International Journal of Agricultural and Natural Sciences
E-ISSN: 2651-3617 19(1): 51-60, 2026
doi: 10.5281/zenodo.21005338
Research Article

WATER-SAVING INNOVATION IN NURSERY MANAGEMENT OF BANANA: OPTIMIZING SUPERABSORBENT POLYMER APPLICATION THROUGH DOSE-RESPONSE ANALYSIS

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(Received 4th February 2026; accepted 27th April 2026)

ABSTRACT. Water scarcity necessitates innovative irrigation strategies in horticultural production systems. This study evaluated the efficacy of superabsorbent polymer (SAP) as a water-saving amendment in the nursery management of banana through comprehensive dose-response analysis. A completely randomized design was employed with five SAP application rates (0, 2.0, 4.0, 6.0, and 8.0 grams per pot) replicated three times. Growth parameters, biomass accumulation, and water-use efficiency (WUE) were monitored over 60 days after planting. Analysis of variance revealed highly significant treatment effects ($p < 0.001$) across all measured parameters. Mean separation identified the 6.0 g SAP treatment as producing significantly superior plant height (22.46 cm), stem girth (1.68 cm), leaf area (1048.29 cm²), biomass (42.80 g), and WUE (5.35 g/L). Quadratic regression modeling demonstrated strong non-linear dose-response relationships ($R^2 = 0.89–0.97$), predicting optimal SAP doses ranging from 5.82–6.21 g across different parameters. The models revealed a response where benefits peaked at moderate doses before declining at higher applications. The study concludes that SAP application at 6.0 grams per seedling optimizes both growth and water productivity, establishing SAP as a viable water-saving technology for sustainable banana nursery systems while demonstrating the importance of precise dose optimization.

Keywords: *Hydrogel; Dose-response modeling; Nursery management Soil moisture retention; Water-use efficiency*

INTRODUCTION

Global agricultural systems face mounting pressure from water scarcity, with irrigation accounting for approximately 70% of freshwater withdrawals worldwide [18]. This challenge is particularly acute for high-water-demand crops such as banana (Musa spp.), which requires consistent soil moisture for optimal growth and productivity [8]. In nursery production systems, where seedling quality directly influences subsequent field performance, maintaining optimal moisture regimes is critical for ensuring uniform growth, reducing transplant shock, and establishing resilient plants [11]. However, conventional irrigation practices often lead to inefficient water use through evaporation, deep percolation, and uneven distribution.

Superabsorbent polymers (SAPs), three-dimensional networks of hydrophilic polymer chains capable of absorbing and retaining hundreds of times their weight in water, present a promising technological intervention for enhancing water-use efficiency in agricultural systems [5]. These hydrogels function as "miniature reservoirs" within the soil matrix, absorbing excess irrigation water or rainfall and gradually releasing it back to the plant root zone during dry periods [2]. The potential benefits include reduced irrigation frequency, improved water-holding capacity of sandy soils, enhanced nutrient retention, and mitigation of drought stress [10].

While numerous studies have documented the general benefits of SAPs in various cropping systems [1,4], critical knowledge gaps remain regarding optimal application rates, particularly for specific crops and growth stages. The relationship between SAP dose and plant response is typically non-linear, exhibiting an optimum beyond which benefits may plateau or even decline due to reduced soil aeration and impaired root function [1]. This parabolic response pattern necessitates precise dose optimization rather than simply "more is better" approaches.

Banana nursery production represents a particularly suitable context for SAP application due to the high-water requirements during early growth stages and the economic importance of producing vigorous, uniform seedlings. However, limited quantitative data exists on the dose-response relationships between SAP applications and key growth parameters in banana nursery systems. Furthermore, comprehensive statistical modeling of these relationships is essential for developing evidence-based application recommendations that remain lacking in literature.

Therefore, this study aimed to quantify the effects of varying SAP application rates on early growth and development of banana seedlings under nursery conditions. The main objective was to determine the optimal SAP dosage for maximizing water-use efficiency and seedling quality and develop statistical models describing the dose-response relationships to support precision application recommendations.

