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Morphological and physiological characteristics of tissue culture derived of banana [*Musa acuminata* Colla (AA) ‘Lakatan’] under drought conditions as influenced by superabsorbent polymers (SAP)

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ABSTRACT

Banana (*Musa acuminata* Colla ‘Lakatan’) production was limited by drought, which had significant consequences for seedlings’ growth, water status and physiological performance. The morphological and physiological responses of tissue culture-derived ‘Lakatan’ banana seedlings to different levels of superabsorbent polymer (SAP) under controlled drought conditions were evaluated in this study at Cagayan State University–Gonzaga, Philippines. The data was analyzed using single factor ANOVA in CRD using the Statistical Tools for Agricultural Research (STAR) with the 5% significant level as a comparison of treatment means. A pot experiment arranged in a completely randomized design with four SAP treatments (0%, 1%, 2%, and 3% per 2 kg pre-mix soil), replicated three times with 20 plants per replicate (n=80 per treatments), was conducted over one seedling duration. Morphological parameters, chlorophyll content, and relative water content (RWC) were assessed during drought and post-drought recovery phases. Results showed that moderate SAP application Treatment 2 (1%) significantly enhanced resilience on drought. This was reflected in the increase in relative growth rate (RGR) plant height (cm) 9.76%, RGR pseudo stem diameter (cm) 1.8%, and RGR leaf area 0.0006 sq.cm compared with T1 (0% SAP). The significant improvement was correlated with maintaining the banana seedlings growth, and balanced root development, while untreated seedlings exhibited compensatory root elongation as response to water stress. Higher SAP levels Treatment 3 ($\geq 2\%$) resulted in the highest relative water content (RWC) at 88.74%; but this treatment suppressed root elongation and limited shoot regrowth, due to altered soil aeration and altered nutrient dynamics. Overall, 1% SAP optimally balanced water retention and plant development, supporting both drought tolerance and recovery. These findings suggest that SAP application at moderate rates is a practical strategy to enhance banana seedling performance under water-limited conditions. Likewise, the economics feasibility of SAP application appears promising in the banana seedlings; nonetheless, field-level validation under diverse environmental conditions is required to validate its practical applicability in large-scale production.

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INTRODUCTION

Banana (*Musa* spp.) is one of the most economically important fruits cultivated in the Philippines in terms of production volume, area, and value. This crop is planted throughout the Philippines, with most of the production areas found in Mindanao, which likewise supplies the export and local markets (PSA, 2020). The total production of bananas in the country from July to September 2020 was 2.36 million metric tons (MT) (Philippine Statistics Authority [PSA], 2020). However, due to the COVID-19 pandemic, production dropped to 1.3% from 2019 to 2020 (PSA, 2020). Production statistics show that the top variety of banana produced in the country is Cavendish (*Musa acuminata* Cavendish), which comprises 55.5% of the total production of banana in the Philippines, followed by 'Saba' (*Musa balbisiana*) and 'Lakatan' (*Musa acuminata* Colla) varieties, comprising 25.6% and 9.3% of the total production, respectively.

The Davao region has the highest production of banana (35.6%), followed by Northern Mindanao and SOCCSKSARGEN with 26.2% and 12.6% of the total production, respectively (PSA, 2021). Despite the low total production, 'Lakatan' is still the most preferred dessert-type banana variety in the country (Department of Agriculture [DA], 2021). It is mostly available all year-round and therefore provides a constant supply of fresh fruits in the domestic and foreign markets. The 'Lakatan' has a total volume of production of 193,950.95 MT in the country as of March 2021. The main producing regions of 'Lakatan' in the country are the Davao Region, Northern Mindanao, and SOCCSKARGEN.

However, the Cagayan Valley Region also produces 'Lakatan' primarily for home consumption in backyard gardens (PSA, 2021). In 2012, Typhoon 'Pablo' caused a sudden decrease in the production of the highest-producing regions of banana in the country, located in Mindanao.

Recovery of the total production from the natural disaster has been aided by different factors like the implementation of pest and disease management

strategies specially to control the spread of banana bunchy top virus (BVTV) and incorporating climate-resilient strategies into farming systems. The 'Lakatan' plants have a smaller root framework in comparison with other banana varieties. It is also highly susceptible to environmental stressors such as water stress and diseases (Elleva *et al.*, 2018).

Drought is one of the major constraints to banana production in the country. Bananas require sufficient irrigation to grow properly (Tuyogon *et al.*, 2020). Important factors to increase crop yield and productivity are the availability of water in the soil and appropriate irrigation management strategies that are critical in banana cultivation in constantly changing climate (Ghoosh *et al.*, 20018). Climate change is likely to contribute to production shifts nowadays.

Climate-change scenarios around the world and their consequences on plants in relation to drought have been widely explored in recent years. Extremely high temperatures and global warming are likely to become more frequent in the coming years and could become major constraints to crop production, especially bananas. According to Ravi *et al.* (2013), bananas are quite sensitive to drought, but genotypes with the "B" genome are more tolerant to abiotic stresses than those with the "A" genome. It is therefore important to gain a better understanding of the effect of frequent drought stress on the biochemical and physiological processes in plants (Kavamura *et al.*, 2013). Superabsorbent polymers (SAP) are materials that can retain a large volume of water and result in high absorption capacities up to 1000 times their own weight (Zheng *et al.*, 2023). It retains aqueous solutions up to several hundred times their own weight and has a tunable rate of absorption (Ahmed, 2013). These materials could increase the availability of water to the plant, reduce bulk density, and lessen drought stress (Metzger *et al.*, 2009).

