ISSN: 2621-4709 E-ISSN: 2621-2528
Journal of Applied Agricultural Science and Technology
Vol. 10 No. 2 (2026): 249-260

Optimizing Hydroponically Cultivated Kale Growth Using Nano-Formulated Organic Fertilizers: A Multivariate Evaluation Using PCA

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Abstract. *Kale (Brassica oleracea var. acephala) cultivated in hydroponic systems commonly relies on inorganic AB Mix nutrients, which raises sustainability concerns. This study evaluated the potential of nano-technology liquid organic fertilizers (nano-POC) derived from Sargassum, Gliricidia sepium (gamal leaves) and Tithonia diversifolia as partial substitutes for AB Mix in hydroponic kale cultivation. The experiment was conducted using different substitution formulations, and plant growth responses were assessed based on morphological and biomass-related parameters. The results showed that partial substitution of AB Mix with nano-POC maintained superior growth performance compared to full organic application. The formulation P3S (50% AB Mix + 50% Sargassum nano-POC) produced the most balanced and consistent growth responses, reaching a plant height of 22.5 cm, an average of seven leaves and a dry weight of 0.17 g, and showed no significant difference from the 100% AB Mix control. In contrast, the exclusive use of nano-POC resulted in significant declines across all growth indicators. Multivariate analysis using Principal Component Analysis (PCA) confirmed the stability and consistency of the optimal treatment across growth parameters. These findings indicate that nano-POC functions effectively as a complementary nutrient source in hydroponic systems. Integrating nano-technology liquid organic fertilizers through partial substitution strategies offers a sustainable approach to reducing dependence on synthetic fertilizers while maintaining hydroponic kale productivity.*
Keywords: *hydroponics; kale; multivariate; organic nano-fertilizer; PCA.*

Type of the Paper: Regular Article.

1. Introduction

Hydroponic cultivation has become an important agricultural strategy to meet the increasing demand for fresh vegetables while minimizing land use and water consumption. This system is particularly suitable for leafy vegetables such as kale (*Brassica oleracea* var. *acephala*), which has high nutritional value and strong market demand. However, conventional hydroponic production still relies heavily on synthetic nutrient solutions, such as AB Mix, which raises concerns related to environmental sustainability, nutrient efficiency and long-term ecological impact [1–3]. The intensive use of inorganic fertilizers in soilless systems may also increase production costs and contribute to environmental pollution, highlighting the need for more sustainable nutrient management strategies.

Recent advances in agricultural nanotechnology have introduced nano-fertilizers as a

https://doi.org/10.55043/jaast.v10i2.565
Received February 1, 2026; Received in revised form February 25, 2026; Accepted March 30, 2026; Published May 30, 2026
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promising alternative to conventional fertilizers [4]. Nano-fertilizers are designed to enhance nutrient solubility, controlled release and bioavailability, thereby improving nutrient use efficiency and reducing losses in agricultural systems [5–7]. In hydroponic cultivation, the integration of nano-formulated fertilizers offers opportunities to optimize nutrient delivery while supporting sustainable production systems. Several studies have reported that nano-fertilizers can improve plant growth, biomass accumulation and stress tolerance under controlled environments, making them suitable for modern and precision agriculture [8,9]. The application of nano-formulated nutrient sources in hydroponic vegetable production has been shown to improve nutrient uptake efficiency, plant growth and biomass accumulation while reducing the required concentrations of conventional inorganic nutrient solutions [10].

Liquid organic fertilizers (in Indonesian contexts known as POC, which stands for pupuk organic cair) derived from locally available organic materials have also gained attention as sustainable nutrient sources. Organic materials such as *Tithonia diversifolia*, *Sargassum* sp. and *Gliricidia sepium* (gamal) are known to contain essential macro- and micronutrients as well as bioactive compounds that act as biostimulants. Previous studies have shown that *Tithonia*-based liquid fertilizers can improve fresh biomass production [10,11], while *Sargassum* extracts enhance plant growth through nutrient supply and hormonal effects [11,12]. Gamal has been widely reported as a nutrient-rich organic resource capable of improving soil and crop fertility [13]. Nevertheless, the application of these organic fertilizers in hydroponic systems remains limited, particularly in nano-formulated forms and as partial substitutes for synthetic nutrient solutions. Previous studies by Fevria et al. [14,15] demonstrated the potential of nano-based liquid organic fertilizers in hydroponic vegetable cultivation. However, most existing studies focus on general vegetable species and univariate growth assessments, whereas investigations specifically addressing kale cultivated hydroponically with integrated nano-POC substitution strategies remain limited.