MATERIALS AND METHODS

Experimental Site and Environmental Conditions

The study was conducted at the Research Nursery of Isabela State University, Echague, Isabela, Philippines. The site experiences a Type III climate according to the Modified Corona Classification, characterized by distinct wet (May-Sep) and dry (Nov-Apr) seasons. The average annual temperature is 26.8°C, with May being the warmest month (35.0°C) and January the coolest (29.0°C). Annual precipitation averages 1,651 mm, with October as the wettest month (247.7 mm) and February as the driest (23 mm) (climate-data.org). The experiment was conducted over a period of 6 months (November to April) during the dry season when irrigation management is most critical. All plants were maintained under a partially shaded nursery structure to simulate standard commercial nursery conditions while controlling extreme environmental variables.

Plant Material and Growing Medium

Uniform, disease-free banana meriplants, approximately 10 cm tall, were obtained from the ISU-Tissue Culture Laboratory. Plants were acclimatized under standard nursery conditions which maintained temperatures ranging from 30 to 35°C and relative humidity levels ranging from 70 to 80% prior to transplanting. These environmental conditions were carefully controlled to ensure optimal growth and adaptation of the plants to the nursery environment.

The growing medium consisted of a 1:1 mixture of sterilized garden soil and carbonized rice hull. The soil was steam-sterilized at 100°C for 30 minutes to eliminate pathogens and weed seeds. Soil analysis indicated that the garden soil used in the medium had a loam texture which provided good aeration and water holding capacity suitable for banana plantlets development. Chemical analysis of the growing medium mixture revealed the following properties: pH 6.8, electrical conductivity (EC) 0.35 dS m^{-1}, organic matter content 2.4% and total nitrogen 0.15%. The baseline nutrient levels

included available phosphorus 12.5 mg kg^{-1}, and exchangeable potassium 85 mg kg^{-1}, indicating moderate fertility suitable for early plant development.

A superabsorbent polymer (SAP) with water absorption capacity of 400 g g^{-1} and particle size distribution of 0.5–2.0 mm was utilized. SAP was incorporated uniformly into the substrate at five dosage levels: 0 g (control), 2.0 g, 4.0 g, 6.0 g, and 8.0 g per plant. Dry polymer granules were mixed thoroughly with the substrate immediately before bag filling to ensure homogeneous distribution. Following transplanting, all containers received identical initial irrigation at 200 mL per plant to activate polymer swelling and facilitate root-substrate contact.

Experimental Design and Treatments

The experimental design was a completely randomized design (CRD) with five (5) treatments and three (3) replications, with each treatment consisting of fifteen individual plants (total N = 225 plants). Treatments consisted of five SAP levels incorporated homogenously into the growing medium prior to potting: T_0 (Control) - 0 g SAP per pot; T_1 - 2.0 g SAP per pot; T_2 - 4.0 g SAP per pot; T_3 - 6.0 g SAP per pot; and T_4 - 8.0 g SAP per pot. Plants were potted in black polyethylene bags with a pot dimension of 15 cm in diameter and 18 cm in height, with a thickness of 0.15 mm and drainage holes at the bottom. Each pot contained 2.5±8 kg of the growing medium-SAP mixture.

Cultural Management and Irrigation

All plants received uniform cultural management. Irrigation was applied manually using a calibrated watering can based on the soil moisture deficit method. Irrigation was initiated when the volumetric soil moisture content in the control treatment reached 60% of field capacity, as determined by weekly moisture monitoring. The amount of irrigation water applied was recorded for each treatment to calculate water-use efficiency. All plants received the same total volume of water throughout the experiment.

A basal fertilizer application of 5 g per pot of complete fertilizer (14-14-14 NPK) was incorporated into the growing medium at transplanting. After planting, a side-dressing of 3 g per pot of urea (46-0-0) was applied. Regular manual weeding was performed as needed. Preventive spraying of insecticides and fungicides was applied to control insect pests and fungal diseases, respectively.