In addition, it promotes conditions conducive to plant growth, with the additional benefit of controlling the

transport of plant nutrients and water (Ekebafé *et al.*, 2011). SAP is a network of polymer chains where water is drawn into the polymer through the process of osmosis. Water is thereafter held within cross-linkages by hydrogen bonding (Ostrand, 2020). In addition, SAP can be utilized as water reservoirs to hold nutrients from fertilizer, preventing them from leaching from the root zone (Wu *et al.*, 2008). It can also influence soil evaporation and soil pH (Nouri *et al.*, 2019). Therefore, SAP can be used primarily in crop production to improve plant growth by increasing water retention, which could mitigate water stress by increasing the permeability of soil to water and making water available to the plants (Abrisham *et al.*, 2018). Superabsorbent polymers (Baromey, 2008) could overcome climate stresses that could be encountered by 'Lakatan'-growing regions. With higher temperatures causing high evapotranspiration and occurrences of drought experienced by major 'Lakatan'-growing areas, climate change can impede productivity and quality of produce. New trends in using SAP to overcome drought could greatly enhance 'Lakatan' production.

The objective of this study was to evaluate the morphological and physiological responses of 'Lakatan' banana (*Musa acuminata* Colla 'Lakatan') seedlings grown at Cagayan State University-Gonzaga, Cagayan Valley, Philippines, to varying rate levels of superabsorbent polymer (SAP) application under controlled drought conditions of tissue cultured-derived seedlings

Specifically, the study aim to assess the effects of different SAP application rate levels on the morphological characteristics of 'Lakatan' banana seedlings under controlled drought conditions; to assess physiological responses associated with drought tolerance in 'Lakatan' banana seedlings subjected to varying SAP rate levels on the total chlorophyll content, and relative water content (RWC); and to identify the SAP application rate that optimally enhances drought resilience of 'Lakatan' banana seedlings by integrating morphological and physiological indicators.

MATERIALS AND METHODS

Experimental design

Pot experiment of 'Lakatan' banana plants with four (4) treatments was arranged following single factor arranged in Completely Randomized Design (CRD) with four (4) mixtures of Superabsorbent polymers (SAP) (0 SAP, 1%, 2%, and 3% of SAP per two (2) kilogram of pre-mix soil medium). A total of 4 treatment combinations, replicated thrice (3) with 20 samples per replicate plants (n=80 per treatments) for a total of 240 plants were used in the experiment. The treatments were: 0 SAP (Control) (T1), 1g SAP; and 2kg of pre-mix soil (T2), 2g SAP; and 2kg of pre-mix soil (T3), and 3g SAP; and 2kg of pre-mix soil (T4).

The experiment was conducted at the screen house of College of Agriculture, and Mangrove and Bamboo Research Innovation Center (MABRIC), Cagayan State University (CSU), Gonzaga Campus, Brgy. Flourishing Gonzaga Cagayan Philippines from January 2024 to December 2025.

Preparation of 'Lakatan' banana plantlets

The tissue-cultured 'Lakatan' banana plantlets were produced at the MABRIC Laboratory of Cagayan State University (CSU), Gonzaga Campus. The plants with 4-7 cm high and 3-4 expanded leaves were used. These were acclimatized in the nursery with no direct sunlight at midday for one week before they were potted out.

Imposition of treatments

The SAP was purchased from Greenthumb Venture Corporation. The required amount of SAP per treatment, was mixed thoroughly with 2 kg pre-mix soil medium and placed in polyethylene bags (12.7 x 12.7 x 25.4 cm) using one 'Lakatan' banana plantlet. Newly transplanted plants were covered with inverted plastic cups to maintain favorable humidity and minimize environmental shock.

Acclimatization of the plantlets

The plantlets were acclimatized by covering them with an inverted plastic cup. The covered plastic cups were gradually tilted weekly until the plants were

hardened and become properly adapted to the outside environment. The plants were gradually exposed to full sunlight within four weeks. The newly grown plantlets were raised in the screen house for the entire duration of the experiment.

Control insect pest and diseases of 'Lakatan' banana plantlets

One month after transplanting, the plantlets were sprayed with karate insecticide (a.i. lambda-cyhalothrin) and lanate fungicide (a.i. Methomyl) to control insect pests and diseases respectively when necessary. Regular monitoring of pests was done to detect early infestations and prevent them from spreading.

Fertilization

One month after transplanting, the plantlets were fertilized individually using 5 grams ammonium phosphate (16-20-0) for proper growth and development.

Imposition of the drought condition and plant recovery period

A drought condition was imposed for all treatments by withholding water for 30 days. Based on result from preliminary experiment, when the soil moisture was 0.8 as provided by the soil moisture tester (DM-15, Takemura Electric Works, LTD., Japan) and when it was 4-7 % as shown by gravimetric method, these conditions were used as determining factor for a drought condition. The plants were grown under greenhouse conditions for the entire duration of the study.

