$	26.21± 1.08	26.50± 1.77	2.24 ± 0.46 a	1.06 ± 0.99 c
$K_{(B+BF)}$	26.25± 0.49	27.09± 2.02	2.17 ± 0.69 a	1.26 ± 1.0 bc
$K_{(B+AF)}$	25.44± 1.70	27.39± 2.18	1.43 ± 0.07 b	1.45 ± 0.80 b
CV (%)	4.8		8.5	

WL = Waterlogging, CONT = Control, $K_{(0)}$ = Control (no K fertilizer), $K_{(B)}$ = Application of full dose of K as basal, $K_{(B+BF)}$ = Application of 50 % of K as basal + 50 % before flooding, $K_{(B+AF)}$ = Application of 50 % of K as basal + 50 % after the termination of flooding. Values with different letters are vary significantly, as determined by ANOVA followed by Duncan's multiple range test (P < 0.05).

produced 38 and 15% higher grain under WL conditions, when K was applied after the recession of flood water as compared to K_B and K_{B+BF}, respectively. It indicated that K fertilizer can be reduced the detrimental effect of flooding. This finding also agreed with the result of Vyas *et al*. (2007). Application of K increased test weight and grain yield (Uddin *et al*., 2013) because photosynthetic activity, translocation, and metabolism of carbohydrates are influenced by K (Lu *et al*., 2016). The greater yield and high-quality grains obtained due to K application might be due to increased photosynthesis, greater carbohydrate translocation toward the sink, and metabolism (Zörb *et al*., 2014).

Straw yield and harvest index of soybean

The interaction of WL × K application revealed a significant effect on straw yield and grain harvest index (GHI) of soybean (Table 5). The tested soybean genotype produced significantly higher straw yield under control than WL condition in all K management approaches. BD2334 produced the highest straw yield during practicing K_{B+BF} management approach (5.86 t ha^{-1}), which was statistically identical with that of K_B (5.22 t ha^{-1}) in control plot (Table 5). The K_{B+BF} management practice produced the maximum straw yield (4.85 t ha^{-1}), which was statistically similar with that of K_{B+AF} (4.80 t ha^{-1}) under WL condition. Under K_0 management approach, the genotype produced the fewest straw yield t ha^{-1} under both control (3.61 t ha^{-1}) and WL (3.27 t ha^{-1}) circumstances. Similar to yield, the straw yield of BD2334 also increased by split application of K fertilizer under control as well as WL condition. A similar finding was also reported by Mamun *et al*. (2023). When K_B management approach was used, the soybean genotype BD2334 gave the highest GHI under control; this was statistically identical to that of K_{B+BF} (Table 5). Conversely, when K_{B+AF} management practices were used, BD2334

Table 5. Effect of WL and K application on straw yield and harvest index of soybean

Mode of K application	Straw yield (t ha^{-1})		Grain harvest index	
	Control	WL	Control	WL
$K_{(0)}$	3.61 ± 0.62 c	3.27 ± 0.25 c	0.24 ± 0.08 b	0.24 ± 0.05 b
$K_{(B)}$	5.22 ± 0.40 ab	4.16 ± 0.75 b	0.30 ± 0.05 a	0.20 ± 0.08 c
$K_{(B+BF)}$	5.86 ± 0.40 a	4.85 ± 0.67 b	0.27 ± 0.03 a	0.21 ± 0.09 bc
$K_{(B+AF)}$	3.98 ± 0.71 c	4.80 ± 0.66 ab	0.26 ± 0.08 ab	0.23± 0.08 b
CV (%)	4.8		8.5	

WL = Waterlogging, CONT = Control, $K_{(0)}$ = Control (no K fertilizer), $K_{(B)}$ = Application of full dose of K as basal, $K_{(B+BF)}$ = Application of 50 % of K as basal + 50 % before flooding, $K_{(B+AF)}$ = Application of 50 % of K as basal + 50 % after the termination of flooding. Values with different letters are vary significantly, as determined by ANOVA followed by Duncan's multiple range test (P < 0.05).

gave 0.23 GHI, which was statistically identical with that of K_0 management practices under WL conditions. A reduction of GHI due to WL was reported in soybean (Mamun *et al*., 2023). According to Nguyen *et al*. (2012), WL stress during the vegetative stage of soybean growth causes a reduction in grain yield of approximately 17–40%, and that the reproductive stage led to a 40–57% yield reduction.

