PREPRINT

TROPICAL AGRICULTURAL SCIENCE

Journal homepage: http://www.pertanika.upm.edu.my/

Effect of Shading and Water Stress on the Vegetative and Generative Growth Patterns of Arrowroot (*Maranta arundinacea* L.)

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ABSTRACT

Arrowroot (*Maranta arundinacea* L.) plants have distinct vegetative and generative growth patterns under shading and water stress. This current study aimed to evaluate the growth patterns of arrowroot plants under various shading and water availability conditions. Two factors, shading levels and water availability, were set as treatments. Four shading levels were 0%, 25%, 50%, and 75%. Water availability treatments were inundation for 5, 10, and 15 days, and watering intervals of 5, 10, 15, and 20 days. A nested design with the watering factor nested in the shading factor was used to arrange the treatments. All treatments were repeated three times. The findings revealed that maximum vegetative growth occurred eight months after planting. While the growth of the generative phase increased in older plants up to ten months following planting. Plant vegetative growth was significantly influenced by shading treatment, whereas tuber growth was unaffected. The inundation treatments enhanced root number and plant biomass, while drought stress inhibited vegetative and generative growth. The 15-day inundation treatment did not significantly affect plant growth; however, growth was enhanced following the stress period. In contrast, drought stress over 20 days caused considerable plant growth retardation. The arrowroot plants can be grown under 50-70% shading and water stress for 10 days.

Keywords: Drought, growth, inundation, light, *Maranta*

ARTICLE INFO

Article history:
Received: 16 June 2025
Accepted: 07 July 2026
Published: 24 July 2026

DOI: https://doi.org/10.47836/pjtas.49.4.05

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INTRODUCTION

Arrowroot is one of the underutilised tuber crops which is cultivated beneath forest canopy or in residential gardens. The tubers

e-ISSN: 2231-8542

are commonly used in food and traditional medicine because of their starch content (Aprianita et al., 2014; Deswina & Priadi, 2020). Arrowroot tubers are used as raw materials for meals (Malki et al., 2023) and health products in industrial sectors (Priatama et al., 2019). Maturity of plants and environmental factors during planting influence production and quality of arrowroot. According to Enesi et al. (2022), favourable environmental conditions promote tuber development and productivity, whereas suboptimal conditions may reduce yield and quality of arrowroot. Understanding the optimal growth of arrowroot is critical for obtaining the optimal growth of the crops.

Studies on the growth pattern of arrowroot crops can indicate the ideal period for collecting the tubers. Vegetative and generative growth are two main growth phases of arrowroot plants. Vegetative growth focuses on the development of roots, stems, and leaves, whereas generative growth includes initiation and maturation of tubers (Brito et al., 2019; Yursak et al., 2021). Understanding the growth pattern of arrowroot is important because the allocation of assimilates between vegetative and storage organs changes throughout plant development. Information on growth dynamics can therefore improve our understanding of how environmental factors, such as shading and water availability, influence crop growth and tuber production (Rusmin et al., 2018).

Light is one of the main environmental factors influencing plant growth. Light is essential for photosynthesis. Arrowroot plants produce optimal yield under around 27% shading, while growth and tuber yield reduce under shading of 51% to 72% (Oktafani et al., 2018). According to Supriyono et al. (2017), arrowroot plants produce optimal yield under 51% shading. These results clearly show the optimal light intensity variability for arrowroot growth.

Another environmental factor which influences arrowroot growth is water. The photosynthetic process, metabolism, nutrient transport, and plant growth are supported by water availability. Optimal water availability promotes optimal plant growth and tuber formation. On the other hand, water deficit or flooding decreases growth and tuber formation. According to Arduini et al. (2019) and Han et al. (2021), inundation and drought stresses reduced plant growth and yields by reducing photosynthesis, transpiration, stomatal conductance, respiration, and nutrient uptake. Flooding limits oxygen availability, and water stress promotes water deficit in plants (Akhtar & Nazir, 2013). In response to water excess, plants generate adventitious roots that enhance oxygen flow to the roots (Yamauchi et al., 2019). Previous studies showed that limited water availability reduced crop growth patterns, for example in rice and wheat (Seleiman et al., 2021; Zhang et al., 2018).

Inundation tolerance in crops can be triggered by flooding for a certain duration during specific growth stages, while drought stress can be induced by altering irrigation intervals. Lin et al. (2006) demonstrated the efficiency of a seven-day flooding interval as a selection tool for sugar beet tolerance. Inundation for 12 days at 105 and 165 days after planting was an effective screening tool for cassava plants (Kerddee et al., 2021). Irrigation intervals of once every seven days reduce the growth and tubers of taro and konjac (Santosa et al., 2004; Hidayatullah et al., 2020a). Each crop exhibits a different response to drought and inundation stresses. Despite extensive studies on various commercial crops, research on the effects of shading, inundation, and drought stresses on the growth patterns of arrowroot plants is still limited (Zhao et al., 2022). Our previous study solely focused on the arrowroot plant growth tolerance to shading and watering in a short period after one month of the treatments; however, it had not yet explored the growth pattern (Sutrisno et al., 2023). Therefore, the objective of this study was to examine the long-term effect (6-10 months after planting (MAP)) of shading, drought, and inundation on the growth patterns and yield of arrowroot plants.