Morphological parameters

Plant height was measured from the base of the plant at soil level up to the tip of the pseudostem using a meter stick. The pseudostem diameter was measured at 1/3 of the plant height above ground level using a digital Vernier caliper (Mitutoyo 530- 119, stainless steel, Mitutoyo America Corporation, Tokyo, Japan). The number of functional leaves produced per plant, which includes the newly opened leaves, was counted as the total number of leaves. The leaf length and leaf width of the youngest fully expanded leaf were

measured for the computation of the leaf area. The leaf area was computed using the equation of Turner, (2003).

$$\text{Leaf Area (m}^2\text{)} = \text{Length (m)} * \text{Width (m)} * 0.8$$

The Relative growth rate (AGR) of plant height and leaf area was computed using the equation below.

$$\text{RGR/day} = (\text{Final growth} - \text{Initial growth}) / \text{Days of observation}$$

Plant dry biomass (pseudo stem, leaves, and roots) The plant dry biomass for pseudostem, leaves, and roots was measured and placed in paper bags and dried at 100 °C in an oven (DHG-90704 Precision, Air Blasting Constant Temperature Drying Oven, Shaihai, China) for 32 hrs. The dry weight was obtained using an analytical balance (Cole-Parmer, TB-800 Series Touch-Screen Analytical Balances, Shaihai, China). All mass measurements were made using an analytical scale. Values of fresh weight (FW) and dry weight (DW) were used to calculate the percentage of plant biomass using the equation Shaw, (1950) as follows.

$$\text{Plant Biomass (\%)} = (\text{DW}/\text{FW}) \times 100$$

Where:

DW - dry weight

FW - fresh weight

Root analysis

The roots of representative plants per treatment were measured manually. Prior to the root analysis, root samples were washed thoroughly to remove the adhering soil particles. The number of primary roots was counted manually, while the root length and root diameter were measured using a ruler and vernier caliper, respectively. Five primary roots were randomly selected and measured in each of the 10 sample plants in each treatment replicated thrice with a total of 1800 individual primary roots.

Total chlorophyll content

The total chlorophyll content was determined using a portable chlorophyll meter (TYS-B 220V 60Hz,

Hangzhou West Tune Trading Co., Zhejiang, China). Chlorophyll measurements were taken between 9 and 10 a.m. from the fully expanded leaf at the base of the plant. Readings were taken at three points on the leaf—base, middle and tip—and were gathered both before and after the imposition of drought stress to assess changes in chlorophyll content during the experiment.

Relative water content (RWC)

The RWC was measured based on Yamasaki and Dillenburg's (1999) method. Leaves were collected from the midsection of the plants. Samples were weighed for fresh weight (FW) and then floated on distilled water inside a closed petri dish for 4 hours at 22°C under dim light. Turgid weight (TW) was obtained after blot-drying the leaves. After the imbibition period, leaf samples were placed in a preheated oven at 80°C for 24 hours to obtain the dry weight (DW). All mass measurements were measured using an Analytical Balance.

$$RWC(\%) = \frac{(FW - DW)}{(TW - DW)} \times 100$$

Where

FW- Fresh weight

DW- Dry weight

TW- Turgid weight

Statistical analysis

Data collected were subjected to a single factor ANOVA in CRD using the Statistical Tools for Agricultural Research (STAR) version 2.0.1 software (IRRI, 2014). A comparison of treatment means was done using LSD at a 5% significance level.

RESULTS AND DISCUSSION

Morphological responses

Water plays a vital role in the growth and development of plants, influencing important physiological functions at every stage of the life cycle (Taiz *et al.*, 2015). Under conditions of limited water availability, plants exhibit pronounced morphological and physiological alterations, including reduced leaf expansion, reduced nutrient uptake, stomatal conductance alteration, and biomass accumulation

decreased, which collectively limit growth and productivity (Farooq *et al.*, 2009). With this, strategic solution will likely increase resistance of crops from drought.

The effects of superabsorbent polymer (SAP) on morphological growth on the conditions of pre-drought

Table 1 showed significant differences ($p \leq 0.05$) of Lakatan's morphological parameters during the pre-drought phase. SAP (T1) had the highest plant height (16.41 cm); number of leaves (5cm); pseudostem diameter (1 cm); leaf area (0.016 sq.cm); and relative growth rates (RGR) for height (0.98 cm) and leaf area (0.0018 sq.cm). In contrast, an increase of SAP level by 1-3% resulted in water immobilization thereby providing limited moisture to the plant. This was evident in polymer swelling limiting soil aeration and nutrient diffusion delay (Abedi-Koupai *et al.*, 2008; Montesano *et al.*, 2015). Hence, adequate soil moisture won't provide growth benefits of SAP treatments.

The responses of growth during drought stress

Under drought stress, plants grown without SAP (T1) exhibited the longest root systems (15.63 cm), which were statistically comparable to those treated with 1% SAP (T2). In contrast, root length declined significantly with increasing SAP concentration, with the shortest roots (9.48 cm) recorded in the 3% SAP treatment (T4).

