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Growth and yield performance of different maize growth stages subjected to waterlogging

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Abstract Waterlogging in various maize growth stages significantly reduces plant height and dry matter and extends the vegetative phase, delaying days to anthesis, silking, and harvest maturity. Effects persist post-stress, with noticeable root and shoot dry weight reductions, indicating incomplete recovery. Older growth stages show resilience to waterlogging's impact on the reproductive cycle. Consistently, waterlogging prolongs harvest maturity due to reproductive phase delays, especially in early growth stages or with repeated incidents. Waterlogging occurs several times in a life cycle, and the early seedling stage has the most adverse effects on yield-related traits, leading to extended anthesis-silking intervals, decreased grain yield, and increased barrenness in maize. The highest yield loss occurs with early growth stage waterlogging, emphasizing the enhanced resilience of older growth stages. Waterlogging stress had detrimental effects on growth, development, and maize yield, with the early growth stages and the repeated stress episodes posing the most significant risks to maize productivity.

Keywords: Climate change, Corn, Excess soil moisture stress, Tolerant and susceptible, Waterlogging

Introduction

The United Nation's (UN) sustainable development goal is to achieve zero hunger by 2030 and food security worldwide. However, this goal has faced several climate change problems that significantly challenged achieving zero hunger and food security. For instance, waterlogging caused by erratic rain patterns, heavy rains, and floods has become a significant concern and limits crop productivity. The impact of changes in precipitation and temperature on agricultural production due to climate change has also become a hot research topic, mainly for crops such as corn (Rubinigg *et al.,* 2022).

According to estimates, waterlogging affects approximately 12% of agricultural land globally (Li *et al*., 2006). In South and Southeast Asia alone, floods and waterlogging affect 15% to over 18% of the total maize-growing area (Lone and Warsi, 2009; Zaidi *et al*., 2009), resulting in annual losses of 25 to

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30% of the maize production (Rathore *et al*., 1998). This scenario would significantly impact the export, food, and feed industries and the source of income for millions of corn farmers around the globe (Esteban and Edwin, 2016; Esteban and Baldo, 2023, 2024). Thus, maize productivity can significantly affect and contribute to not attaining the UN's zero hunger goal. This scenario significantly impacted the export, food, and feed industries and corn farmers' income source. Thus, maize productivity is significantly affected and contributes to not attaining the UN's zero hunger goal.

Maize is essential to agricultural food, livestock feed, and industrial products (Gazal *et al*., 2017). This crop is also a primary source of food and feed in Asia, providing a significant source of income and energy for millions of corn farmers (Shiferaw *et al*., 2011). Moreover, maize can be grown in a wide range of agro-climatic zones, ranging from subtropical to colder temperate regions (Lone *et al*., 2018). As a result, maize is inevitably exposed to excess soil moisture stress caused by temporary waterlogging (Lone *et al*., 2018). Ren *et al.* (2014; 2016) noted that waterlogging at different maize growth stages has different responses. The waterlogging stress may happen at any maize growth stage and may occur several times in the life cycle, significantly affecting maize productivity (Esteban and Edwin, 2016; Esteban and Baldo, 2023; 2024).

Understanding maize responses to waterlogging stress at different growth stages is essential in agronomy and plant breeding. Most of the research has focused on drought and insect resistance development. That is why progress in waterlogging research is slow. This study is designed to address the absence of maize varieties with tolerance to waterlogging stress. Additionally, it aims to contribute to achieving Sustainable Development Goals, explicitly targeting No Poverty (SDG 1), Zero Hunger (SDG 2), Sustainable Cities and Communities (SDG 11), and Climate Action (SDG 13) set by the United Nations.

To have a climate-ready maize with stable and consistent production, a substantial investigation must be conducted to elucidate the maize's response to waterlogging at different growth stages. Hence, this study was conducted to determine the effects of waterlogging stress at different stages, to determine maize growth and yield response to waterlogging, and to identify susceptible maize growth stages negatively affected by waterlogging stress.

Materials and methods

The experiment was conducted in the Agricultural Experimental Station of Central Mindanao University at University Town, Musuan, Maramag, Bukidnon, the Philippines, from August 2020 to January 2021. The experiment was arranged in a randomized complete block design and replicated three times.

The eight days of waterlogging imposed at different maize growth stages served as the treatment.

An Adtuyon soil series was taken from Brgy. Dologon, Maramag, Bukidnon as soil media. A kilogram of soil sample was air-dried and pulverized from the composite soil sample. The pulverized soil samples were analyzed at Central Mindanao University Soil and Plant Tissue Laboratory in Musuan, Maramag, Bukidnon, to obtain the soil physico-chemical analysis. The soil analysis result was used as the basis for fertilizer recommendations.