MATERIALS AND METHODS

Experimental Site and Treatments

The research was conducted at Jambegede Experimental Station, Kemiri Village, Kepanjen District, Malang, East Java, Indonesia (8°10′31″ S, 112°33′36″ E, 330 m). Briefly, the experiment consisted of two factors, that shading level as the first factor and watering level as the second factor. The shading levels were (A1) 0%, (A2) 25%, (A3) 50%, and (A4) 75%, while the watering levels were inundation for (B1) 15 days, (B2) 10 days, and (B3) 5 days, watering intervals of (B4) 5 days as a control, (B5) 10 days, (B6) 15 days, and (B7) 20 days. The treatments were arranged in a nested design with the watering factor nested in the shading factor, with three blocks, resulting in 84 experimental units. The planting distance was set at 40 cm × 40 cm (Anggun et al., 2017). Each experimental unit consisted of 15 polybags with drainage holes at the bottom to facilitate drainage and allow water movement during the inundation treatments.

Propagation Material and Planting Media Preparation

The planting media was prepared for the nursery (7 cm × 12 cm polybag) and treatment media (40 cm × 40 cm polybag). Uniform sizes of arrowroot cuttings were grown in nursery media for six weeks to ensure proper cutting development before moving on to treatment media. Arrowroot plants grown on the treatment media were maintained until harvest. Soil, rice husks, and manure (5:2:1 v/v/v) were used as nursery and treatment media, with one plant per polybag (Sutrisno et al., 2023).

Application of Shading and Waterlogging Stress

Environmental modification was achieved using four separate plastic houses. The control (0% shading) was maintained in a plastic house without additional shading nets. The other three plastic houses were covered with commercial high-density polyethene plastic nets, providing shading levels of 75%, 50%, and 25%. The plastic nets were installed below the plastic house at 2 meters above the ground level. Furthermore, plastic nets were installed around the plastic house to permit light to enter the plastic house during the morning, afternoon, and evening hours, according to the shading levels (Sutrisno et al., 2023).

Watering treatment was conducted on arrowroot plants placed in a pond constructed using plastic-layered wooden planks. The watering was performed according to the specified treatments, which were started two weeks after transferring the plants to the plastic house (Sutrisno et al., 2023).

Growth Observations and Final Harvest Procedures

Throughout the time of observation of 6 to 10 MAP, growth metrics were measured, including stem diameter, stem weight, plant height, number of tillers, number of leaves, leaf area and weight, as well as number, length, weight, and volume of roots. Length, diameter, and weight of tubers were measured at harvesting.

The combined weight of the primary stem and its descendants per plant was calculated as total stem weight. A freely available ImageJ software was used to calculate total leaf area per polybag. The volume of the roots was calculated using a volumetric flask in which, after immersing the roots in water, elevated water volume in the container after the root immersion was the root volume (Sutrisno et al., 2023). The number of saplings grown around the main stem was summed as the number of tillers.

Methods of Data Analysis and Interpretation

The mean value of each parameter at each observation time was plotted to figure the growth pattern from 6 to 10 MAP. The peak growth point represented the maximum growth of each character, which could then be used as a reference point for determining the optimal harvesting time for arrowroot plants grown under different shading and inundation conditions. Graph data were presented as means ± the standard error based on three replications. Statistical analyses were performed using R 4.5.1 (R Core Team, 2025). Analysis of variance was conducted separately for each observation period to evaluate the effect of shading, watering treatments, and their interaction on the observed parameters. Differences among treatments were considered significant at $P \leq 0.05$.

RESULTS AND DISCUSSION

Assessment of Vegetative Parameters

The shading intensity significantly affected plant height throughout the observation period ($P < 0.001$), while watering treatments significantly affected plant height at all observation times. No significant interaction between shading and watering treatments was observed. From 6 to 9 MAP, the plant height increased by 18%. The shading intensity enhanced plant height. The lowest plant height was achieved from arrowroot plants cultivated under 0% shading, whereas the highest was observed from plants grown under 50% shading, except for 9 MAP, where the height was slightly lower than plant height under 75% shading. Similar plant height was achieved under 50% and 75% shading levels at 9 and 10 MAP. Inundation increased plant height; in contrast, drought stress inhibited this parameter. The inundation treatments between 5- and 15-days increased plant height by 2%, whereas the drought decreased arrowroot plant height by 8% compared to the control (Figure 1).