Nutrient accumulation in soybean seed and straw

The interaction of WL × K exerted a significant effect on N, P and K accumulation in grain of soybean (Fig. 4a). Though WL stress showed a negative effect, but K had positive effect on N accumulation in grain of soybean. The highest grain N accumulation was determined under K_B (142 kg ha^{-1}), which was statistically identical with that of K_{B+BF} (134 kg ha^{-1}) under control condition. However, the grain N accumulation of soybean measured from K_{B+AF} applied plots were statistically identical in the case of control (102 kg ha^{-1}) and WL (94.58 kg ha^{-1}) conditions. In the case of straw N accumulation, the highest amount was measured from K_{B+AF} (60.01 kg ha^{-1}) in WL condition, which was statistical identical with K_{B+BF} (55 kg ha^{-1}) under no stress condition. In control condition, K_B (41 kg ha^{-1}) and K_{B+AF} (48 kg ha^{-1}) showed statistically identical straw N accumulation. The highest grain P accumulation was determined under K_B (14 kg ha^{-1}) in control, which was followed by K_{B+AF} (11.36 kg ha^{-1}) under WL condition (Fig. 4b). However, the grain P accumulation of soybean measured from K_{B+BF} was 9 kg ha^{-1}, which was statistically similar with that of K_{B+AF} (7 kg ha^{-1}) under control conditions. In the case of straw P accumulation, the highest amount was measured from K_0 (22.13 kg ha^{-1}) in control condition, which was statistical identical with K_B (21.66 kg ha^{-1}) and K_{B+AF} (21.23 kg ha^{-1}) under WL stress condition. Though WL stress showed

