RESEARCH ARTICLE

CYTOKININ AND GIBBERELIC ACID ALLEVIATE THE EFFECT OF WATERLOGGING IN MUNGBEAN (*VIGNA RADIATA* L. WILCZEK)M Rafiqul Islam^{a*}, Mehruz Hasan^b, Nurunnaher Akter^a, Shahrina Akhtar^c^aDepartment of Agronomy, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur-1706, Bangladesh, Email: rafiarib@yahoo.com^bDepartment of Genetics and Plan Breeding, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur-1706, Bangladesh^cDepartment of Agronomy, Sher-e-Bangla Agricultural University, Dhaka-1207, Bangladesh*Corresponding Author Email: rafiarib@yahoo.com

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ABSTRACT

Recently, waterlogging damage of mungbean is most common in many mungbean growing areas of the world. The exogenous application of phytohormones cytokinin (CK) and gibberellic acid (GA) could be an effective way of managing mungbean under waterlogging stress. Therefore, we applied different levels of CK and GA at the onset of waterlogging and ten days after waterlogging, and the results were observed in waterlogged plants as compared to control. The CK and GA application showed much improvement in depressed morpho-physiological and yield-related traits and seed yield. However, the responses varied depending on the types and doses of CK and GA. The plant height and the number of leaves were higher in GA-applied plants than CK-treated plants. The GA responded more in shoot growth, whereas CK in root development under waterlogged situations. The application of CK at 150 mg/L displayed the highest 33.9% yield advantage. It reveals that exogenous CK could be a good management practice in areas prone to waterlogging stress for attaining better yield in mungbean.

KEYWORDS

Mungbean, Waterlogging damage, Phytohormone application, Plant recovery, Yield increase

1. INTRODUCTION

Mungbean (*Vigna radiata* L. Wilczek) is one of the most promising pulse crops widely grown in tropical and subtropical Asia (Mehandi et al., 2019). Many biotic and abiotic stresses are constraints for its large-scale adaptability. Among abiotic stresses, waterlogging was reported to affect more than 1700 Mha land globally (Voesenek and Bailey-Serres, 2015). The problem is assumed to augment as the frequency and intensity of waterlogging are projected to rise in many areas in the world due to climate change (Watanabe et al., 2013). Such a situation is an extraordinary challenge for the sustainability of growing mungbean (Sarkar et al., 2017). In the future, waterlogging may have more deleterious effects on mungbean cultivation, although some genotypes were found waterlogged-tolerant and able to recover to some extent from the waterlogging injury (Islam et al., 2007; Singh and Singh, 2011; Sarkar et al., 2017). To cope with the situation, investigations directing to improving waterlogging tolerance of the crop through agronomic management manipulation are rather scanty.

Waterlogging affects the root growth resulting in inhibition of shoot growth (Islam et al., 2007, 2008; Ren et al., 2016a). It interrupted the grain filling leading to a decrease in grain yield (Ren et al., 2016b). Waterlogging

used to decrease cytokinin (CK) and gibberellic acid (GA) and increase abscisic acid (ABA) which results in changing endogenous hormonal balance in plants. One of the approaches to dealing with such situations could be the exogenous application of hormones. The phytohormone like GA or CK was found to be diminished the adverse effects of waterlogging on crops by activating various defense mechanisms (Eysholdt-Derzso and Sauter, 2017; Xiang et al., 2017; Ashfaq et al., 2014). Exogenous CK may increase plant endogenous CK levels, delay leaf aging, and enhance photosynthetic efficiency resulting in higher grain yield (Roitsch and Ehneß, 2000). Therefore, the foliar application of CK and GA could be the plausible option for reversing the harmful effects of waterlogging in mungbean.

Nowadays, much attention has been paid to the potential involvement of GA and CK in the management of waterlogging environments in various field crops (Fahad et al., 2015; Bashir et al., 2019; Ren et al., 2016, 2019). Relevant studies on mungbean are not adequately performed so far, although researches are in progress regarding various agronomic management of mungbean for the areas prone to transient waterlogging. The investigations are continued in minimizing the ill effects of waterlogging on the crop but having little attention to the role of CK and GA in alleviating the waterlogging damage of mungbean concerning plant

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growth and yield. Therefore, the study was undertaken to evaluate the role of exogenously applied CK and GA in overcoming the damaging effects of waterlogging on plant growth and seed yield in mungbean.