Waterlogging treatments consisted of filling the plastic containers with approximately 3 cm of water above the soil surface in all maize lines during the second and seventh leaf stages. On the other hand, the control treatments were only applied with water. For eight days, the water level in the plastic containers was monitored daily and was maintained at the same level using a 3 cm marker line placed above the soil surface. Water was added when the water level fell below the marker line due to evaporation. After eight days of waterlogging, water was drained from the waterlogged treatment by opening the cap at the bottom of the inverted plastic containers. After recovery periods, plants were watered regularly to provide the optimum amount of moisture until the termination of the study.

The gathered data were analyzed using analysis of variance (ANOVA) in the RCBD split plot arrangement using Statistical Tool for Agricultural Research (STAR) software version 2.0 at a 5% level of significance. The differences among treatment means were determined using Tukey's honest significant difference (Tukey's HSD).

Results

Maize growth response to waterlogging

Waterlogging at the second leaf stage and waterlogging in the second and on the seven-leaf stage obtained the shortest plant height among growth stages (Table 1). This result implied that waterlogging at different growth stages can shorten the plant height of maize. Notably, when waterlogging occurred at the early seedling stage and occurred multiple times in the maize life cycle, maize plant height shortened. Moreover, growth stages that experience waterlogging remarkably reduce the root dry weight, shoot dry weight, and total dry matter. Notably, waterlogging at the second and on the seven-leaf stage obtained the lowest root dry weight, shoot dry weight, and total dry matter compared to other growth stages exposed to waterlogging.

Table 1. Growth parameters of different maize growth stages subjected

Waterlogging Conditions	Plant Height	Root Length	Root Dry Weight	Shoot Dry Weight	Total Dry Matter
No Waterlogging	142.74^{a}	45.97^{b}	3.88^{a}	34.40^{a}	38.28^{a}
W. at V2 Leaf Stage	98.27^{c}	51.40^{a}	1.98^{c}	13.02^{c}	14.99^{c}
W. at V7 Leaf Stage	122.85^{b}	42.67^{c}	2.62^{b}	20.52^{b}	23.15^{b}
W. at V2, and V7 Leaf Stage	99.66^{c}	59.80^{a}	1.32^{d}	10.58^{c}	11.90^{c}
F test	**	**	**	**	**
CV (%)	12.62	11.23	6.79	25.85	24.95

PH: plant height; RL: root length; RDW: root dry weight; SDW: shoot dry weight; TDM: total dry matter; CV = coefficient of variation; ns = non-significant; * = significant ($p < 0.05$); ** = highly significant ($p < 0.01$).
Values (mean ± SD) in each row superscripted with different lowercase letters are significantly ($p < 0.05$) different

Table 2. Yield and yield components of different maize growth stages subjected to waterlogging stress

W. Conditions	DA	DS	ASI	ED	EL	NKPR	NKR	GY	PYR	HM
No W.	59.97^{d}	67.22^{c}	7.25^{b}	3.39^{a}	6.33^{a}	7.76^{a}	10.43^{a}	9.24^{a}	0.00^{c}	102.53^{c}
W. at V2 LS	65.44^{a}	79.86^{a}	14.42^{a}	2.33^{bc}	3.77^{c}	1.34^{c}	2.20^{c}	1.31^{c}	84.68^{a}	113.36^{a}
W. at V7 LS	61.56^{b}	70.69^{b}	9.14^{b}	2.78^{b}	4.69^{b}	4.00^{b}	5.71^{b}	4.22^{b}	54.01^{b}	105.97^{b}
W. at V2, and V7 LS	66.28^{a}	81.56^{a}	15.28^{a}	1.88^{c}	3.46^{c}	0.99^{c}	1.55^{c}	1.17^{c}	87.31^{a}	115.67^{a}
F test	**	**	**	**	**	**	**	**	**	**
CV (%)	4.28	6.79	29.20	23.03	20.43	20.04	31.31	26.33	30.86	4.02

DA: days to anthesis; DS: days to silking; ASI: anthesis silking interval; EL: ear length; NKPR: number of kernels per row; NKR: number of kernels per row: GY: grain yield: HM: harvest maturity; W: waterlogging; LS: Leaf Stage; CV = coefficient of variation; ns = non-significant; * = significant ($p < 0.05$); ** = highly significant ($p < 0.01$).
Values (mean ± SD) in each row superscripted with different lowercase letters are significantly ($p < 0.05$)

Yield performance of maize growth stages experience waterlogging

The result showed that waterlogging on the second leaf stage and waterlogging on the second and on seventh leaf stages increased the vegetative period, resulting in delayed anthesis and increasing the days to silking, prolonged period on the anthesis silking interval, and extended the days to harvest maturity

(Table 2). It also showed that waterlogging on the seven-leaf stage had a comparable number of days to anthesis and anthesis silking interval than non-waterlogging conditions. On the other hand, waterlogging during vegetative growth stages significantly reduced ear length, ear diameter, number of kernel rows/ear, and grain yield compared to normal conditions. Waterlogging several times in the life cycle and waterlogging at the early seedling stage obtained the lowest ear length and smallest ear diameter, kernel rows per ear, and lowest grain yield per plant, followed by waterlogging at the seven-leaf stage. Moreover, waterlogging in the second-leaf stage and waterlogging in the second and seventh-leaf stages obtained the highest percentage of yield loss.