An adaptive drought-avoidance response, in which plants extend their root systems to explore deeper and wider soil zones in quest of available moisture, is suggested by the longer roots shown in the control treatment. Drought stress has been shown to induce root extension in bananas and other crops as a compensatory mechanism to enhance water intake (Turner *et al.*, 2007; Taiz *et al.*, 2015). Likewise, the current study supports the findings of Xiong *et al.* (2006) that the primary root can lengthen to reach deeper soil water sources during drought stress (Julkowska *et al.*, 2017). Furthermore, this root action is recognized as a drought-avoidance response

connected to physiological whole-plant mechanisms that allow the root to penetrate deeper into the soil, enhance its density, roots sturdiness increases, and encourage hair production (Rivero *et al.*, 2007). The plants treated with 0 SAP (T1) had the largest average

root length (15.67 cm) during the recovery period. The outcome shows that the plants are experiencing a water shortage. This result is consistent with Turner's (2003) findings that roots prefer to extend in order to search for water in the soil during drought.

Table 1. Morphological characteristics of 'Lakatan' banana plants as affected by different levels of superabsorbent polymers (SAP) as a treatment during pre-drought, drought, and recovery conditions

Treatments	Plant height (cm)	Pseudostem diameter (cm)	Number of leaves	Leaf area (sq.cm)	RGR plant height (cm)	RGR pseudostem diameter (cm)	RGR leaf area (sq.cm)
Pre-drought							
T1	16.41 a	1.00 a	5 a	0.016 a	0.98 a	0.04 a	0.0018 a
T2	9.38 b	0.79 b	3 b	0.005 b	0.57 b	0.05 a	0.0006 b
T3	7.97 bc	0.65 bc	3 c	0.005 b	0.35 bc	0.014 ab	0.0005 b
T4	6.45 c	0.58 c	3 c	0.004 b	0.09 c	0.00 b	0.0004 b
p-value	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0359*	0.0002*
Drought							
T1	12.58 d	0.55 c	4 b	0.004 d	0.08 c	-0.09 b	-0.0000 c
T2	25.30 a	1.38 a	5 a	0.016 a	0.82 a	0.05 a	0.0006 a
T3	20.98 b	0.99 a	4 bc	0.012 a	0.58 b	0.04 a	0.0004 ab
T4	16.42 c	0.82 b	4 c	0.008 c	0.20 c	0.04 a	0.0003 bc
p-value	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0481*	0.0224*
Recovery							
T1	22.56 b	1.16 b	3 b	0.005 b	0.69 a	0.045 a	-0.0003 b
T2	30.65 a	1.58 a	5 a	0.014 a	0.70 a	0.038 a	0.0005 a
T3	30.38 a	1.46 a	4 a	0.013 a	0.72 a	0.024 ab	0.0003 a
T4	14.29 c	0.85 c	4 a	0.006 c	0.36 b	0.007 b	0.0005 a
p-value	0.0000*	0.0000*	0.0023*	0.0000*	0.0099*	0.0394*	0.0310*

Means with the same letters are not significantly different at 5% LSD level. T1- 0 SAP + 2 kg premix soil, T2-1% SAP + 2 kg premix soil, T3. 2% SAP + 2 kg premix soil, and T4- 3% SAP + 2 kg premix soil.

Moreover, according to Shoaib *et al.* (2022), plants that are experiencing drought prefer to lengthen their roots in order to improve their capacity to absorb water. The same root lengths of T1 and T2 indicate that the mild SAP treatment (1%) preserved enough soil moisture. Higher SAP levels (2–3%), on the other hand, considerably limited root elongation. This is probably because of increased soil water retention close to the root zone, which lowers the physiological signal for root extension. In addition, severe SAP swelling can hinder penetration of roots cause by poor soil aeration and mechanical resistance (Abedi-Koupai *et al.*, 2008; Montesano *et al.*, 2015).

Recovery growth after drought stress

Significant differences between treatments continued for the majority of growth during the recovery phase (Table 1). As supported by sustained

plant height, pseudostem diameter, increased leaf number, and positive RGR for leaf area, plants treated with 1% SAP (T2) showed the best recovery. According to these findings, moderate SAP used to improve post-drought resistance and sped up canopy development rebuilding.

Control plants (T1) showed a negative RGR for leaf area, indicating a delayed and insufficient recovery of photosynthetic ability after drought stress, while achieving high absolute plant height and pseudostem diameter. With slower growth rates and smaller leaf areas, plants with higher SAP levels (T3 and T4) demonstrated limited recovery, suggesting long-term impacts of inadequate root aeration or changed soil physical conditions.

Sustained root hydration and less cellular damage during drought have been correlated to improved

recovery in SAP treatments, enabling a faster restart of shoot growth if water becomes available (Sivapalan, 2006; Wang and Gregg, 1990).

The effects of superabsorbent polymer (SAP) under drought and recovery conditions on root length

In Table 2, the average root length of 'Lakatan' banana plants was significantly affected ($p \leq 0.05$). It has improved its root system due to the soil moisture modification induced by SAP.