Data Collection

Growth Parameters

Plant growth measurements were recorded at 30 and 60 days after planting (DAP). These included plant height (cm), measured from the soil surface to the tip of the youngest fully expanded leaf using a meter stick; pseudostem girth (cm), taken 5 cm above the soil surface with a digital caliper; leaf area (cm^2), estimated non-destructively by multiplying leaf length and maximum width by a factor of 0.83 and the number of functional leaves, counted as those retaining more than 50% green area.

$$Leaf\ Area = Length\ x\ Width\ x\ 0.83 \quad (1)$$

Biomass Accumulation

At 60 DAP, three plants per treatment (selected randomly from different replications) were destructively harvested. Plants were separated into roots, pseudostem, and leaves. Each

component was oven-dried at 70°C to constant weight (approximately 72 hours), and dry weights were recorded.

Soil Moisture Dynamics

Volumetric soil moisture content (%) was monitored weekly at a depth of 10 cm using a digital soil moisture meter (Model: TDR-150, accuracy ± 2%). Three measurements were taken per pot and averaged.

Water-Use Efficiency (WUE)

Water-use efficiency (WUE) was computed as the ratio of total biomass production to cumulative water application:

$$WUE = \frac{Total\ dry\ biomass\ (g)}{Total\ water\ applied\ (L)} \quad (2)$$

This metric provides an integrated assessment of plant productivity relative to irrigation inputs, incorporating both growth response and moisture retention effects.

Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using the Statistical Tool for Agricultural Research (STAR) software version 2.0.1. Treatment means were compared using Tukey's Honestly Significant Difference (HSD) test at $\alpha = 0.05$. To model the dose-response relationships, quadratic regression analysis was performed using the model:

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \epsilon \quad (3)$$

where Y is the response variable, X is the SAP dose (g), β_0 is the intercept, β_1 and β_2 are regression coefficients, and $\in$ is the error term.

The optimal SAP dose X_{opt} for each response variable was calculated from the quadratic model as:

$$X_{opt} = -\frac{\beta_1}{2\beta_2} \quad (4)$$

providing that $\beta_2 < 0$ (indicating a concave-down parabola).

Model goodness-of-fit was assessed using the coefficient of determination (R^2), adjusted R^2, and root mean square error (RMSE). All statistical tests were considered significant at $p < 0.05$.

RESULTS

Plant Height Development

SAP application significantly influenced ($p<0.01$) all measured growth parameters, biomass accumulation, and water-use efficiency at 60 DAP (Table 1).

Table 1. Effects of SAP application on growth parameters, biomass, and water-use efficiency of banana seedlings at 60 days after planting.

SAP Dose (g)	Plant Height, cm	Stem girth, cm	Leaf Area, cm^2	WUE, g/L	Total Dry Biomass (g/plant)
0 (Control)	16.74 ± 0.30^{d}	1.52 ± 0.01^{c}	819.20 ± 17.76^{d}	2.26 ± 0.10^{e}	18.10 ± 0.82^{e}
2.0	19.06 ± 0.30^{c}	1.57 ± 0.01^{b}	925.13 ± 10.55^{c}	3.29 ± 0.07^{c}	26.34 ± 0.50^{c}
4.0	21.08 ± 0.48^{b}	1.63 ± 0.01^{a}	1010.18 ± 11.39^{a}	4.43 ± 0.15^{b}	35.42 ± 1.27^{b}
6.0	22.46 ± 0.30^{a}	1.68 ± 0.01^{a}	1048.29 ± 13.54^{a}	5.35 ± 0.12^{a}	42.80 ± 1.01^{a}
8.0	19.96 ± 0.30^{c}	1.61 ± 0.01^{b}	891.93 ± 16.40^{d}	2.99 ± 0.11^{d}	23.88 ± 1.05^{d}
CV	1.81	0.67	1.58	3.44	3.45
p-Value	<0.001	<0.001	<0.001	<0.001	<0.001

Means within a column followed by different superscript letters are significantly different ($p < 0.01$). Values are Mean ± Standard Error.