2. MATERIALS AND METHODS

2.1 Experimental site and growing conditions

The experiment was carried out at the Stress Research Site (24°02'16.8" N latitude and 90°23'46.6" E longitude having an elevation of 14.9 m from mean sea level) of the Department of Agronomy, Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Bangladesh from August to November 2017 during the Kharif-II season. The site was characterized with a relative humidity of 77-90%, average night and day temperature ranging from 24.3 to 31.8°C, and rainfall of 941 mm. A semi-controlled condition was maintained by constructed a vinyl house for protecting unexpected rains and maintaining the treatment condition during the experiment.

2.2 Plant material and seedling establishment

We used the BUMug 4 mungbean variety as the plant material that was found waterlogging-tolerant in an earlier study (Shibly et al., 2020). A total of 24 wagoner pots of 25 cm diameter and 30 cm height were taken and filled with sandy clay soil. Seeds of mungbean were sown on 31 August 2017 directly in the pot containing 10 kg of well-decomposed cowdung and soil (1:4, v/v). Each pot was applied with nitrogen, phosphorus, and potassium at 0.64 g, 1.29 g, 0.48 g as urea, triple superphosphate (TSP) and muriate of potash (MP). One-third of urea and the whole amount of TSP and MP were mixed with the soil as basal dose during final pot preparation. The remaining two-third of urea was applied in two equal installments: one at 15 days after emergence (DAE) and another at 25 DAE. Water was uniformly applied to maintain optimum soil moisture condition in each pot. Most of the seedlings emerged within 5-6 days of sowing. Seedlings were thinned out after ten days of emergence by keeping three healthy seedlings of uniform growth in each pot. Insecticide Ripcord 10 EC (BASE Bangladesh Limited) at 1 ml/L water was sprayed to protect plants from insects. Weeding and loosening the soil were done wherever necessary to keep the pots free from weeds and better aeration to maintain proper growth of the seedlings.

2.3 Treatments and experimental design

There were six treatment conditions viz. (i) control (no waterlogging + no phytohormone), (ii) waterlogging (waterlogging + no phytohormone), (iii) CK100 (waterlogging + cytokinin at 100 mg/L), (iv) CK150 (waterlogging + cytokinin at 150 mg/L), (v) GA100 (waterlogging + gibberellic acid at 100 mg/L) and (vi) GA150 (waterlogging + gibberellic acid at 150 mg/L). The experiment was complete randomized design (CRD) with six replications (each replicate is constituted by a single plant of mungbean).

2.4 Preparation of CK and GA concentrations and treatment imposition

Previously collected CK and GA were stored in the freezer, and their solutions were made a few hours before spraying into the plants. For each hormone, 1 mg/ml stock solution was prepared. From it, 100 and 150 mg/L of CK and 100 and 150 mg/L of GA were prepared through dilution processes for foliar spray. From the established seedlings, 24 wagoner pots were kept for the imposition of six treatments. Each treatment was applied in four wagoner pots, of which two pots containing six plants were harvested at 30 days after waterlogging (DAW) for determining morpho-physiology and growth parameters (first set), and the remaining two pots were harvested at maturity for assessing yield-related parameters and seed yield (second set). Waterlogging was imposed at 15 DAE and continued for five days. The flooding depth was maintained 2.5 cm above the soil surface. At the same time, phytohormone CK and GA were applied as per treatment. Such application was repeated ten days after the date of the initial spray.

2.5 Measurement of plant growth parameters

From the first set of plants, the measurement of plant height and the number of leaves plant⁻¹ were recorded from six plants at 5-day intervals at the onset of waterlogging to 30 DAW in each treatment. The measurements of the growth parameters such as root and shoot dry weight plant⁻¹ were recorded at 30 DAW, where shoot dry weight was

taken by summing the dry weights of stem, petiole, and leaf and the total dry weight was calculated by adding root dry weight with shoot dry weight. The root to shoot ratio was measured as: dry weight of root/dry weight of shoot of plant.