Discussion

Msize growth response to waterlogging

Waterlogging at the second leaf stage and waterlogging in the second and on the seven-leaf stages obtained the shortest plant height among growth stages. This result implied that waterlogging at different growth stages can shorten the plant height of maize. Notably, when waterlogging occurred at the early seedling stage and occurred multiple times in the maize life cycle, maize plant height shortened. This result was similar to Tian *et al*. (2020), who found that early seedling stage waterlogging decreases plant height significantly than in later growth stages. Further, Rathore *et al*. (1998) reported that the maize plant was more susceptible to waterlogging during the early seedling stage. The findings of Paril *et al*. (2017) supported the result that waterlogging in the seven-leaf growth stage has a lower plant height than normal, which indicates that waterlogging influences the plant height of maize. He also noted that stunted plants have a lower capacity for photosynthesis, which is essential for ear growth and development. Kaur *et al*. (2019) emphasized that plant growth is slower after waterlogging ceases than in normal conditions.

Moreover, growth stages that experience waterlogging remarkably reduce the root dry weight, shoot dry weight, and total dry matter. Notably, waterlogging at the second and on the seven-leaf stage obtained the lowest root dry weight, shoot dry weight, and total dry matter than other growth stages exposed to waterlogging. This finding revealed that the adverse effect of waterlogging remained even after waterlogging stress was removed, showing that root dry weight, shoot dry weight, and total dry matter growth stages that experienced waterlogging did not recover. Furthermore, the result showed that the most significant reduction of root dry weight, shoot dry weight, and total dry matter occurred at the waterlogging stage several times in the life cycle, followed by the V2 and V7 leaf stages. Waterlogging several times in the life cycle was expected to have the most reduced shoot dry weight.

Meanwhile, the early seedling stage on shoot dry weight was much more sensitive than the older growth stage when experiencing waterlogging. This result was similar to Ren *et al*. (2016) and Liu *et al*. (2010), who reported that the V2 leaf stage is much more sensitive than other growth stages exposed to waterlogging. However, waterlogging on the second leaf stage and waterlogging on the second leaf and the seven-leaf stage obtained the longest root than the other waterlogging conditions. Interestingly, waterlogging at early stages and several times in a life cycle developed longer roots than in normal conditions.

Hence, this result proved that waterlogging at various growth stages profoundly influences maize plant height and root development. The most significant reductions in plant height, root dry weight, shoot dry weight, and total dry matter were observed when waterlogging struck during the early seedling stage and recurred throughout the plant's life cycle. Moreover, these findings underscored the detrimental impact of waterlogging on vital photosynthetic capacity, which is crucial for maize growth and development. Furthermore, the persistence of waterlogging stress hampered the recovery of root and shoot dry weights, especially evident in multiple waterlogging events during the plant's life cycle or at the V2 and V7 leaf stages.

Yield performance of maize growth stages experience waterlogging

The result showed that waterlogging on the second leaf stage and waterlogging on the second and on seventh leaf stages increased the vegetative period, resulting in delayed anthesis and increasing the days to silking, prolonged period on the anthesis silking interval, and extended the days to harvest maturity. It also showed that waterlogging on the seven-leaf stage had a comparable number of days to anthesis and anthesis silking interval than non-waterlogging conditions. This result implied that waterlogging at the older vegetative stage did not affect the reproductive phases and harvest maturity. This further indicated that older growth stages that experience waterlogging could tolerate the adverse effects of stress on reproductive phases and the period of harvest maturity compared to the earlier growth stage.

This study further revealed that all growth stages that experienced waterlogging stress increased the days of harvest maturity. These longer days to harvest maturity were attributed to the delay of the reproductive phase. Furthermore, the result revealed that waterlogging during early growth and waterlogging several times in the life cycle obtained a more extended period to reach the reproductive phase. This result indicated that a more extended period to reach the productive stage means a longer vegetative growth stage, resulting in late harvest maturity. This implication was congruent with Ren *et al.* (2014) findings that waterlogging can lead to a more extended period of harvest.