Table 2. Average root length (cm) of 'Lakatan' banana plants as affected by different levels of superabsorbent polymers (SAP) as a treatment during drought and recovery conditions

Treatments	Average root length (cm)	
	Drought	Recovery
T1	15.63 a	18.72 a
T2	15.38 ab	15.78 b
T3	11.78 b	11.68 ab
T4	9.84 c	7.49 c
<i>p</i> -value	0.0005*	0.0000*

Means with the same letters are not significantly different at 5% LSD level. T1- 0 SAP + 2 kg premix soil, T2-1% SAP + 2 kg premix soil, T3. 2% SAP + 2 kg premix soil, and T4- 3% SAP + 2 kg premix soil.

Root response under drought conditions

Under drought stress, plants grown without SAP (T1) exhibited the longest root systems (15.63 cm), which were statistically comparable to those treated with 1% SAP (T2). In contrast, root length declined significantly with increasing SAP concentration, with the shortest roots (9.48 cm) recorded in the 3% SAP treatment (T4).

An adaptive drought-avoidance response, in which plants extend their root systems to explore deeper and wider soil zones in quest of available moisture, is suggested by the longer roots shown in the control treatment. Drought stress has been shown to induce root extension in bananas and other crops as a compensatory mechanism to enhance water intake (Turner *et al.*, 2007; Taiz *et al.*, 2015). Likewise, the current study supports the findings of Xiong *et al.* (2006) that the primary root can lengthen to reach

deeper soil water sources during drought stress (Julkowska *et al.*, 2017). Furthermore, this root action is recognized as a drought-avoidance response connected to physiological whole-plant mechanisms that allow the root to penetrate deeper into the soil, enhance its density, roots sturdiness increases, and encourage hair production (Rivero *et al.*, 2007). The plants treated with 0 SAP (T1) had the largest average root length (15.67 cm) during the recovery period. The outcome shows that the plants are experiencing a water shortage. This result is consistent with Turner's (2003) findings that roots prefer to extend in order to search for water in the soil during drought. Moreover, according to Shoaib *et al.* (2022), plants that are experiencing drought prefer to lengthen their roots in order to improve their capacity to absorb water.

The same root lengths of T1 and T2 indicate that the mild SAP treatment (1%) preserved enough soil moisture. Higher SAP levels (2–3%), on the other hand, considerably limited root elongation. This is probably because of increased soil water retention close to the root zone, which lowers the physiological signal for root extension. In addition, severe SAP swelling can hinder penetration of roots cause by poor soil aeration and mechanical resistance (Abedi-Koupai *et al.*, 2008; Montesano *et al.*, 2015).

The response of roots during recovery phase

During the recovery phase, noticeable differences in root length continued among the different treatments. Control treatment (T1) yielded the longest roots (18.72 cm), and T2 gave roots about 15.78 cm long. Plants which had been exposed to the 3% solution of SAP only showed root length of 7.49 cm. The continuous elongation of roots throughout the entire recovery process in T1 plants may indicate an initial delayed rehydration and then slow re-establishment of shoot growth.

T2's roots were even shorter, though they appeared more substantial, showing that a better balance had occurred between the roots and shoot. Increased SAP must have caused this more equilibrium between shoots and roots due to better moisture

retention in the soil during drought conditions. The presence of a large concentration of SAP also causes soil physical characteristics, such as aeration and pore distribution to change making soil potentially less accommodating to root growth, even when the soil is rewatered.

There also appears to be some correlation with shorter root development in plants treated at high SAP concentrations upon recovering from their effects. Similar findings have been reported in container-grown crops, where increased water availability led to reduced root extension due to high SAP levels.

Implications for root architecture and drought adaptation

Overall, the findings suggest that in higher application rates, root elongation in “Lakatan” bananas exhibits a negative correlation with soil water availability enhanced by SAP. Moderate SAP application (1%) reduced the need for excessive root growth by maintaining more distinct moisture at root zone levels. For drought conditions, survival

mechanism induced root elongation in untreated plants.

These findings align from previous research where SAP can enhance water-use efficiency and overall plant resilience by shifting the plant’s drought response from structural adaptation (root elongation) to physiological maintenance (Wang and Gregg, 1990; Hüttermann *et al.*, 2009). However, higher SAP application appear detrimental in the growth of the root system and compromise long-term plant stability and nutrient uptake.

The effects of superabsorbent polymer (SAP) during drought and recovery conditions on biomass allocation and root system traits

During times of drought and recovery, the SAP application significantly influenced the growth of primary roots and how biomass was distributed in “Lakatan” banana plants, as shown in Table 3. This indicates that SAP helps manage the allocation of dry matter and the structure of the root system based on the amount of water available.