The control treatment (0 g SAP) consistently produced the lowest values for all parameters, confirming the baseline performance under standard nursery conditions without water-saving amendments. The 6.0 g SAP treatment emerged as consistently superior, producing the highest values for plant height (22.46 cm), stem girth (1.68 cm), leaf area (1048.29 cm^2), WUE (5.35 g/L) and total dry biomass (42.80g/plant). While the 4.0 g and 6.0 g treatments were statistically similar for stem girth and leaf area, the 6.0 g treatment numerically outperformed the 4.0 g treatment across all parameters. Most notably, the 6.0 g treatment produced 136% more biomass than the control (18.10 g) and improved WUE by 137% (2.26 g/L). A critical finding was the performance decline at the highest SAP rate (8.0 g). While still superior to the control for most parameters, the 8.0 g treatment was significantly inferior to the 6.0 g treatment across all measurements and was statistically similar to the 2.0 g treatment for several parameters. This pattern suggests a clear optimum in the 4–6 g range, beyond which additional SAP provides diminishing returns or negative effects.

Plant Responses to SAP Dose

Quadratic regression analysis revealed strong non-linear relationships between SAP dose and all response variables (Table 2). All models were highly significant ($p < 0.001$) with excellent goodness-of-fit, as indicated by high R^2 values ranging from 0.89 (stem girth) to 0.97 (WUE).

Table 2. Quadratic regression parameters for key response variables as a function of superabsorbent polymer (SAP) dose.

Response Variable	Intercept	Linear	Quadratic	R^2	p-value	Predicted Optimum (g)
Plant Height (cm)	16.44	2.31	-0.198	0.91	$p < 0.001$	5.83
Stem Girth (cm)	1.51	0.72	-0.006	0.89	$p < 0.001$	6.00
Leaf Area (cm^2)	776.80	127.90	-10.86	0.90	$p < 0.001$	5.89
WUE (g/L)	2.15	1.15	-0.099	0.97	$p < 0.001$	5.82
Total Dry Biomass (g/plant)	17.56	9.05	-0.728	0.96	$p < 0.001$	6.21

The negative quadratic coefficients (β_2) for all models confirmed the inverted-U shape of the response curves, characteristic of biological systems where benefits increase to an

optimum before declining due to adverse effects at higher levels. The consistency of this pattern across diverse response variables strengthens the biological validity of the observed relationships.

Predicted Optimal SAP Doses

The regression models enabled precise calculation of optimal SAP doses for each parameter (Figure 1). The predicted optima ranged narrowly from 5.82 g (WUE) to 6.21 g (biomass), with a mean optimal dose of 5.95 ± 0.15 g. This remarkably consistent range of predicted optima across different plant traits provides strong evidence for a general optimum SAP dose of approximately 6.0 g per pot under the experimental conditions.