Moreover, it was found that waterlogging can prolong the vegetative period, resulting in delayed pollen shedding. This result conformed to the findings of Ren *et al.* (2014), who noted that waterlogging delayed maize growth and development and prolonged the days of silking. Ren *et al*. (2014) reported that waterlogging at vegetative leaf growth stages 3 and 7 significantly delayed growth processes, resulting in delayed days of silking. Consequently, growth stages that obtained more extended periods to silk had lower yields (Ren *et al*., 2014).

On the other hand, waterlogging during vegetative growth stages significantly reduced ear length, ear diameter, number of kernel rows/ear, and grain yield compared to normal conditions. Waterlogging several times in the life cycle and waterlogging at the early seedling stage obtained the lowest ear length and smallest ear diameter, kernel rows per ear, and lowest grain yield per plant, followed by waterlogging at the seven-leaf stage. This finding was similar to Ren *et al*. (2014) and Tian *et al*. (2020), who reported that the early growth stage dramatically reduces the ear diameter, and number of kernel rows per ear, and significantly decreases grain yield compared to the older growth stages—also, a significant reduction in ear length when stress happens numerous times in the life cycle. Moreover, the ear length, ear diameter, number of kernel rows/ear, and grain yield trait are highly influenced by waterlogging.

Notably, growth stages that experienced waterlogging stress were low on grain yield per plant and had a long period of anthesis silking interval. This long period of anthesis silking interval reduced the grain yield per plant. Furthermore, it was noted that growth stages that experienced stress had several barren maize, contributing to lower yield. The barrenness of maize due to waterlogging was also noted by Ren *et al*. (2014) on summer maize. Moreover, reduced maize grain yields due to waterlogging or flooding were previously reported (Howell and Hiler, 1974; Bhan, 1977; Mason *et al*., 1987; Kanwar *et al*., 1988).

The reduced maize number of kernels per row subjected to waterlogging stress was associated with an increased number of days of anthesis silking. The growth stages that experienced excess moisture stress have an extended period for anthesis silking intervals, resulting in low grain development. This long period for anthesis silking interval promotes the not timing of pollen shedding and stigma receptivity, resulting in a low number of kernels per row and kernel rows per ear, eventually reducing the grain yield per plant. This implication conforms to the finding of Paril *et al*. (2017).

Moreover, waterlogging in the second leaf stage and waterlogging in the second and seventh leaf stages resulted in the highest percentage yield loss (Table 2). This result indicates that waterlogging in the early growth stage and multiple waterlogging stress in the life cycle remarkably increase the percentage yield reduction. The study of Shin *et al*. (2016) confirms this finding that the percentage yield loss at the V2 growth stage is about 80.00%. Moreover, it was noted that the older growth stages, such as the seven-leaf stage, show a lower percentage yield reduction than the early growth stage that experienced waterlogging stress. This result confirms the findings of Shin *et al*. (2016) that the older growth stage exposed to waterlogging has a lower percentage of yield reduction, which is about 50.00% reduction of yield.

Meanwhile, waterlogging several times in the maize life cycle has a comparable percentage yield reduction to waterlogging at the early seedling stage. This result implies that waterlogging stress can increase yield reduction, which was lower in the older growth stage than in the early growth stage. This implication is congruent with the findings of Tian *et al*. (2020).

Furthermore, a reduction in yield on different growth stages that experienced waterlogging stress associated with multiple factors, such as the widening of anthesis silking interval, results in a lower chance of successful pollination of maize (Paril *et al*., 2017), resulting in the barrenness of summer maize due to waterlogging as noted by Ren *et al.* (2014), consequently increasing yield loss. This finding conforms to the result of Ren *et al*. (2014) that lower maize yield is contributed by a reduction in plant height, ear height, leaf area index, ear characteristics (grains per ear and 1000-grain weight), grain filling period, and dry matter accumulation and distribution due to waterlogging stress.

Hence, waterlogging during the second leaf stage and waterlogging at the second and on seventh leaf stages substantially prolong the vegetative phase, resulting in delayed anthesis, extended silking periods, and expanded anthesis-silking intervals, consequently delaying harvest maturity. Intriguingly, waterlogging at the seven-leaf stage shows resilience in not affecting the reproductive phases and harvest maturity, suggesting that older growth stages can better withstand such stress. Generally, these waterlogging scenarios lead to delayed harvest maturity, primarily attributable to disruptions in the reproductive phases. Moreover, stress promotes a longer reproductive phase. In addition, waterlogging detrimentally impacts ear length, diameter, kernel rows per ear, and grain yield, especially when experiencing stress repeatedly during early growth stages. These findings emphasize the critical need to consider the timing and frequency of water management in maize cultivation, as it substantially influences crop yield and overall plant development. These findings underscore the imperative to employ effective mitigation strategies to mitigate the adverse effects of waterlogging on crop productivity.

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