Table 3. Number of primary roots, pseudo-stem biomass (g), primary root biomass, and secondary root biomass (g) of ‘Lakatan’ banana plants as affected by different levels of superabsorbent polymers (SAP) as a treatment during drought and recovery conditions

Treatments	Number of primary roots	Pseudo-stem biomass (g)	Primary root biomass (g)	Secondary root biomass (g)
Drought				
T1	12.82 a	8.84 a	8.63 a	10.88 a
T2	12.00 a	6.32 b	7.78 a	7.80 a
T3	10.63 ab	5.83 b	7.83 a	6.72 a
T4	8.64 b	6.65 b	9.81 a	10.32 a
<i>p</i> -value	0.0047*	0.0003*	0.3219 ns	0.2624 ns
Recovery				
T1	17.19 a	17.32 a	47.76 a	87.32 a
T2	16.08 ab	25.43 a	29.64 b	70.47 a
T3	14.37 b	26.73 a	37.42 b	76.82 a
T4	12.01 c	32.31 a	31.88 b	71.65 a
<i>p</i> -value	0.0001*	0.0513 ns	0.0002*	0.0102*

Means with the same letters are not significantly different at 5% LSD level. T1- 0 SAP + 2 kg premix soil, T2-1% SAP + 2 kg premix soil, T3. 2% SAP + 2 kg premix soil, and T4- 3% SAP + 2 kg premix soil.

The responses during drought conditions on number of primary roots, pseudo-stem biomass, primary root biomass, and secondary root biomass

The plants undergo to drought stress, the number of primary roots varies significantly depending on the

treatment ($p \leq 0.05$). Plants that received no SAP (T1) had the most primary roots with an average value of 12.82 which is not significantly different from T2 (1% SAP treatment). As SAP concentration increased, average primary roots decreased to a minimum value in T4 (3% SAP) treatment of 8.64. This result implies

that in an absence of SAP, the plants in the drought condition initiate an increase in root growth to find available water in the soil to overcome their drought stress. This reaction is also reported in banana and other crop plants as a form of drought survival (Turner *et al.*, 2007; Taiz *et al.*, 2015). Since no significant difference was observed in the number of roots in T2 (1% SAP) it can be assumed that moderate SAP can retain sufficient water from the soil for normal growth and plant activities, so that plants don't require much rooting growth to mitigate drought stress.

The pseudostem biomass for the T1 treatment (8.84 g) at drought was much more prominent as compare to others. On contrary all the plants which were received SAP treatment shown significant loss in biomass. It might be possible due to carbon redirection from growth to maintenance of crucial physiological functions during stress. In SAP provided increased level of water alters normally functioning of SAP-effected signalings pathway under drought stress.

In contrast, in the soil amendments tested primary and secondary root biomass did not differ significantly between treatments over time during the drought. Even if SAP modified the quantity of roots, their global biomass was not altered among treatments. This may mean that roots get thicker, have their density altered in soil amendments made with SAP so that root mass did not vary although less extension of root branches occurred (Hüttermann *et al.*, 2009).

Responses during recovery conditions on primary root number, pseudo-Stem biomass, primary root biomass and secondary root biomass

After the recovering period, the amount of primary roots, primary root biomass and secondary root biomass was significantly different ($p \leq 0.05$) whereas the pseudostem biomass was not. T1 sustained the greatest number of primary roots per plants which amount to 17.19. The reduction in number of primary

roots followed an increase in the level of SAP, indicates that plant previously suffer more intensive drought and delayed dehydration phase also sustained root growth during recovery which may due to drought memory and slow recovery from drought conditions.

The pseudostem biomass across all SAP treatments was statistically similar during recovery, with slightly higher values noted at higher SAP levels (32.31g). This indicates that SAP enhanced the accumulation of shoot biomass after drought, even though the differences were not statistically significant. This improvement is likely due to better water availability and reduced hydraulic constraints during the rewatering period.

Primary root biomass was significantly higher in the T1 (47.76g), while SAP-treated plants exhibited lower values. This implies that untreated plants continue allocating biomass to root systems during recovery, whereas SAP-treated plants shifted biomass partitioning toward shoot regrowth. Such shifts in root-shoot allocation have been associated with improved water availability and reduced need for extensive root systems in moisture-retentive soils (Sivapalan, 2006; Montesano *et al.*, 2015).

There was a noticeable shift in secondary root biomass, with T1 (87.32g) maintaining the highest values. However, SAP did not significantly limit fine root formation during recovery, as seen by the equivalent secondary root biomass displayed by SAP-treated plants. The conservation of fine roots, which are essential for nutrient uptake, indicates that SAP-treated plants maintained their functional absorptive ability while favoring aboveground recovery.

Implications for biomass allocation and drought resilience

Overall, the findings show that SAP alters biomass allocation strategies in "Lakatan" bananas, especially during and post-drought recovery. Plants exhibited a structural drought-avoidance strategy in the absence of SAP, responding to the drought by increasing the

number of roots and biomass investment. On the other hand, plants were able to reallocate assimilates toward shoot regrowth during recovery because moderate rate level of SAP decreased the need for excessive root development

Nevertheless, excessive SAP (3%) consistently decreased the number of primary roots in both phase, indicating that high SAP concentrations may have an adverse effect on root initiation, either as a result of changed soil aeration or mechanical impedance brought on by excessive polymer swelling (Abedi-Koupai *et al.*, 2008).

Effects of superabsorbent polymer (SAP) on chlorophyll content under pre-drought, drought, and recovery conditions

Chlorophyll content, as measured by SPAD readings, was significantly affected ($p \leq 0.05$) by SAP application across pre-drought, drought, and recovery conditions (Table 4), indicating that SAP levels strongly influenced leaf greenness and photosynthetic status of 'Lakatan' banana plants seedling.