2.6 Measurement of leaf chlorophyll index

For estimating leaf chlorophyll index as Soil Plant Analysis Development - SPAD value, we used a portable Chlorophyll Meter (SPAD-502, Minolta, Japan). The SPAD values were recorded from fully matured leaves (usually third leaf) of the six selected plants in each treatment. Three measurements were taken from a single leaf, and their average readings were considered as SPAD readings of each plant. The leaf SPAD values were taken at 5-day intervals starting from the onset of waterlogging and continued up to 30 DAW.

2.7. Determination of yield-related parameters and seed yield

From the second set of plants, pods were harvested in three pickings, and the total number of pods plant⁻¹ was recorded. At the same time, the seed yield plant⁻¹ was determined by summing up three harvests adjusting at 12% moisture. The straw yield plant⁻¹ was recorded at the final harvest. Finally, the harvest index was calculated as the ratio of seed yield to seed and straw yield.

2.8 Statistical Analysis

The data were subjected to analysis statistically by using software Statistix 10. All the recorded data were analyzed using analysis of variance (ANOVA) and means were compared by using Least Significant Difference (LSD) test at a significance level of $p \leq 0.05$. The standard deviation was performed by Microsoft Excel and used to detect the treatment variability.

3. RESULTS AND DISCUSSIONS

The effect of various phytohormone levels on plant height, the number of leaves per plant, leaf chlorophyll index (SPAD value), shoot and root growth, and yield-related traits and seed yield were evaluated.

3.1 Responses of CK and GA on plant height

Figure 1: Effect of exogenous cytokinin and gibberellic acid on plant height of mungbean (var. BUMug 4) plants subjected to waterlogging. Data represent average of six replicates ($n = 6$). Vertical bars indicate significant differences at $P < 0.05$ (Least Significant Difference test).

Plant height remarkably varied due to waterlogging and subsequent application of phytohormone (Figure 1). There were no significant differences in plant height at the time of waterlogging imposition, but height growth increased with the increase of plant age irrespective of treatments. A comparable remark was noted in waterlogged mungbean genotypes by Amin et al. (2016), where they observed that waterlogging reduced the plant height. Such detrimental consequences due to waterlogging had been also glaring in other legumes (Solaiman et al., 2007; Palta et al., 2010; Koo et al., 2014). However, GA showed a higher increase in plant height compared to control and waterlogging, and a higher dose (GA 150) showed increased plant height (78.33 cm). Generally, GA is substantially considered as a stress escape method under waterlogged conditions (Colebrook et al., 2014). The exogenous GA was found to cause stem elongation resulting in increasing plant height (Seo et al., 2017). However, CK application at a lower dose (CK 100) also showed

to increase plant height to some extent but at a slower rate compared to control and GA treated plants but at a higher rate compared to waterlogging. It might be because CK became located to decorate stem girth by promoting cell division (Ren et al., 2016, 2019). Waterlogging showed the shortest plant height (53.33 cm) at 30 DAW, where the application of phytohormone in waterlogged plants increased plant height, and the extent of increase depends on the types and types of phytohormone.

3.2 Responses of CK and GA on the number of leaves

Figure 2: Effect of exogenous cytokinin and gibberellic acid on the number of leaves of mungbean (var. BUMug 4) plants subjected to waterlogging. Data represent average of six replicates ($n = 6$). Vertical bars indicate significant differences at $P < 0.05$ (Least Significant Difference test).

The number of leaves also varied remarkably depending on the treatments (Figure 2). It increased with the increase of plant age irrespective of treatments. The number of leaves continuously increased from the time waterlogging in control plants but remarkably increased in plants treated with CK and GA from 10-20 DAW depending on their types and doses. The GA showed a greater increase in the number of leaves compared to that of control and waterlogging conditions, and GA 100 showed the highest number of leaves. In contrast, CK 150 showed to increase in the number of leaves moderately. Waterlogging showed the lowest number of leaves at 30 DAW. However, both CK and GA increased the number of leaves that varied depending on their types and doses. Waterlogging generally exerts a robust ill effect on leaves number (Zhou et al., 2020). Waterlogging induced leaf senescence, and subsequent reduction in green leaves was reported in many legumes including mungbean (Islam et al., 2007; Striker, 2012; Ploschuk et al., 2018). However, exogenous application of GA increased the number of leaves (Damanik and Siregar, 2019). Yennita (2009) affirmed that GA can be used to improve plants through the increasing number of leaves in soybean.