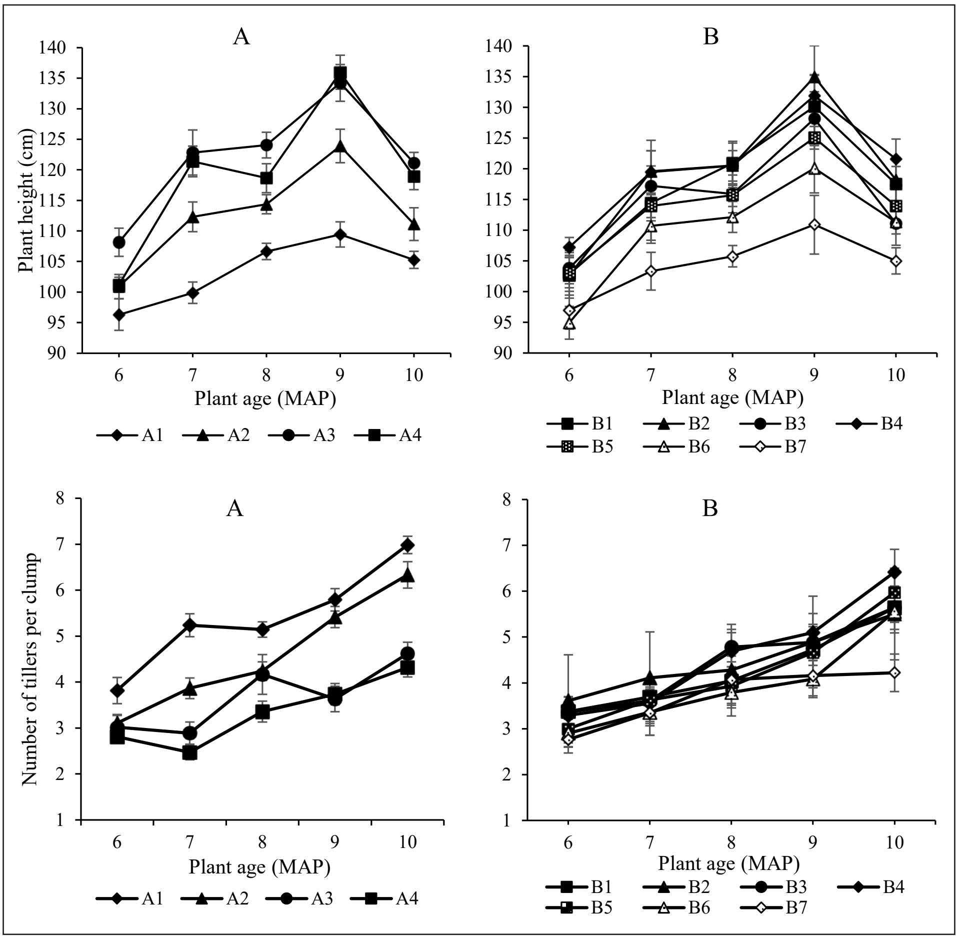

Figure 1. Arrowroot plant height and number of tillers at different plant ages under four shading levels (A) and seven watering levels (B)
Note. (A1) 0% shading, (A2) 25% shading, (A3) 50% shading, (A4) 75% shading, (B1) 15-day inundation, (B2) 10-day inundation, (B3) 5-day inundation, (B4) 5-day irrigation interval, (B5) 10-day irrigation interval, (B6) 15-day irrigation interval, (B7) 20-day irrigation interval, (MAP) months after planting. Bars represent the standard error

The maximum increase in plant height up to 9 MAP and subsequent reduction at 10 MAP suggested that the vegetative growth of arrowroot reached a maximum at 9 MAP and declined thereafter. The plants then enhanced the generative phase to optimise tuber enlargement. Prioritising growth from the vegetative to the generative phases has also been reported in cassava (Phoncharoen et al., 2019). The increased growth under shading conditions was due to the reduced light intensity, prompting plants to accelerate height growth to maximise light energy acquisition (Kalaitzoglou et al., 2019). The higher plant growth under inundation than drought stress was because the drought-stressed plants received limited water, thus unable to maximise plant height (Zhen et al., 2019).

The number of tillers per clump increased from 6 to 10 MAP. Analysis of variance showed that shading significantly affected the number of tillers throughout the observation period, whereas watering treatments significantly affected this parameter only at 10 MAP. At 6 MAP, the number of tillers ranged from 2 to 4 tillers per clump, while at 10 MAP, the number of tillers ranged from 4 to 7 tillers per clump, with an increase of one tiller per clump per month. The shading intensity decreased the number of tillers per clump. The highest number of tillers per clump was produced by arrowroot plants under 0% shading, while the lowest was under 75% shading. The effect of watering intervals on the number of tillers varied. The same number of tillers was produced by plants treated with 15 days of inundation and 15 days of drought. However, treatment of 20 days of drought stress produced the lowest number of tillers. The number of tillers under the 20-day watering interval treatment did not increase (4 tillers) at 8 to 10 MAP, while in the other treatments, the number increased by 5-6 tillers (Figure 1). This finding suggested that arrowroot continued to experience vegetative growth alongside the process of tuber formation and enlargement. Some plant species that propagate through tillers produce numerous tillers when actively forming tubers (Hamaoka et al., 2022). The higher number of tillers under shading suggested that plants were more adaptable to shading conditions than open areas (Sudrajat et al., 2023). The increase in the number of tillers was greater under inundation than under drought stress, as water deficiency inhibited the growth of new tillers in plants (Hidayatullah et al., 2020b).

Statistical analysis indicated that shading significantly affected leaf number only at 10 MAP, whereas watering treatments significantly affected leaf number at 9 and 10 MAP. A significant interaction between shading and watering treatments was observed at 8 and 9 MAP. The highest number of leaves was produced at 8 MAP, with an increase of 36% compared to the number of leaves produced at 6 MAP. However, the number of leaves then decreased by 14.6% at 9 and 10 MAP. Shading intensity suppressed the number of leaves. At 8-10 MAP, 0% shading yielded the highest number of leaves, while 50% and 75% shading levels produced the fewest. Watering treatments also affected leaf number, with drought stress causing a greater reduction than inundation. At 8-10 MAP, inundation for 15 and 10 days reduced the number of leaves by 13-23%, while drought for 15-20 days suppressed the leaf number by 24-50% in comparison to the 5-day irrigation interval or the control (Figure 2).

The maximum increase in the number of leaves at 8 MAP and the subsequent decrease at 9-10 MAP suggested that arrowroot plants maximised the number of leaves until 8 MAP and then started to reduce leaf number at 9-10 MAP to enhance their generative growth (Khalid et al., 2019). The reduction of leaf number due to shading was a consequence of plant adaptation to the limited light conditions by reducing leaf number while attempting to maximise their generative growth with the available light (Fan et al., 2018). Inundation reduced leaf number because plants were stressed by oxygen shortage, which inhibited plant metabolism and the formation of new leaves (Huang et al., 2022). Meanwhile, drought stress reduced the number of leaves due to water deficiency to support photosynthesis and plant growth (Mathobo et al., 2017).