Table 4. Chlorophyll content of 'Lakatan' banana plants as affected by different levels of superabsorbent polymers (SAP) as a treatment during drought and recovery conditions

Treatments	Chlorophyll content (SPAD reading)		
	Pre-drought	Drought	Recovery
T1	28.42 a	6.83 c	7.68 c
T2	20.54 a	24.78 a	38.82 a
T3	9.32 b	17.10 b	30.75 b
T4	10.62 b	16.88 b	7.48 c
p-value	0.0006*	0.0000*	0.0000*

Means with the same letters are not significantly different at 5% LSD level. T1- 0 SAP + 2 kg premix soil, T2-1% SAP + 2 kg premix soil, T3. 2% SAP + 2 kg premix soil, and T4- 3% SAP + 2 kg premix soil.

Response to pre-drought conditions by chlorophyll

T1 and T2 showed much higher SPAD value during pre-drought compared to T3 and T4 plants, suggesting that when water is not limiting, excessive amounts of SAP may inhibit the production of chlorophyll; possible because the swelling SAP may

block the availability of nutrients, including water. Furthermore, the negative response of SPAD to SAP concentration during pre-drought may be associated with suboptimal nitrogen uptake; since chlorophyll production is dependent on the level of nitrogen in the plant leaves; there has been some evidence to suggest that in well watered environments this is also seen in container culture especially at high polymer levels (Abedi-Koupai *et al.*, 2008; Montesano *et al.*, 2015) as the interaction between roots and soil is affected by the concentration of the polymer.

Chlorophyll response during drought stress

Untreated plants (T1) with drought show severe decrease in chlorophyll in treatment and the lowest value 6.83. This great decrease was caused by an extreme damage of chlorophyll the process of photosynthesis was largely blocked by damages of membranes and the production of Reactive oxygen species, leading to leaf senescence at an increased rate at an excessive pace, to protect plant by reducing its activity (Farooq *et al.*, 2009; Taiz *et al.*, 2015). Drought stimulates chlorophyll degradation process through increased activity of chlorophyllase (Yen *et al.*, 2003; Taiz *et al.*, 2015) or the membranes of chloroplast (Farooq *et al.*, 2009; Taiz *et al.*, 2015).

In contrast, plants that were treated with SP (Superabsorbent Polymer) retained much higher chlorophyll levels during the period of drought, where a maximum SPAD value of 24.78 occurred at 1% SAP (T2), with other SAP-treated plants yielding values of 17.10 (T3) and 16.88 (T4). The SPAD values obtained suggest that SAP use increased leaf water status and decreased chlorophyll degradation under the given circumstances of water shortage, in agreement with results reported by Nazarli *et al.* (2010), who concluded that in green house cultivation, chlorophyll in sunflower increased with increased rate of SAP addition in the substrate. This retention of chlorophyll levels may be related to maintaining soil water and reduced stomatal closure, thus preserving the rate of photosynthesis (Hüttermann *et al.*, 2009).

Response of chlorophyll under recovery conditions

Also some difference was observed in both treatments during their recovery period. Higher SPAD value was recorded by T2 (1%SAP) as 38.82 followed by T3 (2%SAP) which were 30.75, where SPAD values of T1 (0%SAP) and T4 (3%SAP) remained lowest (7.68 and 7.48) in recovery of both treatments.

The large increase in chlorophyll concentration of the T2 post-recovery confirms that photosynthetic performance bounced back quickly. Thus a moderate dose of SAP helped not only slow chlorophyll decline during the drought but also aided chloroplast repairs and pigments production during the recovery phase. Increased moisture retention capacity due to the presence of SAP in the soil have been demonstrated to keep leaves alive and promote photosynthesis during recovery.

The low chlorophyll concentration throughout, as found in the T4 treatment, could imply that excessive SAP application could even hinder recovery from drought through altered aeration or delayed nutrient uptake. These findings are in line with those reported by other researchers that have found the high concentrations of SAP could indeed retain water while possibly harming the plant's access to nutrients and recovery from stress (Montesano *et al.*, 2015).

Overall implications for photosynthetic resilience

SAP appears essential for sustained levels of chlorophyll in drought stress, but there appears to be optimal doses of applications depending on drought level. A 1% SAP application (T2) showed best response to help and maintain the levels of chlorophyll and allow photosynthesis to continue.

Impact of drought, SAP treatments during drought, and recovery conditions on relative water content

Water was applied during both droughts and recoveries and has shown that water contents of

“Lakatan” banana plants were significantly affected by SAP treatment (Table 5). SAP helped prevent desiccation in during scarcity of water.

Table 5. Relative water content of ‘Lakatan’ banana plants as affected by different levels of superabsorbent polymers (SAP) as a treatment during drought and recovery conditions

Treatments	Relative water content (%)	
	Drought	Recovery
T1	74.33 b	81.72 b
T2	72.67 b	73.87 b
T3	83.76 a	84.41 a
T4	87.73 a	89.82 a
p-value	0.0005*	0.0092*

Means with the same letters are not significantly different at 5% LSD level. T1- 0 SAP + 2 kg premix soil, T2-1% SAP + 2 kg premix soil, T3. 2% SAP + 2 kg premix soil, and T4- 3% SAP + 2 kg premix soil.