3.3 Responses of CK and GA on leaf chlorophyll index

Figure 3: Effect of exogenous cytokinin and gibberellic acid on SPAD chlorophyll index of mungbean (var. BUMug 4) plants subjected to waterlogging. Data represent average of six replicates ($n = 6$). Vertical bars indicate significant differences at $P < 0.05$ (Least Significant Difference test).

There were no significant differences in leaf chlorophyll index (SPAD value) during waterlogging imposition (Figure 3). The SPAD value of control plants increased with the increase of plant age. Conversely, both waterlogged, and CK- and GA-treated waterlogged plants could not maintain SPAD value up to 15 DAW. After that, they showed better recovery in SPAD chlorophyll. After 25 DAW, both the waterlogging and control plants showed a drastic reduction in SPAD values, but phytohormone-treated plants maintained better leaf chlorophyll content. The results indicate that phytohormone had no positive impact on chlorophyll contents in leaves of waterlogged plants for a while after waterlogging but had a high impact on the later stage (reproductive phase) of crop growth. A study indicates waterlogging had no appreciable decrease in chlorophyll content of *Vigna sinensis* within ten days of treatment, and then an extensive reduction in chlorophyll occurred (El-Shihaby et al., 2002). Ploschuk et al. (2018) found a revolutionary decline in the SPAD value of matured leaves after one week of waterlogging in field pea. Probably the waterlogged plants initially contributed assimilates to the development of damaged root and shoot systems, and eventually, chlorophyll content decreased in leaves. Later leaf chlorophyll content increased due to recovery of the damaged root system and foliage development (Ciura and Kruk, 2018). Interestingly, it was observed that the exogenously applied kinetin showed inhibitory effects on leaf chlorophyll content in waterlogged plants (Seo et al., 2017).

3.4 Responses of CK and GA on plant growth

Waterlogging remarkably affects the dry weights (DW) of the shoot, root, and total plants (Table 1). The immediate effect of waterlogging is the impairing root system resulting in shoot growth of mungbean plants (Shibly et al., 2020; Islam et al., 2010). The root is the first organ to experience a decrease in oxygen tension and experiences major phenotypic changes including a reduction in taproot and adventitious root dry matter (Zhou et al., 2020; Yang et al., 2018). The application of GA at 100 mg/L showed some remarkable improvement of shoot growth. However, the application of CK had pronounced effects on root growth development under waterlogging situations. A much improvement (17.7%) was observed for CK application to waterlogged plants at 100 mg/L. The GA application was found to reduce the adverse effect of waterlogging on root growth.

The results indicate that cytokinin helps to improve root growth and gibberellic acid enhances shoot development. This outcome is also reflected in the root: shoot ratio, where CK 100 showed the highest root : shoot ratio of 0.182, which was much higher than control. Since GA and CK are synthesized and transformed in roots, waterlogging can affect their development directly. Kinetin was found to nullify the inhibitory effects of waterlogging on the dry weights of shoot and root fully in *Zea mays* and partially in *Vigna sinensis* (Younis et al., 2003). The study showed that the application of GA and CK at low concentrations (100 mg/L) significantly alleviated the adverse effects of waterlogging on total dry matter production in mungbean. Waterlogging was observed to reduce total biomass production in mungbean (Kumar et al., 2013). Exogenously apply GA and CK may prompt endogenous phytohormone accumulation under water waterlogging situations and provides strength for growth and survival, and thereby assisting the plant to tolerate waterlogging stress (Hedden and Thomas, 2012; Wani et al., 2016; Ciura and Kruk, 2018).

3.5 Response of CK and GA on yield-related traits and seed yield

Waterlogging showed a reduced number of pods and seed yield corresponding to 63.2 and 62.4%, respectively (Table 2). A full-size yield reduction due to waterlogging was stated by many researchers in mungbean (Islam et al. 2008; Kumar et al., 2013; Amin et al., 2016) and the cause of reduction was waterlogging induced adverse modifications in morpho-physiological and yield contributing traits (Islam et al., 2007). Both CK and GA applications remarkably increased the number of pods and grain. The yield improvement was much better for using CK compared to GA. The CK at 150 mg/L showed the 28.5% yield reduction against 62.4% estimated in control indicating 33.9% yield advance. Exogenously applied CK was efficient in alleviating waterlogging damage by delaying leaf senescence, growing extra leaf chlorophyll, and enhancing photosynthetic performance that eventually gave better grain yield in maize (Ren et al., 2016b).