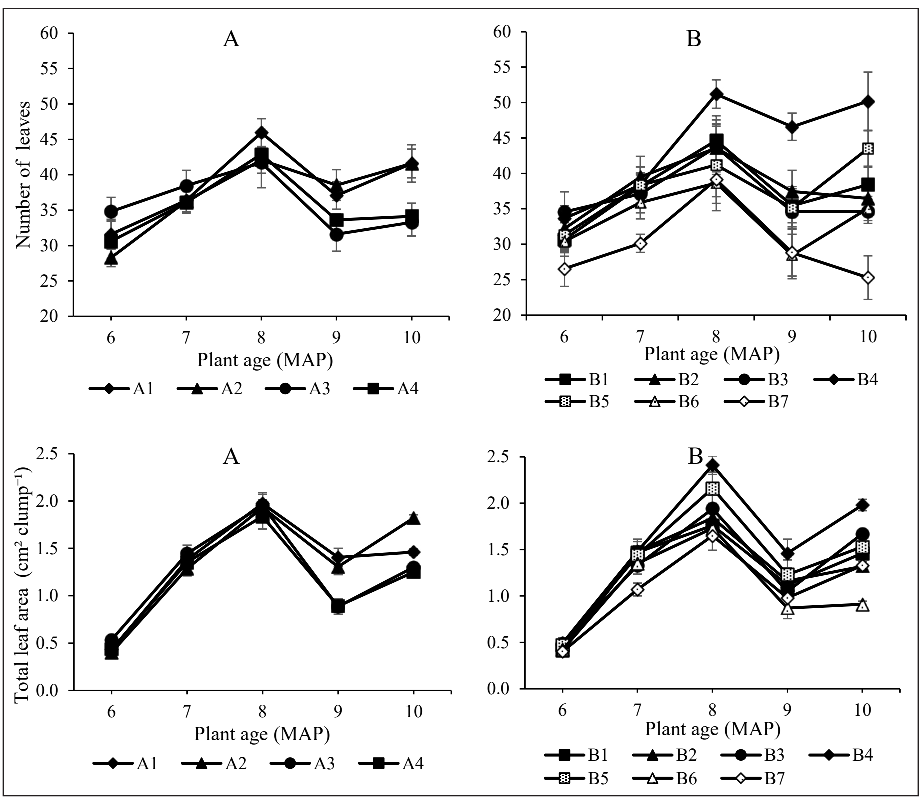

Figure 2. Number of leaves and total leaf area per clump at 6-10 MAP under four shading levels (A) and seven watering levels (B)

Note. (A1) 0% shading, (A2) 25% shading, (A3) 50% shading, (A4) 75% shading, (B1) 15-day inundation, (B2) 10-day inundation, (B3) 5-day inundation, (B4) 5-day irrigation interval, (B5) 10-day irrigation interval, (B6) 15-day irrigation interval, (B7) 20-day irrigation interval, (MAP) months after planting. Bars represent the standard error

Shading significantly affected total leaf area at 6, 9, and 10 MAP, whereas watering treatments significantly affected total leaf area from 8 to 10 MAP based on the analysis of variance. A significant interaction between shading and watering treatments was observed at 8 and 9 MAP. The increase in total leaf area per clump by approximately 400 % occurred from 6 to 8 MAP, and decreased by 40 % at 9-10 MAP. Treatments of 0% and 25% shading produced larger total leaf area than 50% and 75% shading. At 10 MAP, the treatment of 0% shading showed the highest total leaf area, while 75% shading produced the lowest total leaf area. Watering stress suppressed total leaf area. A 15-day period of inundation at 8-10 MAP resulted in 22-28% total leaf area reduction, while a 15-day drought stress reduced 31-54% total leaf area compared to the control (Figure 2).

The maximum increase in total leaf area at 8 MAP was related to the increase in the number of leaves during this period. The number of leaves correlated to the size of the total leaf surface area. The lower shading levels, particularly 0% and 25%, produced a larger total leaf area because the plants had more leaves than 50% and 75% shading levels. Inundation treatments resulted in a larger leaf area than drought stress because inundation produced more leaves than drought stress. The increase in total leaf area due to the number of leaves was also reported by Supriyono et al. (2017).

Shading significantly affected stem fresh weight at most observation periods, whereas watering treatment significantly influenced this parameter except at 8 MAP. Stem fresh weight reached the maximum at 8 MAP and declined at 9 to 10 MAP. Between 6 and 8 MAP, the fresh weight was increased by 36%, while between 8 and 10 MAP, the weight decreased by 33%. Shading intensity suppressed stem fresh weight. From 7 to 10 MAP, the stem fresh weight under 50% and 75% shading levels decreased by 17-35% compared to 0% and 25% shading levels. Meanwhile, water stress suppressed the stem fresh weight. At 6 MAP, 15 days of inundation suppressed the stem fresh weight by 8%, while drought stress for 15 and 20 days suppressed the fresh weight by 29-43%. At 10 MAP, the inundation suppressed the stem fresh weight by 15-25%, while drought stress for 15 and 20 days also suppressed this parameter by 17% and 35% (Figure 3).

The increase in the stem fresh weight at 6-8 MAP was because the plants were actively engaged in vegetative growth. At 9-10 MAP, the plants diverted to the generative phase, resulting in the reduction of stem fresh weight. The plants turned senescent, as shown by wilting and weakening stems. The decreased stem weight of the plants under shading because light limitation inhibiting vegetative growth (Liu et al. 2018). The significant stem weight decreases under drought conditions compared to inundation could be due to plant recovery following a period of flooding. In contrast, drought stress causes limited water supply, therefore reducing stem growth (Creek et al., 2018).