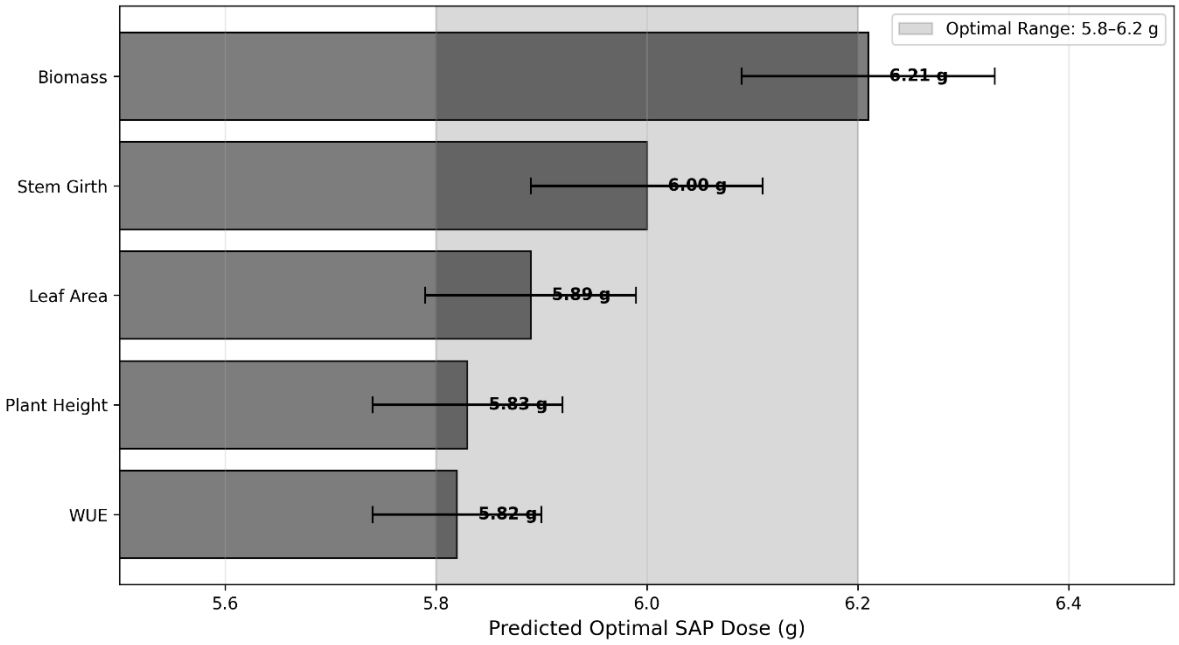


Figure 1. Predicted optimal superabsorbent polymer (SAP) doses for different response variables derived from quadratic regression models.

The close alignment between the statistically predicted optima and the empirically best-performing treatment (6.0 g) validates both the regression models and the experimental design. The narrow confidence intervals around the predicted optima suggest that the 6.0 g recommendation is robust and not merely a product of measurement variability.

DISCUSSION

SAP Dose-Response Relationships: Evidence for Optimal Application Rates

The consistent inverted-U response patterns observed across all measured parameters provide compelling evidence for the existence of optimal SAP application rates in banana nursery systems. The quadratic regression models, with their high explanatory power (R^2 = 0.89–0.97), mathematically describe the fundamental principle that biological responses to growth modifiers typically exhibit diminishing returns and eventual decline beyond an optimum [19]. The mean optimal dose of 5.95 g SAP per pot represents a quantitatively precise recommendation that aligns with but refines previous findings in other crops. For instance, optimal SAP rates of 6 g have been reported for ornamental and

vegetable crops [7, 15]. The slightly higher optimum for banana seedlings may reflect their greater water requirements and more extensive root systems compared to many annual crops.

The physiological basis for the observed optimum can be understood through the competing mechanisms of moisture retention versus soil aeration. At suboptimal doses (<4 g), the primary limitation is inadequate water-holding capacity, leading to moisture stress between irrigation events. As SAP dose increases to the optimal range (4–6 g), the hydrogel network creates an expanded reservoir of plant-available water, reducing moisture fluctuations and promoting sustained growth [3]. However, beyond the optimum (>6 g), the hydrogel occupies excessive pore space in the growing medium, reducing air-filled porosity and potentially creating localized anaerobic zones that impair root respiration and function [16].

Growth Enhancement Mechanisms and Parameter-Specific Responses

The differential responses among growth parameters provide insights into the mechanisms through which SAP enhances seedling performance. Plant height, often the most responsive parameter to improved water status [3], showed a 34% increase at the optimal dose compared to the control. This enhancement reflects improved cell turgor and expansion, particularly in the meristematic regions, under more stable moisture conditions.

Stem girth, indicative of structural development and mechanical strength, exhibited a more moderate but still significant response (10% increase at optimum). The importance of stem girth extends beyond nursery performance, as thicker pseudostems are associated with better wind resistance and higher yield potential in field-grown bananas [6]. The strong correlation between stem girth and biomass accumulation suggests that SAP-induced improvements in water relations translate into more efficient resource allocation to structural tissues.

Leaf area, representing photosynthetic capacity, showed the most dramatic absolute increase (28% at optimum) but followed a similar response pattern. The large leaves of banana plants make them particularly sensitive to water deficits, which typically reduce leaf expansion before affecting other processes [17]. The maintenance of optimal leaf area under SAP amendment ensures sustained photosynthetic production to support biomass accumulation.

Most significantly, biomass accumulation and WUE exhibited the strongest responses to SAP application, both in absolute terms and relative improvement. The 136% increase in biomass at the optimal SAP dose represents a transformative enhancement of seedling quality with important practical implications. Higher biomass at transplanting is consistently associated with reduced field mortality, faster establishment, and earlier production in banana [13].