Table 1: Effect of exogenous cytokinin and gibberellic acid on the shoot, root and total plant dry weight of mungbean (var. BUMug 4) plants subjected to waterlogging

Treatment	Shoot		Root		Root shoot Ratio		Total plant	
	DW g/plant	% change	DW g/plant	% change	Values	% change	DW (g/plant)	% change
Control	9.68 ±0.54	-	1.24 ±0.27	-	0.128 ±0.029		10.92 ±0.59	-
Waterlogging	3.24 ±0.55	-66.4	0.44 ±0.19	-64.5	0.144 ±0.073	12.5	3.69 ±0.41	-66.2
CK100	3.62 ±0.37	-62.6	0.66 ±0.17	-46.8	0.181 ±0.033	41.4	4.28 ±0.52	-60.8
CK150	3.26 ±0.58	-66.3	0.55 ±0.18	-55.6	0.165 ±0.030	28.9	3.81 ±0.76	-65.1
GA100	4.27 ±0.99	-55.9	0.37 ±0.03	-70.2	0.092 ±0.029	-28.1	4.64 ±0.96	-57.5
GA150	3.56 ±0.78	-63.2	0.35 ±0.13	-71.8	0.095 ±0.015	-25.8	3.91 ±0.91	-64.2

Values are means ± standard deviation (n=6). Control - no waterlogging, cytokinin (CK) and gibberellic acid (GA); waterlogging - waterlogging but no CK and GA; CK100/150 - waterlogging + CK at 100/150 mg/L; GA100/GA150 - waterlogging + GA at 100/150 mg/L; % change: calculated as relative to control.

Table 2: Effect of exogenous cytokinin and gibberellic acid on number of pods, grain yield, straw yield and harvest index of mungbean (var. BUMug 4) plants subjected to waterlogging

Treatment	Number of pods		Grain yield		Straw yield		Harvest index	
	No./plant.	% change	g/plant	% change	g/plant	% change	values	% change
Control	35.33 ±2.08		14.09 ±2.41	-	15.35 ±3.14	-	0.48 ±0.05	-
Flooding	13.00 ±3.61	-63.2	5.30 ±1.82	-62.4	8.57 ±1.59	-44.2	0.38 ±0.08	-20.8
CK 100	24.33 ±4.93	-31.1	9.28 ±2.76	-34.1	12.72 ±1.83	-17.1	0.42 ±0.04	-12.5
CK 150	21.33 ±3.21	-39.6	10.08 ±1.91	-28.5	10.76 ±2.67	-29.9	0.49 ±0.02	2.1
GA 100	20.67 ±1.53	-41.5	7.50 ±1.21	-46.8	11.91 ±1.98	-22.4	0.39 ±0.01	-18.8
GA150	20.33 ±0.58	-42.5	7.28 ±1.37	-48.3	10.22 ±1.58	-33.4	0.42 ±0.05	-12.5

Values are means ± standard deviation (n=6). Control - no waterlogging, cytokinin (CK) and gibberellic acid (GA); waterlogging - waterlogging but no CK and GA; CK100/150 - waterlogging + CK at 100/150 mg/L; GA100/GA150 - waterlogging + GA at 100/150 mg/L; % change: calculated as relative to control.

Waterlogged plants of mungbean showed a 44.2% straw yield reduction. Such reduction was much less in waterlogged plants treated with the phytohormone. However, the performance of the CK and GA varied with the types and amount of hormones applied. The higher the dose, the higher was the reduction in straw yield. The CK at 100 mg/L showed only 17.1% straw yield reduction in plants subjected to waterlogging. The harvest index of waterlogged mungbean plants showed a 20.8% reduction. Numerous investigations have pointed out that waterlogging stress extended the embryo abortion and lack of seed weight which resulted in the cutback of grain yield and harvest index of mungbean genotypes (Islam *et al.*, 2008; Neashat *et al.*, 2020). In our study, the application of phytohormone showed less reduction in harvest index. It indicates that both CK and GA increased harvest index by improving assimilates translocation from straw to the grain. The CK at 150 performed better, showing a 2.1% higher harvest index compared to control plants. Overall, GA at low concentration and CK at high concentration increased waterlogging tolerance of mungbean plants with the aid of maintaining better leaf number, accumulating extra chlorophyll content, having more root-shoot growth, and better overall biomass manufacturing and its extra contribution to grain yield.