Leaf fresh weight increased from 6 to 8 MAP and reached the maximum value at 8 MAP before declining. Between 6 and 8 MAP, the leaf fresh weight increased by 26%

and decreased by 36% at 10 MAP. Shading intensity suppressed the leaf fresh weight as observed from 8 MAP onwards, whereas watering treatments significantly affected this parameter at 8-10 MAP. The decrease in leaf fresh weight under shading levels between 0% and 75% reached 26%. Water stress suppressed the fresh leaf weight from 6 to 10 MAP. At 6, 8, and 10 MAP, inundation reduced leaf weight by 15%, 22%, and 35%, respectively, while drought stress reduced the leaf weight by 29%, 25%, and 49%, respectively. This finding confirmed that drought stress caused a greater reduction in leaf fresh weight than inundation (Figure 3).

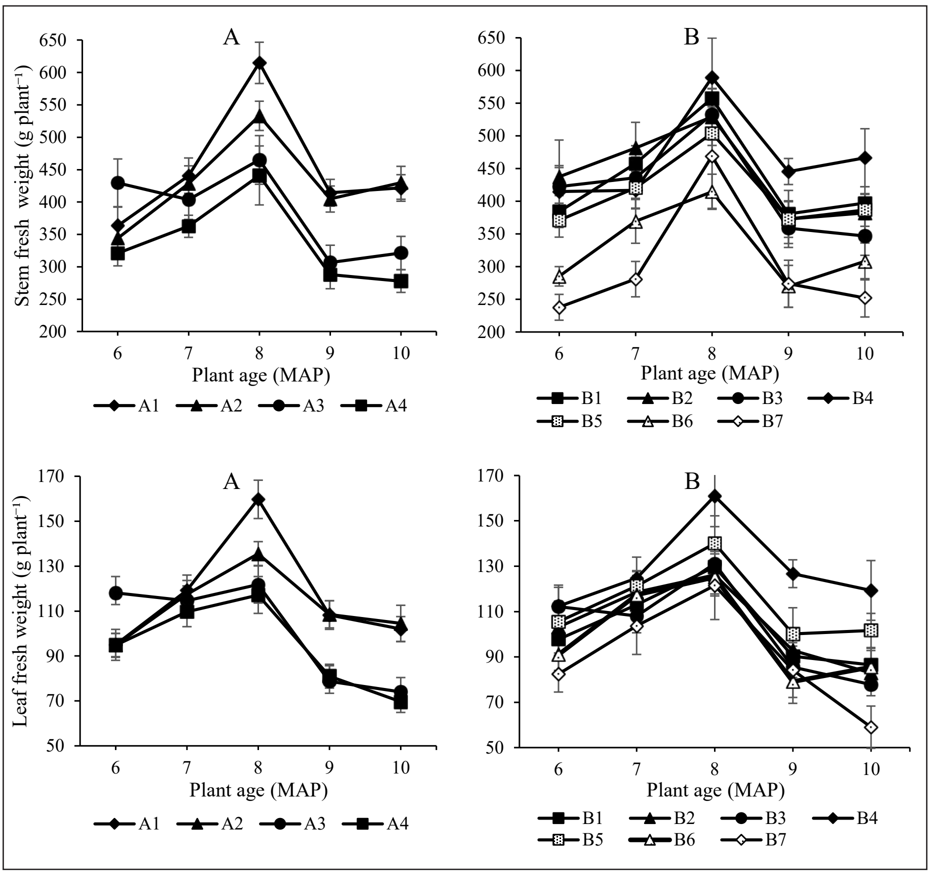

Figure 3. Stem and leaf fresh weight at 6-10 MAP under four shading levels (A) and seven watering levels (B)
Note. (A1) 0% shading, (A2) 25% shading, (A3) 50% shading, (A4) 75% shading, (B1) 15-day inundation, (B2) 10-day inundation, (B3) 5-day inundation, (B4) 5-day irrigation interval, (B5) 10-day irrigation interval, (B6) 15-day irrigation interval, (B7) 20-day irrigation interval, (MAP) months after planting

The gradual increase in leaf fresh weight at 8 MAP and the subsequent decrease at 10 MAP could mean the plants were actively maximising vegetative growth at 8 MAP, while at 10 MAP, the plants shifted to generative growth. The greater decrease in leaf fresh weight under higher shading intensities because the plants reduced vegetative growth under limited light conditions. The greater decrease in drought compared to inundation was because the plants showed recovery under the inundation treatments; on the other hand, the growth pressure continued under drought stress (Creek *et al.,* 2018).

The number of roots increased by approximately 48% in the older plants between 6 and 10 MAP. Both shading and watering treatments affected root number significantly, whereas the interaction between the two factors was significant at 9 MAP. Shading intensity suppressed the number of roots. At 6 MAP, the difference in root number under shading treatments was relatively small; however, from 7 to 10 MAP, the treatments of 0% shading produced the highest root numbers, while plants under 75% shading produced the fewest. Plants under 25% shading also yielded higher root numbers compared to the 50% and 75% shading intensities. At 7 MAP, 25-75% shading levels reduced the root number by 14%, 34%, and 46%, respectively, while at 10 MAP, the root numbers decreased by 2%, 32%, and 39%, respectively. Inundation treatments increased the root number, while drought stress had the opposite effect of reducing the root number. The average number of roots under inundation increased by 7% at 7 MAP, while drought stress reduced the number by 17%. The average number of roots under inundation and drought increased by 20% and decreased by 26%, respectively, compared to the control at 9 MAP. The highest number of roots was produced by plants under inundation for 10 and 15 days, while the lowest was produced by plants under drought stress for 20 days (Figure 4).