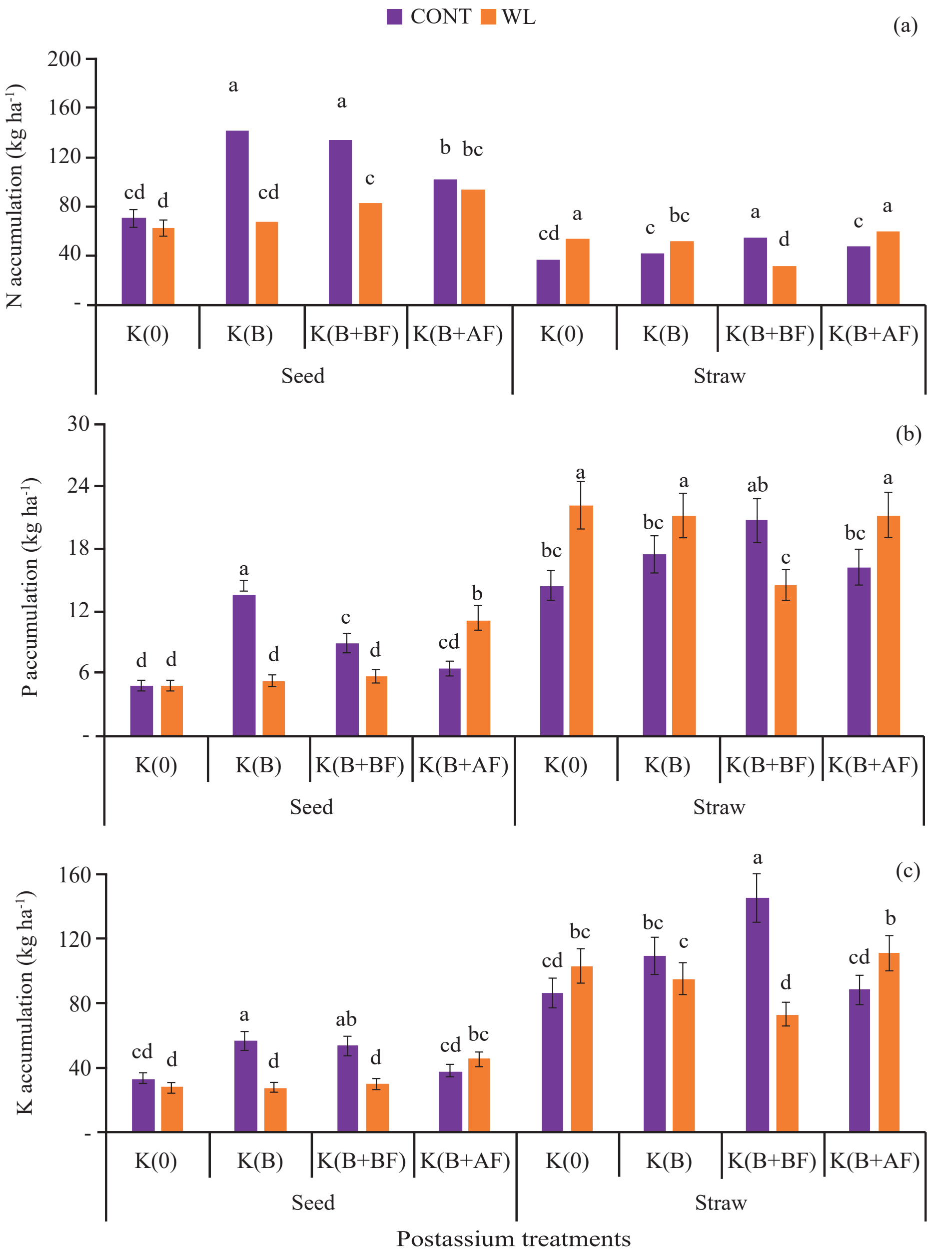

Fig. 4. Effect of WL and K application on N, P and K accumulation in grain and straw of soybean. WL = Waterlogging, CONT = Control, $K_{(0)}$ = Control (no K fertilizer), $K_{(B)}$ = Application of full dose of K as basal, $K_{(B+BF)}$ = Application of 50 % of K as basal + 50 % before flooding, $K_{(B+AF)}$ = Application of 50 % of K as basal + 50 % after the termination of flooding. Bars with different letters are vary significantly, as determined by ANOVA followed by Duncan's multiple range test ($P < 0.05$). Small bars on bar graphs indicate mean ± standard error.

a negative effect, but K had positive effect on K accumulation in grain and straw of soybean. The highest grain K accumulation was determined under K_B (57 kg ha^{-1}), which was statistically similar with that of K_{B+BF} (54 kg ha^{-1}) under control condition (Fig. 4c). However, the grain K accumulation of soybean measured from K_{B+AF} applied WL (45.45 kg ha^{-1}) conditions. In the case of straw K accumulation, the highest amount was measured from K_{B+BF} (145 kg ha^{-1}) in control condition. The second highest straw K accumulation was obtained from K_{B+AF} (111.34 kg ha^{-1}) under WL condition, which was statistical similar with K_B (110 kg ha^{-1}) under no stress condition (Fig. 4). Exogenous K administration resulted in considerably greater concentrations of macronutrients (K, Ca_2^+, and N) and micronutrients (Fe_2^+ and Mn_2^+) in cotton plant roots, stems, and leaves under both normal and waterlogged circumstances (Ashraf *et al*., 2011).

Nitrogen translocation from straw to grain and protein content

The interaction of WL × K exerted a significant effect on N translocation from grain to straw which was expressed as N translocation coefficient (NTC) (Fig. 5a). The highest NTC was calculated under K_B (3.4) in control.