Moreover, although multivariate statistical tools such as Principal Component Analysis (PCA) are increasingly applied in agronomic research to synthesize complex and correlated growth variables [16,17], their application in evaluating nano-formulated organic fertilizer substitution in hydroponic kale systems has not been comprehensively explored. This gap indicates the need for an integrated experimental and multivariate framework capable of identifying not only individual parameter responses but also overall treatment performance and stability.

Therefore, this study aimed to optimize hydroponic kale growth through partial substitution of AB Mix with nano-formulated liquid organic fertilizers (nano-POC) derived from *Tithonia*, gamal and *Sargassum*, using a factorial experimental design supported by multivariate PCA to obtain a comprehensive assessment of treatment effects. This research is expected to contribute to the development of sustainable hydroponic nutrient management strategies that enhance productivity, reduce reliance on synthetic fertilizers and utilize locally abundant organic resources.

2. Materials and Methods

This research was conducted over six months, from April to September 2024, at the Experimental Greenhouse and Biotechnology Laboratory, Department of Biology, Padang State University, Padang City, West Sumatra. The experimental design used a Completely Randomized Design (CRD) with 15 treatments and five replications, resulting in a total of 75 experimental units. Nano-POC was developed from three local organic materials: *Tithonia* (T), gamal (G) and *Sargassum* (S). These materials were chosen for their high macro- and micronutrient contents, abundant availability and previous research showing their effectiveness in supporting the growth of hydroponically cultivated plants. Different substitution levels of nano-POC were applied to evaluate the effect of dosage on the growth of hydroponically cultivated kale.

The nano-POC substitution treatments consisted of five combinations for each material: P1 (control, 100% AB Mix), P2 (75% AB Mix + 25% nano-POC), P3 (50% AB Mix + 50% nano-POC), P4 (25% AB Mix + 75% nano-POC) and P5 (100% nano-POC). The substitution levels were formulated based on the targeted nutrient concentration (ppm) of the final nutrient solution. For each treatment, the proportion of nano-POC to AB Mix was adjusted to achieve comparable total nutrient strength across treatments, and electrical conductivity (EC) was monitored to ensure consistency of nutrient availability.

The nano-POC production process involved chopping 5 kg of each organic material, then fermenting it in a 144-L plastic container containing 15 L of coconut water, 15 L of mineral water and 200 mL of EM4. Anaerobic fermentation for seven days aimed to increase microbial activity and nutrient solubility. After filtration, the POC solution was subjected to nanobubbling using a UV Bubble Fina device for 72 hours. According to the operational specifications of the device, the process generates oxygen nanobubbles within the nano-scale range (approximately 50–100 nm). The nano-formulation procedure followed previously established protocols reported in earlier studies [14,15]. This approach was intended to enhance nutrient dispersion and solution dynamics under hydroponic conditions.

Grand Rapids variety kale seeds were germinated on rockwool for eight days, then transferred to a wick hydroponic system with one plant per hole. This wick system was chosen because it is simpler, capable of providing even nutrient distribution and suitable for controlled experiments. Environmental conditions were kept constant at a temperature of 25 ± 2°C, a humidity of 70 ± 5%, a light intensity of 800–1000 μmol/m²/s measured as photosynthetic photon flux density, a standard parameter in controlled-environment agriculture [18] and a photoperiod of

16 hours of light and eight hours of darkness. The nutrient solution was checked every three days to maintain optimal composition.

Growth indicator observations were made every three days for five weeks after transplanting, including plant height, number of leaves, fresh weight and dry weight (after drying at 70°C for 48 hours) [19,20]. Nutrient solution quality parameters, such as Total Dissolved Solids (TDS) and pH, were also measured every three days using a Hanna digital meter.

Data were analyzed using one-way Analysis of Variance (ANOVA) at a 5% significance level to compare responses among the 15 treatment combinations. If significant differences were found, Duncan's Multiple Range Test (DMRT) was used for further analysis to determine differences between treatments, with different letter notations indicating significant differences.

Pearson's correlation analysis was conducted to examine the relationships among growth parameters. Principal Component Analysis (PCA) was performed using R software (version 4.5.2). Prior to PCA, all growth variables were standardized using Z-score normalization to eliminate differences in measurement scales. The analysis was conducted based on the correlation matrix, and the number of principal components retained for interpretation was determined using scree plot analysis.