The increase in the number of roots between 6-10 MAP showed that the plant roots continued to grow. This increase was an effort of the plant to enhance water and nutrient uptake to meet the plant metabolic needs. The increase in vegetative growth, particularly the upper parts of the plant, such as the stems and leaves, was in line with the increase in root numbers. This occurred in both 0% and 25% shading intensities as well as under inundation treatments. Furthermore, a positive correlation between the increase in root number and stem and leaf growth has been reported in maize crops (Guo et al., 2021).

The fresh weight of roots increased with the older arrowroot plants. Shading influenced root fresh weight at all observation periods, whereas watering treatments affected it from 8 to 10 MAP. At 6 MAP, the root fresh weight ranged from 28 to 92 grams, while at 10 MAP, the weight ranged from 40 to 220 grams, representing an increase from 40 to 139%. Shading levels suppressed the root fresh weight. At 6 MAP, the root fresh weight under a 75% shading level decreased by 30%, while at 10 MAP it experienced a significant decrease by 81% compared to the 0% shading level. Inundation treatments increased the root fresh weight; on the other hand, drought stress decreased this parameter. At 6 MAP, the root fresh weight under inundation was similar to the control, while the root weight under drought stress was slightly lower than the control. At 10 MAP, inundation increased the root fresh weight by 55%; in contrast, this parameter under drought stress decreased by 67% (Figure 4).

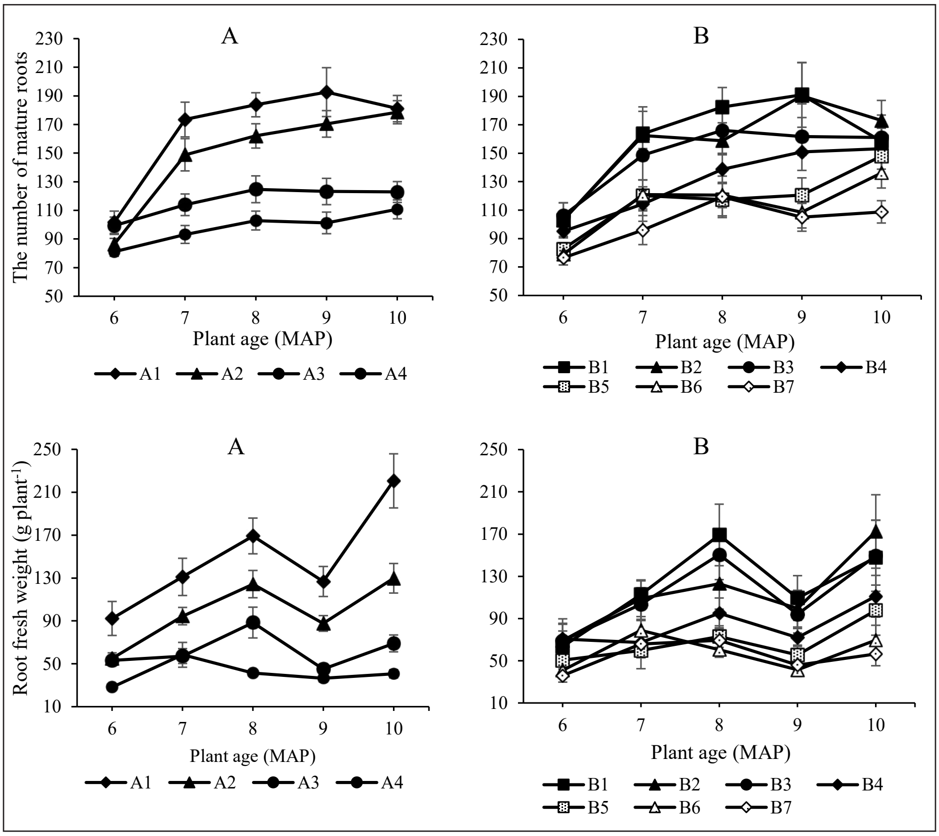

Figure 4. The number of mature roots and fresh weight of roots at 6-10 MAP under four shading levels (A) and seven watering levels (B)
Note. (A1) 0% shading, (A2) 25% shading, (A3) 50% shading, (A4) 75% shading, (B1) 15-day inundation, (B2) 10-day inundation, (B3) 5-day inundation, (B4) 5-day irrigation interval, (B5) 10-day irrigation interval, (B6) 15-day irrigation interval, (B7) 20-day irrigation interval, (MAP) months after planting. Bars represent the standard error

The increase in the root fresh weight was due to the plant's requirement for vegetative growth of the leaves and stems. To support leaf and stem growth, the plant developed root growth to supply water and nutrients to the upper parts of the plant and to support the growth of tubers. The decrease in root weight under shading was because of the plant's adaptation to the growth of the upper parts. The shading resulted in slow vegetative growth of the upper part of the plant, thus leading to slow root growth. The same conditions also occurred under inundation and drought treatments (Gaballah et al., 2021).

Assessment of Reproductive Parameters

The older plants showed a significant increase in the number of arrowroot tubers. The number of tubers between 6 and 10 MAP demonstrated a noticeable growth of approximately 100-120%. Shading levels played a crucial role in regulating the rate of tuber proliferation. From 6 to 10 MAP, the number of tubers under 0% shading was 181% higher than that under 75% shading. Inundation treatments increased tuber quantity. The treatment of inundation for 15 days produced the least tuber quantity, in comparison with 10 and 5 days of inundation at the same time of the observation. The highest number of tubers was observed in the 10-day inundation. It was not surprising that drought stress suppressed the tuber quantity. At 6 MAP, the number of tubers under drought stress was similar to the control; however, from 8 to 10 MAP, the tuber quantity under drought stress was lower. Prolonged drought stress suppressed the tuber quantity, showing the lowest number of tubers under 20-day drought treatment (Figure 5).