The second highest NTC was determined under K_{B+BF} (2.6) under WL condition, which statistically identical with control under same management practice. However, the protein content of soybean was the highest in the case of K_{B+AF} (44.6%) under control condition (Fig. 5b). The second highest protein content was measured from K_{B+AF} (40.77%) in WL condition, which was statistical identical with K_B (39.6% in control and 40.5% in WL) and K_{B+BF} (38.6% in control and 40.86% in WL).

Relative contribution of crop establishment method on yield

The relative contribution of K management practice on grain and straw yield have been shown in Table 6. The relative contribution of WL management was 25.07%, while K management method had 17.62% for grain yield. Regarding straw yield, WL and K application technique contributed by 2.93% and 12.71%, respectively. The results revealed that the contribution K application technique was mentionable for grain and straw yield of soybean under WL condition.

Table 6. Sum of squares from the analysis of variance of soybean under WL condition.

Sources of Variation	Sum of squares for grain yield	Sum of squares for straw yield
Replication	0.75 (10.16)	0.43 (1.34)
WL	1.85 (25.07)	0.94 (2.93)
K	1.30 (17.62)	4.08 (12.71)
WL × K	1.62 (21.95)	10.73 (33.42)
Error	1.86 (25.20)	15.93 (49.61)
Total	7.38 (100%)	32.11 (100%)

Values within parentheses indicate the percent contribution of different sources of variation

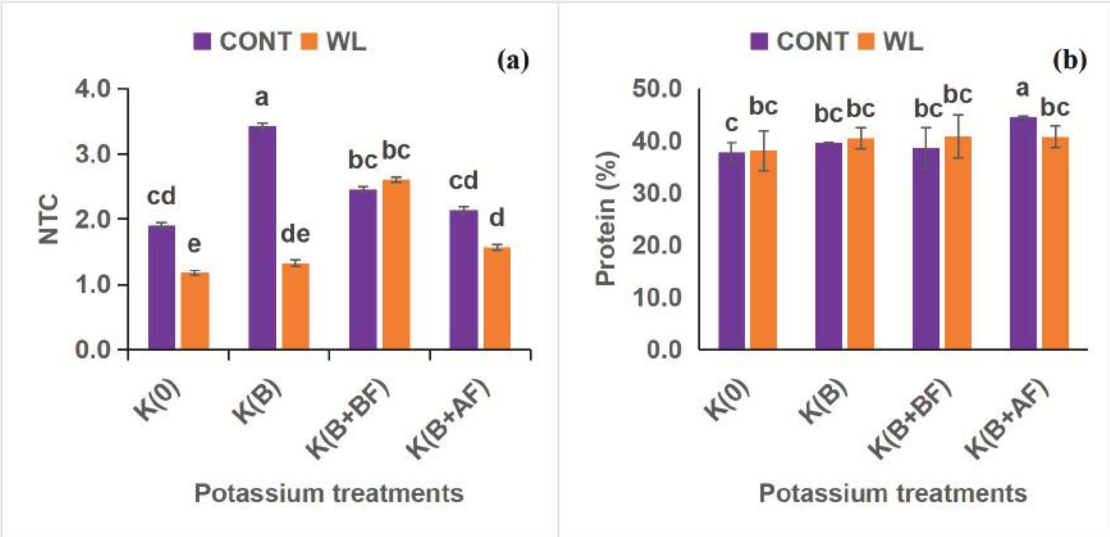

Fig. 5. Effect of WL and K application on nitrogen translocation from straw to grain (NTC) of soybean and seed protein content. WL = Waterlogging, CONT = Control, $K_{(0)}$ = Control (no K fertilizer), $K_{(B)}$ = Application of full dose of K as basal, $K_{(B+BF)}$ = Application of 50 % of K as basal + 50 % before flooding, $K_{(B+AF)}$ = Application of 50 % of K as basal + 50 % after the termination of flooding. Bars with different letters are vary significantly, as determined by ANOVA followed by Duncan's multiple range test ($P < 0.05$). Small bars on bar graphs indicate mean ± standard error.