3. Results and Discussion

3.1. *The Effect of Nano-POC on Kale Growth Parameters*

The application of nano-POC derived from *Tithonia*, gamal and *Sargassum* significantly influenced the growth and biomass production of hydroponically cultivated kale. Variations in plant height, number of leaves, fresh weight and dry weight were observed among treatments, indicating that both the source of organic material and the proportion of AB Mix substitution with nano-POC played important roles in determining plant performance (Table 1).

Table 1. The effect of nano-POC substitution treatments on plant height, number of leaves, fresh weight and dry weight of kale

Treatment	Average Plant Height (cm)	Average Number of Leaves (leaves)	Wet Weight (g)	Dry Weight (g)
P1T	18.04	7.60	4.60^{a}	0.2160^{ab}
P2T	21.88	7.20	4.80^{a}	0.2220^{ab}
P3T	19.22	7.00	4.20^{a}	0.2840^{a}
P4T	20.14	7.40	4.80^{a}	0.1380^{bc}
P5T	8.70	6.40	2.60^{b}	0.0400^{c}
P1G	20.82^{a}	7.00^{a}	4.20	0.3140^{b}
P2G	19.76^{a}	7.20^{a}	3.40	0.3480^{b}
P3G	16.90^{a}	7.40^{a}	3.40	0.4960^{a}
P4G	18.68^{a}	7.20^{a}	4.00	0.3220^{b}
P5G	10.14^{b}	5.00^{b}	3.00	0.1680^{c}
P1S	17.74^{b}	6.60^{ab}	3.40	0.2180
P2S	19.68^{ab}	6.40^{ab}	3.60	0.1700
P3S	22.50^{a}	7.00^{a}	4.20	0.1700
P4S	16.80^{b}	7.80^{a}	3.80	0.4320
P5S	8.74^{c}	5.40^{b}	2.60	0.2520

Overall, partial substitution of AB Mix with nano-POC (25–50%) maintained or improved plant height, number of leaves and biomass compared to the full synthetic control, whereas complete substitution (100% nano-POC) consistently reduced growth performance. This trend is consistent with previous reports that nano-fertilizers are most effective when integrated with conventional nutrient sources rather than applied independently [5–7].

Among the tested formulations, the intermediate substitution level showed the most favorable responses. *Tithonia*-based treatments (P2T and P3T) enhanced dry weight accumulation, while P3G produced the highest dry weight among gamal treatments. *Sargassum*-based nano-POC exhibited the most consistent overall performance, particularly P3S (50% AB Mix + 50% nano-POC), which achieved superior plant height and balanced biomass production comparable to the 100% AB Mix control. These observations indicate that moderate substitution levels tend to support stable vegetative growth across different organic sources. Previous studies have reported that *Tithonia*-derived liquid fertilizers can enhance leafy vegetable biomass [11], while *Gliricidia sepium* is recognized for its nutrient-rich composition and growth-promoting potential [13]. Similarly, *Sargassum* extracts have been associated with improved plant performance in hydroponic and controlled-environment systems [12]. These responses may reflect improved nutrient dynamics and biostimulant activity as suggested in previous studies.

Across all organic sources, number of leaves followed a similar trend, where partial substitution sustained vegetative development, while full substitution resulted in reduced leaf formation. This decline under 100% nano-POC treatments may indicate that nano-POC alone does not fully satisfy the macronutrient requirements of kale under hydroponic conditions. Similar limitations of fully organic nutrient solutions in soilless cultivation have been reported [19–21].

Dry weight data further confirmed the advantage of partial substitution strategies. Higher dry biomass observed under intermediate nano-POC treatments reflects improved nutrient uptake efficiency and photosynthetic performance. Dry weight is considered a more reliable indicator of plant productivity than fresh weight, as it represents actual organic matter accumulation rather than water content [22]. The enhancement of dry biomass under partial nano-POC substitution supports previous findings [14,15,23].

Overall, the findings suggest that moderate nano-POC substitution maintains nutrient balance and solution stability, whereas excessive substitution may reduce macronutrient sufficiency and alter nutrient dynamics, thereby limiting optimal plant performance.