The tuber length was not affected by plant age. The length measured was between 16 and 18 cm at 6 to 10 MAP. The shading level had a minor effect on the tuber length.

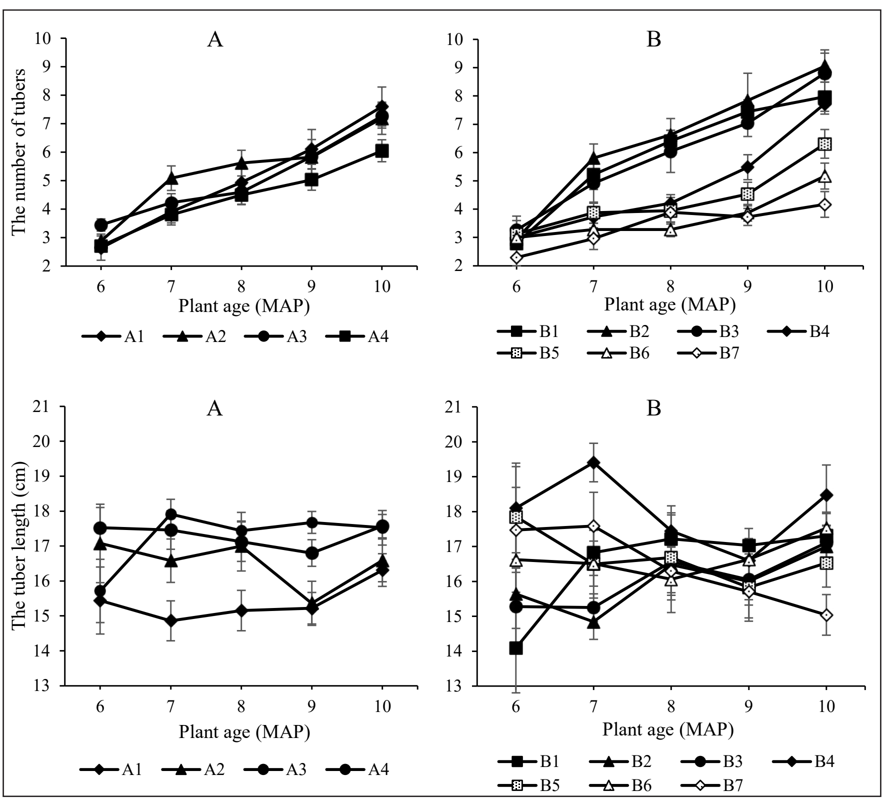

Figure 5. The number and length of tubers at 6-10 MAP under four shading levels (A) and seven watering levels (B)

Note. (A1) 0% shading, (A2) 25% shading, (A3) 50% shading, (A4) 75% shading, (B1) 15-day inundation, (B2) 10-day inundation, (B3) 5-day inundation, (B4) 5-day irrigation interval, (B5) 10-day irrigation interval, (B6) 15-day irrigation interval, (B7) 20-day irrigation interval, (MAP) months after planting. Bars represent the standard error

The absence of shading and under 25% shading intensity resulted in shorter tuber length compared to the shading intensities of 50% and 75%, particularly at 7 and 10 MAP. Plants grown without shading had the shortest length, in contrast to the plants grown under 75% shading, which yielded the longest tuber. Furthermore, water stress inhibited tuber length. Drought stress resulted in slightly longer tubers compared to inundation at 6 MAP. However, a comparison at 10 MAP showed that tubers produced under drought stress were shorter than those produced under inundation stress. The 20-day drought stress produced the smallest and the longest tubers. Inundation reduced tuber length by 6%, while drought stress decreased tuber length by 16% (Figure 5).

No significant tuber length variation among treatments from 6 to 10 MAP was observed. This was because the arrowroot plants emphasised tuber length growth, starting from the beginning of tuber development. After 6 MAP, the plants focused on tuber enlargement. The plant's ability to optimise tuber production while minimising vegetative growth may account for the increased tuber size. Conversely, under low shading conditions, there was an increase in plant growth but a decrease in tuber size.

The diameter of arrowroot tubers continually increased until 10 MAP; however, the growth rate was faster at 6 to 8 MAP than from 8 to 10 MAP. The tuber diameters at 6 to 8 MAP increased by 45%, while from 8 to 10 MAP the increase was only 10%. The shading intensity influenced the tuber diameter. From 7 to 10 MAP, the tuber diameter under 0% shading was consistently the lowest compared to the 25-75% shading levels. The tuber diameter under 25-75% shading was similar at all plant ages from 6 to 10 MAP (Figure 6).

The effect of watering stress on the tuber diameter at 6 to 10 MAP was insignificant. However, the effects of inundation and drought treatments differed at various stages of plant development. At 6 to 7 MAP, inundation resulted in the smallest tuber diameter, but this parameter increased from 8 to 10 MAP. Conversely, the drought treatment showed an opposite pattern, with the largest tuber diameter observed in the control (Figure 6).

The elevated increase in tuber diameter at 6 to 8 MAP suggested that the plant was prioritising the expansion of the tuber dimensions. The accelerated growth of the vegetative organs was observed at 6 to 8 MAP and less at 8 to 10 MAP. The decline in vegetative growth and tuber growth rate at 8 to 10 MAP suggested that the tuber dimensions were not the only factor driving plant development at this stage. At 6-7 MAP, the modest tuber diameter increase was most likely due to plant recovery from flooding. After the recovery process, the plants saw accelerated tuber growth at 8-10 MAP. However, water deficit slowed tuber growth at 8-10 MAP, resulting in decreased tuber diameter. This finding was in line with a study conducted by Kengkanna et al. (2019).