Conclusions

Morpho-physiological parameters, yield and yield characteristics, and nutrient uptake were negatively impacted by the WL stress in soybeans. Applying 50% K as basal + 50% after WL termination demonstrated a noteworthy contribution to stress recovery, improved photosynthetic efficiency, and the production of healthier seeds and more pods. Soybean genotype BD2334 produced 1.06 t grain ha^{-1} under WL conditions when K fertilizer was applied at a basal. This amount rose to 1.45 t ha^{-1} when K was applied as 50% of basal + 50% after WL ended. Additionally, under WL conditions, applying K as 50% of basal + 50% after WL enhanced the grain's nutrient uptake. The K management practices had a 17.62% and 12.71% relative impact on grain and straw yield, respectively. The current K application method should be changed in light of the study's findings to improve grain and straw yield in waterlogged circumstances.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: MAAM (Md. Abdullah Al Mamun) and MAK (M. Abdul Karim). Methodology, Validation, and Data curation: MAAM and SN (Shefayed Naserat). Visualization: MAAM. Original draft preparation, Reviewing, and Editing, MAAM, MAK and MABM (Md. Abdul Baset Mia). All authors have read and agreed to the published version of the manuscript.

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References

Ahmed, A., S. Aftab, S. Hussain, H. Nazir Cheema, W. Liu, F. Yang and W. Yang. 2020. Nutrient accumulation and distribution assessment in response to potassium application under maize–soybean intercropping system. *Agron.* 10(5): 725.

Ahmed, M., A. Riaz, M. Ishaque and A. U. Malik. 2009. Response of maize hybrids to varying potassium application in Pakistan. *Pakistan J. Agric. Sci.* 46(3): 179–184.

Ahsan, M. K., M. A. A. Mamun, T. K. Ghosh and M. A. Karim. 2023. Dissecting drought stress tolerance of soybean genotypes based on morphological and physiological attributes. *J. Bangladesh Acad. Sci.* 47(2): 223-240.

Akter, M., M. A. A. Mamun, M. Akter, M. A. B. Mia and M. A. Karim. 2024. Extricating short-duration and bold-grained high-yielding soybean genotypes under waterlogging conditions. *Acta Biol. Szegediensis* 68(2): 124-141.

Amin, M. R., M. A. Karim, Q. A. Khaliq, M. R. Islam and S. Aktar. 2017. The influence of waterlogging period on yield and yield components of mungbean (*Vigna radiata L. Wilczek*). *Agricul.* 15(2): 88-100.

Ashraf, M. A., M. S. A. Ahmad, M. Ashraf, F. Al-Qurainy and M. Y. Ashraf. 2011. Alleviation of waterlogging stress in upland cotton (*Gossypium hirsutumL.*) by exogenous application of potassium in soil and as a foliar spray. *Crop Pasture Sci*. 62(1): 25-38.

BBS, 2020. Bangladesh Bureau of Statistics. Yearbook of Agricultural Statistics-2020. *Bangladesh Bureau of Statistics*, Ministry of Planning, Government of the People's Republic of Bangladesh.

Devi, K. N., L. N. K. Singh, M. S. Singh, S. B. Singh and K. K. Singh. 2012. Influence of sulphur and boron fertilization on yield, quality, nutrient uptake and economics of soybean (Glycine max) under upland conditions. *J. Agric Sci*. 4(4): 1.

Divito, G. A. and V. O. Sadras. 2014. How do phosphorus, potassium and sulphur affect plant growth and biological nitrogen fixation in crop and pasture legumes? A meta-analysis. *Field Crops Res*. 156: 161-171.

Dola, D. B., M. A. Mannan, U. Sarker, M. A. A. Mamun, T. Islam, S. Ercisli, M. H. Saleem, B. Ali and R. A. Marc. 2022. Nano-iron oxide accelerates growth, yield, and quality of Glycine max seed in water deficits. *Front. Plant Sci.* 13*:* 992535.