Drought condition effect on relative water content with the superabsorbent polymer (SAP)

When there was no rain, the RWC of 2% (T3) and 3% SAP (T4) were higher than 0% SAP (T1) and 1% SAP (T2). For example, at 87.73 and 83.76 %, T4 and T3 have relatively highest RWC. Higher doses of SAP could keep the leaf turgidity by retaining soil moisture. Under drought conditions, untreated (T1) and treated with 1% SAP (T2) resulted in relatively lower RWC, signifying a high degree of water deficit. The decrease in RWC is due to decreased cell turgor pressure; reduced water uptake by plants; stomatal closure; suppression of photosynthesis and growth processes (Farooq *et al.*, 2009; Taiz *et al.*, 2015). By gradually releasing stored water into plant roots with adequate water during drought situations, SAP can conserve soil water and maintain the water status of plant. The higher RWC of leaves of T3 and T4 indicates increased water retention by the roots and increased root permeability to water. It is possible to hold a significant amount of water within theSAP as SAP releases this to the plant when the soil matric potential reaches its lowest. In general, it is assumed that improved water relation status has a beneficial effect on crop development,

but this is not the case for all crop and not under any circumstance, For “Lakatan” banana seedlings the effect of improved water relation status do not induce improve development.

The effects of recovery conditions using super absorbent polymer (SAP) on the relative water content

After the recovery stage, treatments with higher SAP levels- 3% SAP (T4) and 2% SAP (T3)- maintained significantly greater relative water content (RWC), recording 89.82% and 84.41%, respectively, compared with the control (0% SAP, T1) and 1% SAP (T2), which recorded 81.72% and 73.87%, respectively. This sustained higher leaf water content indicates that superabsorbent polymer effectively supplied water during the post-irrigation period, thereby facilitating improved water uptake and rehydration during the post-drought recovery phase.

Decreased soil RWC in T1 and T2 after recovery is likely associated with poor soil water retention ability, enhanced drought damage to root systems, and poor rehydration. Studies on SAP effects on post-stress recovery also confirmed that SAP maintains the best soil moisture levels to alleviate hydraulic constrictions, as observed by Hüttermann *et al.* (2009) and Sivapalan (2006).

Implications for drought tolerance and SAP optimization

According to the study, plants perform better with higher SAP concentrations (2 to 3 percent) when they are subjected to dry spells or recovery phases by remaining more well-watered in each phase, indicating drought resilience is tied to this cell-hydration characteristic preventing premature stress damage. Yet the findings do indicate the highest level of relative water content is not directly associated with highest growth rate based on their data on plant biomass and chlorophyll data analysis. Even if excessive quantities of superabsorbent polymer (SAP) could maintain better retention of moisture within cells, the effect of excessive amounts of saponin can also negatively alter other soil functions, for example soil aerability, balance of nutrient supply, reducing plant efficiency in growth (Abedi-

Koupai *et al.*, 2008; Montesano *et al.*, 2015). Thus, a balanced amount of saponin should improve drought resilience as well as plant growth and performance.

CONCLUSION

The study demonstrated that superabsorbent polymer (SAP) application significantly influences the morphological and physiological responses of tissue culture-derived *Musa acuminata* (AA) ‘Lakatan’ banana seedlings under drought conditions. The findings indicate that drought stress induces adaptive responses in untreated plants, particularly through enhanced root elongation as a survival mechanism to access limited soil moisture. However, such structural adaptation was associated with reduced shoot growth and limited recovery efficiency.

Among the treatments, the application of 1% SAP provided the most favorable balance between water retention and plant development. This level enhanced relative growth rate, maintained leaf area, preserved chlorophyll content, and supported balanced root–shoot development during both drought and recovery phases. In contrast, higher SAP concentrations (2–3%) improved relative water content but negatively affected root architecture, soil aeration, and nutrient dynamics, ultimately limiting plant growth and recovery.

The study highlights that optimal SAP application enhances drought tolerance not merely through increased water availability but by maintaining physiological stability and balanced growth. Thus, moderate SAP application (1%) is identified as the most effective strategy for improving drought resilience in ‘Lakatan’ banana seedlings.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

1. Application of 1% superabsorbent polymer (SAP) is recommended for tissue culture-derived ‘Lakatan’ banana seedlings, particularly under water-limited or drought-prone conditions, as it optimizes growth performance and physiological resilience.

2. Higher SAP concentrations (2-3%) should be avoided in nursery conditions, as they may adversely affect root development, soil aeration, and overall plant growth despite improving water retention.
3. SAP can be considered a practical soil amendment in areas with limited irrigation or irregular rainfall; however, its application should be carefully optimized to avoid negative soil-plant interactions.
4. Further studies are recommended to evaluate the long-term effects of SAP application under field conditions, including its influence on soil physical and chemical properties, nutrient dynamics, and crop yield.
5. Additional research should also investigate the economic feasibility and scalability of SAP use in commercial banana production systems across diverse environmental conditions.

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