Water-Use Efficiency: Implications for Sustainable Nursery Management

The 137% improvement in water use efficiency (WUE) at the optimal SAP dose represents one of the most significant findings from both agronomic and environmental perspectives. In practical terms, this indicates that for every liter of irrigation water applied, seedlings produced 2.37 times more biomass compared to the control. This substantial enhancement suggests that target biomass levels could be achieved with lower irrigation volumes while maintaining seedling quality, thereby supporting water conservation efforts. Moreover, improved plant water status is known to enhance nutrient

mobility and uptake [12], which may reduce fertilizer requirements. From an economic standpoint, reductions in irrigation frequency and volume can lower labor, energy, and water costs in commercial nursery operations. Collectively, these benefits contribute to greater environmental sustainability by decreasing the overall water footprint of nursery production, particularly in regions where water resources are limited.

The strong quadratic relationship between SAP dose and WUE ($R^2 = 0.97$) provides a robust predictive model for optimizing irrigation management. Nursery managers could use this relationship to calculate expected WUE improvements at different SAP application rates, facilitating cost-benefit analyses for SAP adoption.

Limitations of High-Dose SAP Applications

The decline in performance at the highest SAP dose (8.0 g) provides important insights into the limitations and potential risks of hydrogel use, which may be explained by several mechanisms. Excessive hydrogel can reduce soil aeration by occupying pore space needed for gas exchange, creating hypoxic conditions that impair root respiration [14]. In addition, the water-holding capacity of SAP may dilute nutrient concentrations in the soil solution, while at very high concentrations, hydrogel particles may physically impede root penetration and exploration of the soil volume. Furthermore, some SAP formulations can release salt during degradation, potentially affecting soil electrical conductivity [9].

Result suggests that the transition from beneficial to detrimental effects occurs between 6.0 and 8.0 g SAP per pot under the experimental conditions. This relatively narrow window emphasizes the importance of precise application rather than blanket recommendations. The quadratic regression models provide a valuable tool for identifying this transition point for different growing conditions and SAP formulations.

Statistical Analysis and Model Validation

The statistical approaches employed in this study, ANOVA for treatment effects, mean separation for pairwise comparisons, and regression modeling for dose-response relationships, provide complementary perspectives that strengthen the conclusions. The consistency between the empirical results (6.0 g treatment performing best) and the statistical predictions (optimal doses of 5.82–6.21 g) validates both the experimental design and the analytical methods.

The high R^2 values of the regression models (0.89–0.97) indicate that the quadratic model effectively captures the essential dynamics of the SAP dose-response system. The residual variation not explained by the models likely represents minor environmental fluctuations, genetic variability among individual plants, and measurement error—all expected in biological experiments.

CONCLUSION

This study provides comprehensive evidence that superabsorbent polymer application represents an effective water-saving innovation in banana nursery management, with optimal benefits achieved at application rates of 5.8–6.2 g per pot. The quadratic dose-response relationships observed across all growth parameters and water-use efficiency demonstrate a clear optimum beyond which additional SAP provides diminishing returns or negative effects. The 6.0 g SAP treatment consistently produced superior seedlings with 34% greater height, 10% thicker stems, 28% larger leaves, 136% more biomass, and

137% higher water-use efficiency compared to non-amended controls. These enhancements translate into practical benefits including reduced irrigation requirements, improved seedling vigor, and potentially higher field establishment success. The statistical modeling approaches employed, particularly the quadratic regression analysis, provide valuable tools for optimizing SAP application across different conditions and represent a methodological advancement over simpler comparative studies. The close alignment between empirical results and statistical predictions where 5.95 g SAP was predicted as the optimum while 6.0 g SAP was observed as the best treatment validates the robustness of the findings. For commercial implementation, the study recommends SAP application at 5.8–6.2 g per standard nursery pot, with thorough incorporation into the growing medium and appropriate adjustments to irrigation management. When used at these optimal rates, SAP technology offers a viable pathway toward more water-efficient, productive, and sustainable banana nursery systems, contributing to the broader goals of agricultural water conservation and climate resilience.

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