4. CONCLUSION

It reveals that waterlogging affected morpho-physiology, growth, and yield traits of the mungbean. Exogenously applied CK and GA can alleviate the detrimental effects of waterlogging in mungbean. Such release of waterlogging stress depends on the type and concentration of applied phytohormone. CK was more pronounced in relieving the waterlogging-induced damage of mungbean plants. There is significant progress in understanding the hormonal effects on improving waterlogging tolerance in plants. However, the plant biochemical and molecular basis of improving waterlogging tolerance and increasing crop yield from exogenous hormone remains elusive. Therefore, the investigation needs to determine the exact amount of hormone required for increasing the

productivity of mungbean in waterlogging conditions. Besides, exploring molecular knowledge associated with phytohormone application is imperative to obtain sustainable production of the crop. The functional genomics approach will help recognize this in the response of mungbean to waterlogging stress. This investigation was performed in pot culture under a semi-controlled environment, but estimating precise hormonal responses to plants under a waterlogged situation needs to be studied under green-house conditions.

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REFERENCES

- Amin, M. R., Karim, M. A., Islam, M. R., Aktar, S., Hossain, M. A., 2016. Effect of flooding on growth and yield of mungbean genotypes. Bangladesh Journal of Agricultural Research, 41(1), Pp. 151-162.
- Ashfaque, F., Khan, M. I. R., Khan, N. A., 2014. Exogenously applied H₂O₂ promotes proline accumulation, water relations, photosynthetic efficiency and growth of wheat (*Triticum aestivum* L.) under salt stress. Annual Research & Review in Biology, 105-120.
- Bashar, K. K., Tareq, M., Amin, M., Honi, U., Tahjib-Ul-Arif, M., Sadat, M., & Hossen, Q. M., 2019. Phytohormone-mediated Stomatal response, escape and quiescence strategies in plants under flooding stress. Agronomy, 9(2), Pp. 43.