FAOSTAT. 2022. Food and Agriculture Organization (www.fao.org/faostat/en/#data/qc).

Fatema, M. K., M. A. A. Mamun, U. Sarker, M. S. Hossain, M. A. B. Mia, R. Roychowdhury, S. Ercisli, R. A. Marc, O. O. Babalola and M. A. Karim. 2023. Assessing morpho-physiological and biochemical markers of soybean for drought tolerance potential. *Sustainability*, 15(2): 1427.

FRG. 2018. Fertilizer Recommendation Guide-2018. BARC, Farmgate, Dhaka, 91p.

Gomez, K. A. and A. A. Gomez. 1984. Statistical Procedures for Agricultural Research (2nd edition). John Willey and Sons, Inc. Singapore, pp. 139-240.

Hasanuzzaman, M., K. Nahar, A. Rahman, J. A. Mahmud, M. S. Hossain and M. Fujita. 2016. Soybean production and environmental stresses. *In Environmental Stresses in Soybean Production*; Academic Press: Cambridge, MA, USA, pp. 61–102.

Hossain, M. S., M. A. A. Mamun, M. Akter, A. J. M. S. Karim, Q. A. Khaliq, M. A. R. Khan and M. A. Karim. 2019. Effect of waterlogging stress on yield and yield contributing traits of soybean. *Bangladesh J. Ecol.* 1(2): 83-89.

Hossen, M. M., M. A. A. Mamun, M. M. Rahman and M. A. Karim. 2023. Exogenous application of potassium fertilizer alleviates the detrimental effect of waterlogging on soybean. *J. Bangladesh Acad. Sci.* 47(2): 155-167.

Islam, M. R., N. Akter, S. S. Parvej and K. S. Haque. 2014. Growth and yield response of mungbean (*Vigna radiata L. Wilczek*) genotypes to wet puddling, flooding and saturated soil culture. *J. Plant Sci*. 2(6): 311-316.

Khatoon, S., M. Mahajan and M. I. R. Khan. 2025.. Ethylene–potassium interactions safeguard ionic balance, chlorophyll biosynthesis, and source–sink metabolism to sustain wheat growth and yield responses under salt stress. *Plant Stress*, 18: 101049.

Kim, Y., C. W. Seo, A. L. Khan, B. G. Mun, R. Shahzad, J. W. Ko, B. W. Yun and I. J. Lee. 2018. Ethylene mitigates waterlogging stress by regulating glutathione biosynthesis-related transcripts in soybeans. *BioRxiv*, 252312.

Lu, Z., J. Lu, Y. Pan, P. Lu, X. Li, R. Cong and T. Ren. 2016. Anatomical variation of mesophyll conductance under potassium deficiency has a vital role in determining leaf photosynthesis. *Plant Cell Environ.* 39(11): 2428–2439.

Madhu, M. and J. L. Hatfield. 2016. Dry matter partitioning and growth analysis of soybean grown under elevated CO_2 and soil moisture levels. *Current Sci.* 981-984.

Mamun, M. A. A., Julekha, U. Sarker, M. A. Mannan, M. M. Rahman, M. A. Karim, S. Ercisli, R. A. Marc and K. S. Golokhvast. 2022. Application of potassium after waterlogging improves quality and productivity of soybean seeds. *Life*. 12: 1816.

Mannan, M. A. and M. A. A. Mamun. 2018. Selection of vegetable soybean suitable for Bangladesh through multivariate analysis. *Ann. Bangladesh Agril.* 22(2): 51-57.

Mamun, M. A. A., M. M. Haque, M. A. Saleque, Q. A. Khaliq, A. J. M. S. Karim, M. A. R. Khan, A. Khatun and M. A. Karim. 2020. Management strategy, uptake and translocation of nitrogen in tidal flooded rice ecosystem. *J. Plant Nutr.* 43(14): 2186-2199.