The tuber fresh weight increased with the older arrowroot plants. From 6 to 10 months, the tuber fresh weight increased by 380%. Shading affected the tuber fresh weight at all observation times, whereas watering treatments influenced the tuber fresh weight at 6 and 8-10 MAP. The 0% shading level produced the lightest tuber fresh weight compared to the

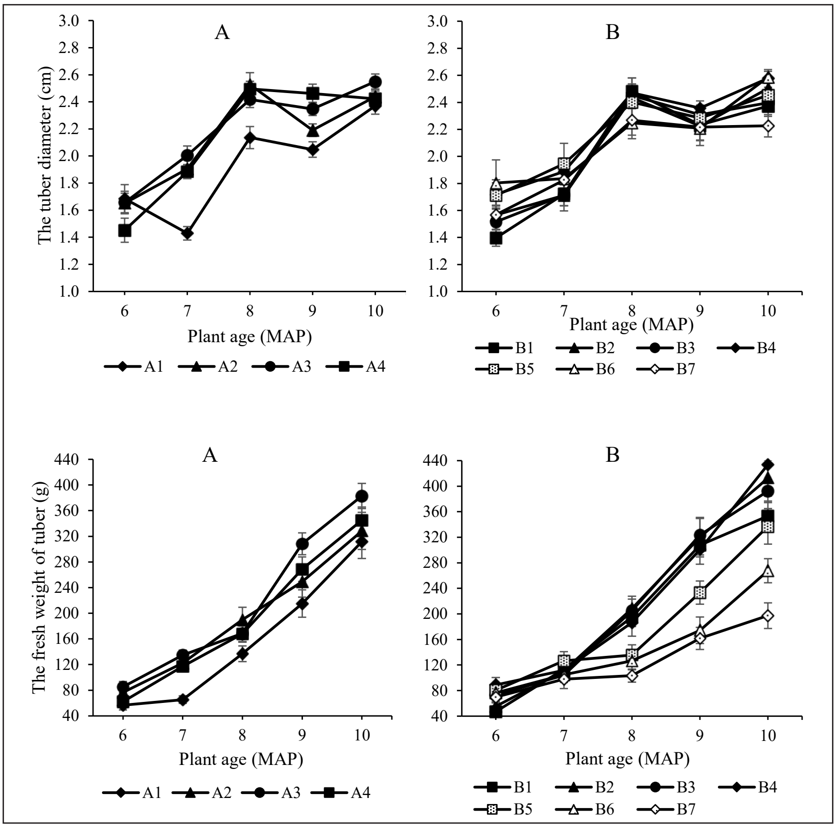

Figure 6. The diameter and fresh weight of tubers at 6-10 months after planting under four shading levels (A) and seven watering levels (B)
Note. (A1) 0% shading, (A2) 25% shading, (A3) 50% shading, (A4) 75% shading, (B1) 15-day inundation, (B2) 10-day inundation, (B3) 5-day inundation, (B4) 5-day irrigation interval, (B5) 10-day irrigation interval, (B6) 15-day irrigation interval, (B7) 20-day irrigation interval, (MAP) months after planting. Bars represent the standard error

25%-75% shading, with the heaviest tuber fresh weight under the 50% shading. Watering treatments affected the increase in tuber fresh weight. The control treatment yielded the heaviest tuber fresh weight, followed by inundation and drought conditions. The tuber fresh weight of the control increased by 360% from 6 to 10 MAP, whereas under inundation and drought conditions, the increases were 300% and 182%, respectively (Figure 6).

The correlation between the heavier tuber fresh weight and the older arrowroot plants (8-10 MAP) suggested that this phase emphasised tuber development. The heavier tuber fresh weight under a higher level of shade suggested that arrowroot plants exhibited higher tolerance to low-light than full light conditions. The increase in tuber fresh weight under inundation showed that the arrowroot plants were more tolerant to waterlogging than drought. Taro was also reported to be tolerant to inundation stress (Hidayatullah et al., 2020b).

The vegetative growth of plant organs, including leaf number, stem weight, leaf weight, and root number, reached the highest at 8 and 9 MAP and started to decline at 9 and 10 MAP. However, the number of stems, tubers, tuber diameter, and tuber weight continued to increase until 10 MAP. Between 9 and 10 MAP, the growth rate of the vegetative organs was slow. However, a notable increase in tuber mass occurred during this period. This finding suggested that the plant shifted its metabolic process from photosynthesis, which was responsible for leaf growth, to tuber growth. Furthermore, the reduced quantity and mass of the leaves suggested that the stored and consumed photosynthetic compounds were reallocated to the tubers (Golovko & Tabalenkova, 2019).

CONCLUSION

The vegetative growth of arrowroot rose until 8 MAP, but tuber development grew during the generative phase until 10 MAP. During the entire observation period, shading influenced the majority of vegetative and generative growth parameters. Although shading lowered several vegetative traits, arrowroot plants could produce substantial tuber formation, demonstrating good adaptation to low-light conditions. Watering treatments had a considerable impact on plant growth and yield components, especially in the late growth phases. Arrowroot plants tolerated inundation for up to 15 days, but prolonged drought stress with a 20-day irrigation interval inhibited considerable growth and tuber production. These findings demonstrate that arrowroot plants are promising underutilised tuber crops for cultivation under shading with fluctuating water availability, where other crops may face significant growth constraints. Further research is required to assess arrowroot response to extended periods of flooding and to determine tolerance mechanisms at various growth stages.

ACKNOWLEDGEMENT

The authors appreciate and are thankful for the support provided by the Director of the Indonesian Legume Crops Instrument Standard Testing Institute, the Ministry of Agriculture of the Republic of Indonesia, for providing the research location. The authors would like to acknowledge the late Eko Sulistyono for his contributions to this study.

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