<https://doi.org/10.3390/agronomy9020043>

- Ciura, J., Kruk, J., 2018. Phytohormones as targets for improving plant productivity and stress tolerance. *Journal of Plant Physiology*, 229, Pp. 32-40. <https://doi.org/10.1016/j.jplph.2018.06.013>
- Colebrook, E. H., Thomas, S. G., Phillips, A. L., Hedden, P., 2014. The role of gibberellin signalling in plant responses to abiotic stress. *Journal of Experimental Biology*, 217(1), Pp. 67-75. doi:10.1242/jeb.089938
- Damanik, R. I., Siregar, L. A. M., 2019. Growth and production of soybean (*Glycine max* L. Merrill) varieties in response to waterlogging at vegetative (V5) growth phase by application of gibberellic acid and salicylic acid. In: IOP Conference Series: Earth and Environmental Science, 260 (1), p. 012143.
- El-Shihaby, O. A., Younis, M. E., El-Bastawisy, Z. M., Nemat Alla, M. M., 2002. Effect of kinetin on photosynthetic activity and carbohydrate content in waterlogged or seawater-treated *Vigna sinensis* and *Zea mays* plants. *Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology*, 136(3), Pp. 277-290.
- Fahad, S., Nie, L., Chen, Y., Wu, C., Xiong, D., Saud, S., Hongyan, L., Cui, K., Huang, J., 2015. Crop plant hormones and environmental stress. *Sustainable Agriculture Reviews*, 371-400.
- Hedden, P., Thomas, S.G., 2012. Gibberellin biosynthesis and its regulation. *Biochemical Journal*, 444(1), Pp. 11-25. DOI: 10.1042 /BJ20120245
- Islam, M. R., Hamid, A., Karim, M. A., Haque, M. M., Khaliq, Q. A., Ahmed, J. U., 2008. Gas exchanges and yield responses of mungbean (*Vigna radiata* L. Wilczek) genotypes differing in flooding tolerance. *Acta Physiologiae Plantarum*, 30(5), Pp. 697-707. DOI 10.1007/s11738-008-0168-0
- Islam, M. R., Hamid, A., Khaliq, Q. A., Ahmed, J. U., Haque, M. M., Karim, M. A., 2007. Genetic variability in flooding tolerance of mungbean (*Vigna radiata* L. Wilczek) genotypes. *Euphytica*, 156(1), Pp. 247-255. DOI 10.1007/s10681-007-9372-z
- Islam, M. R., Hamid, A., Khaliq, Q. A., Haque, M. M., Ahmed, J. U., Karim, M. A., 2010. Effects of soil flooding on roots, photosynthesis and water relations in mungbean (*Vigna radiata* (L.) Wilczek). *Bangladesh Journal of Botany*, 39(2), Pp. 241-243. DOI: 10.3329/bjb.v39i2.7487
- Koo, S., Kim, H., Kang, B., Lee, Y., Oh, K., Kim, H. Y., Beak, I. Y., Yun, H. T., Choi, M. S., 2014. Screening of flooding tolerance in soybean germplasm collection. *Korean Journal of Breeding Science*, 46(2), Pp. 129-135. DOI: 10.9787/KJBS.2014.46.2.129
- Kumar, P., Pal, M., Joshi, R., Sairam, R. K., 2013. Yield, growth and physiological responses of mungbean [*Vigna radiata* (L.) Wilczek] genotypes to waterlogging at vegetative stage. *Physiology and Molecular Biology of Plants*, 19(2), Pp. 209-220. DOI: 10.1007/s12298-012-0153-3
- Mehandi, S., Quatadah, S. M., Mishra, S. P., Singh, I. P., Praveen, N., Dwivedi, N., 2019. Mungbean (*Vigna radiata* L. Wilczek): Retrospect and Prospects. In: *Legume Crops-Characterization and Breeding for Improved Food Security*. IntechOpen. DOI: 10.5772/intechopen.85657
- Neashat, N. J., Islam, M. R., Hasan, M., Islam, M. M., 2021. Assessment of waterlogging tolerance in mungbean genotypes utilizing morphological traits and SSR markers. <http://journals.org.ge/index.php>
- Palta, J. A., Ganjeali, A., Turner, N. C., Siddique, K. H. M., 2010. Effects of transient subsurface waterlogging on root growth, plant biomass and yield of chickpea. *Agricultural Water Management*, 97(10), Pp. 1469-1476. DOI:10.1016/j.AGWAT.2010.05.001
- Ploschuk, R. A., Miralles, D. J., Colmer, T. D., Ploschuk, E. L., Striker, G. G., 2018. Waterlogging of winter crops at early and late stages: impacts on leaf physiology, growth and yield. *Frontiers in Plant Science*, 9, p. 1863. doi: 10.3389/fpls.2018.01863
- Ren, B., Hu, J., Zhang, J., Dong, S., Liu, P., Zhao, B., 2019. Spraying exogenous synthetic cytokinin 6-benzyladenine following the waterlogging improves grain growth of waterlogged maize in the field. *Journal of Agronomy and Crop Science*, 205(6), Pp. 616-624. <https://doi.org/10.1111/jac.12355>