Manzur, M. E., A. A. Grimoldi, P. Insausti and G. G. Striker. 2009. Escape from water or remain quiescent? *Lotus tenuis* changes its strategy depending on depth of submergence. *Ann. Bot.* 104(6): 1163–1169.

Minjian, C., Y. Haiqiu, Y. Hongkui and J. Chunji. 2007. Difference in tolerance to potassium deficiency between two maize inbred lines. *Plant Prod. Sci.* 10(1): 42–46.

Nguyen, V. T., T. D. Vuong, T. VanToai, J. D. Lee, X. Wu, M. R. Mian, A. E. Dorrance and H. T. Nguyen. 2012. Mapping of quantitative trait loci associated with resistance to Phytophthora sojae and flooding tolerance in soybean. *Crop Sci.* 52(6): 2481–2493.

Pereira, Y. C., F. R. D. Silva, B. R. S. D. Silva, F. J. R. Cruz, D. J. Marques and A. K. D. S. Lobato. 2020. 24-epibrassinolide induces protection against waterlogging and alleviates impacts on the root structures, photosynthetic machinery and biomass in soybean. *Plant Signal. Behav.* 15(11): 1805885.

Rawat, J., N. Pandey and J. Saxena. 2022. Role of potassium in plant photosynthesis, transport, growth and yield. *Role of potassium in abiotic stress*, 1-14.

Rehman, S. and S. J. Yun. 2006. Developmental regulation of K accumulation in pollen, anthers, and papillae: are anther dehiscence, papillae hydration, and pollen swelling leading to pollination and fertilization in barley (*Hordeum vulgare* L.) regulated by changes in K concentration? *J. Expt. Bot.* 57(6): 1315–1321.

Rocío, A. P., D. J. Miralles, T. D. Colmer, E. L. Ploschuk and G. G. Striker. 2018. Waterlogging of winter crops at early and late stages: impacts on leaf physiology, growth, and yield. *Front. Plant Sci.* 9: 1863.

Sathi, K. S., A. A. C. Masud, M. R. Falguni, N. Ahmed, K. Rahman and M. Hasanuzzaman. 2022. Screening of soybean genotypes for waterlogging stress tolerance and understanding the physiological mechanisms. *Adv. Agric.* 2022: 5544665.

Talukder, S., M. A. A. Mamun, M. S. Hossain, M. A. R. Khan, M. M. Rahman, M. R. Talukder, M. M. Haque and J. C. Biswas. 2022. Duration of low temperature changes physiological and biochemical attributes of rice seedling. *Agron. Res.*20(S1): 1163-1176.

Uddin, S., M. A. R. Sarkar and M. M. Rahman. 2013. Effect of nitrogen and potassium on yield of dry direct seeded rice cv. NERICA 1 in Aus season. *Int. J. Agron. Plant Prod.* 4(1): 69-75.

Vyas, A. K., S. D. Billore, A. Ramesh, O. P. Joshi, G. K. Gupta, A. N. Sharma and P. Imas. 2007. Role of potassium in balanced fertilization of soybean-wheat cropping system. In *Proceedings of the Regional Seminar on Recent Advances in Potassium Nutrition Management for Soybean Based Cropping Systems, Indore, India,* pp. 28-29.

Whippo, C. W., N. Z. Saliendra and M. A. Liebig. 2024. Cover crop inclusion and residue retention improves soybean production and physiology in drought conditions. *Heliyon,* 10: e29838.

Yasmin, A., M. A. Mannan, U. Sarker, D. B. Dola, H. Higuchi, S. Ercisli and O. O. Babalola. 2022. Foliar application of seaweed extracts enhances yield and drought tolerance of soybean. *Front. Plant Sci.* 13: 992880.

Yoshida, S. and F. T. Parao. 1976. Climatic influence on yield and yield components of lowland rice in the tropics. *Clim. Rice.* 20: 471–494.

Zörb, C., M. Senbayram and E. Peiter. 2014. Potassium in agriculture–status and perspectives. *J. Plant Physiol.* 171(9): 656–669.