- Ren, B., Zhang, J., Dong, S., Liu, P., & Zhao, B., 2016a. Root and shoot responses of summer maize to waterlogging at different stages. *Agronomy Journal*, 108(3), Pp. 1060-1069. <https://doi.org/10.2134/agronj2015.0547>
- Ren, B., Zhang, J., Dong, S., Liu, P., Zhao, B., 2016b. Effects of duration of waterlogging at different growth stages on grain growth of summer maize (*Zea mays* L.) under field conditions. *Journal of Agronomy and Crop Science*, 202(6), Pp. 564-575. <https://doi.org/10.1111/jac.12183>
- Ren, B., Zhu, Y., Zhang, J., Dong, S., Liu, P., Zhao, B., 2016. Effects of spraying exogenous hormone 6-benzyladenine (6-BA) after waterlogging on grain yield and growth of summer maize. *Field Crops Research*, 188, Pp. 96-104. DOI: 10.1016/j.fcr.2015.10.016
- Roitsch, T., Ehneß, R., 2000. Regulation of source/sink relations by cytokinins. *Plant Growth Regulation*, 32(2), Pp. 359-367.
- Sarkar, M., Datta, S., Kundagrami, S., 2017. Global climate change and mungbean production: a road map towards future sustainable agriculture. In: Pandey, D., Sarkar, A., (Eds.), *Sustaining Future Food Security in Changing Environment*, Nova Science Publishers, New York, pp. 99-120.
- Seo, C., Lee, S., Kang, S., Park, Y., Kim, A., Park, H., Kim, Y., Lee, I., 2017. Selection of suitable plant growth regulators for augmenting resistance to waterlogging stress in soybean plants (*Glycine max* L.). *Korean Journal of Crop Science*, 62(4), Pp. 325-332. <https://doi.org/10.7740/kjcs.2017.62.4.325>
- Shibly, N. N., M. R. Islam, M. Hasan, M. N. Bari and J. U. Ahmed. 2020. Evaluation of yield and yield-related traits for waterlogging tolerance in mungbean genotypes using multivariate techniques. *Journal of Agricultural Sciences* 65, Pp. 99-120. DOI: 10.2298/jas2002099s
- Singh, D. P., Singh, B. B., 2011. Breeding for tolerance to abiotic stresses in mungbean. *Food Legumes*, 24(2), Pp. 83-90.
- Singh, R. K., Maurya, J. P., Azeez, A., Miskolczi, P., Tylewicz, S., Stojkovic, K., Delhomme, N., Busov, V., Bhalerao, R. P., 2018. A genetic network mediating the control of bud break in hybrid aspen. *Nature communications*, 9(1), No. 4173. DOI: 10.1038/s41467-018-06696-y
- Solaiman, Z., Colmer, T. D., Loss, S. P., Thomson, B. D., Siddique, K. H. M., 2007. Growth responses of cool-season grain legumes to transient waterlogging. *Australian Journal of Agricultural Research*, 58(5), Pp. 406-412. <https://doi.org/10.1071/AR06330>
- Striker, G. G., 2012. Flooding stress on plants: anatomical, morphological and physiological responses. *Botany*, 1, Pp. 3-28.
- Voesenek, L. A., Bailey-Serres, J., 2015. Flood adaptive traits and processes: an overview. *New Phytologist*, 206(1), Pp. 57-73. <https://doi.org/10.1111/nph.13209>
- Wani, S. H., Kumar, V., Shriram, V., Sah, S. K., 2016. Phytohormones and their metabolic engineering for abiotic stress tolerance in crop plants. *The Crop Journal*, 4(3), Pp. 162-176. <https://doi.org/10.1016/j.cj.2016.01.010>
- Watanabe, S., Kim, H., Kanae, S., 2013. Global food risk under climate change. *Nat. Clim. Change*, 3(9), p. 816821. <https://doi.org/10.1038/nclimate1911>
- Yang, X., Jansen, M. J., Zhang, Q., Sergeeva, L., Ligterink, W., Mariani, C., Rieu, I., Visser, E. J. W., 2018. A disturbed auxin signaling affects adventitious root outgrowth in *Solanum dulcamara* under complete submergence. *Journal of Plant Physiology*, 224, Pp. 11-18. <https://doi.org/10.1016/j.jplph.2018.03.006>

Yennita, 2009. The Response of Soybean Plants (*Glicine max*) to GA₃ (Gibberellic acid) in Generative Phase. *Exacta*, 5, Pp. 16-23.

DOI:10.1051/AGRO:2003010

Younis, M., El-Shahaby, O., Alla, M. M. N., El-Bastawisy, Z., 2003. Kinetin alleviates the influence of waterlogging and salinity on growth and affects the production of plant growth regulators in *Vigna sinensis* and *Zea mays*. *Agronomie*, 23(4), Pp. 277-285.

Zhou, W., Chen, F., Meng, Y., Chandrasekaran, U., Luo, X., Yang, W., Shu, K. (2020). Plant waterlogging/flooding stress responses: From seed germination to maturation. *Plant Physiology and Biochemistry*, 148, 228-236. DOI: 10.1016/j.plaphy.2020.01.020