3.2.Partial Substitution Strategy and Nutrient Efficiency in Hydroponic Kale Cultivation

The superior performance of kale under partial substitution highlights the importance of nutrient balance in hydroponic systems. Hydroponically grown leafy vegetables require precise and readily available macronutrients, particularly nitrogen, potassium and calcium [24,25].

While nano-POC contributes micronutrients, organic compounds and biostimulants, its ionic strength and nutrient composition alone may not match the rapid macronutrient demand of kale when used as the sole nutrient source. Previous studies have reported that insufficient nutrient concentration can limit biomass accumulation in hydroponically cultivated crops [21,22]. Therefore, maintaining the proportion of AB Mix ensures adequate macronutrient supply, while nano-POC enhances nutrient efficiency.

In addition, nano-scale nutrient delivery contributes to improved nutrient use efficiency by increasing surface area and facilitating root–nutrient interactions. Nano-fertilizers have been shown to reduce nutrient losses and improve uptake efficiency when integrated with conventional fertilization strategies [5,7]. The presence of bioactive compounds in *Sargassum* and *Tithonia* may further stimulate physiological processes under partial substitution regimes [26,27].

The declines in growth observed under 100% nano-POC treatments may also be associated with potential fluctuations in electrical conductivity (EC) and pH stability in the nutrient solutions. Organic nutrient sources often release nutrients more gradually and variably, which can influence nutrient equilibrium in hydroponic systems. Maintaining stable EC and pH is critical for nutrient availability [24,25]. Partial substitution allows nano-POC to improve nutrient dynamics without compromising the chemical stability provided by inorganic nutrient solutions.

The response pattern observed across substitution levels visually resembles a quadratic trend, where moderate substitution (approximately 50%) produced optimal growth followed by declines at higher substitution levels. Future studies employing polynomial regression analysis could provide a more precise quantitative estimation of the optimal substitution threshold.

Overall, these findings demonstrate that partial substitution of AB Mix with nano-formulated liquid organic fertilizers represents an efficient nutrient management strategy for hydroponic kale cultivation.

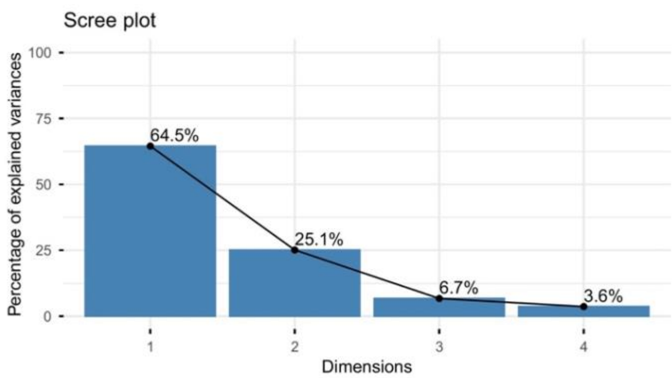

Fig. 1. Scree Plot of Principal Component Analysis (PCA): Elbow Point Identified at the Second Component

3.3. Multivariate Principal Component Analysis of Kale Growth Responses

Multivariate analysis using PCA was employed to integrate multiple growth parameters and evaluate the overall treatment performance.

The scree plot (Fig. 1) indicates that the first principal component (Dim.1) explained 64.5% of the total variance, while the second principal component (Dim.2) explained 25.1%. Together, these two components accounted for 89.6% of the total variability, indicating that the multidimensional growth responses of kale can be reliably interpreted within a two-dimensional PCA framework. The remaining components (Dim.3 = 6.7% and Dim.4 = 3.6%) contributed only marginally and were therefore not emphasized in subsequent biological interpretation.

The PCA biplot (Fig. 2) reveals that all measured growth variables loaded positively along Dim.1. This indicates that Dim.1 primarily represents overall vegetative growth performance, integrating plant height, number of leaves, fresh weight and dry weight into a single gradient of general growth magnitude. Treatments positioned further along the positive side of Dim.1 therefore exhibited higher overall growth responses across parameters.

Dim.2, in contrast, differentiates biomass characteristics rather than overall growth intensity. Dry weight showed strong positive loading along Dim.2, while fresh weight contributed in the opposite direction. This pattern suggests that Dim.2 reflects variation in biomass composition, distinguishing treatments with relatively greater dry matter accumulation from those characterized by higher fresh biomass. Plant height and number of leaves contributed less strongly to Dim.2, indicating that morphological parameters were primarily associated with Dim.1.

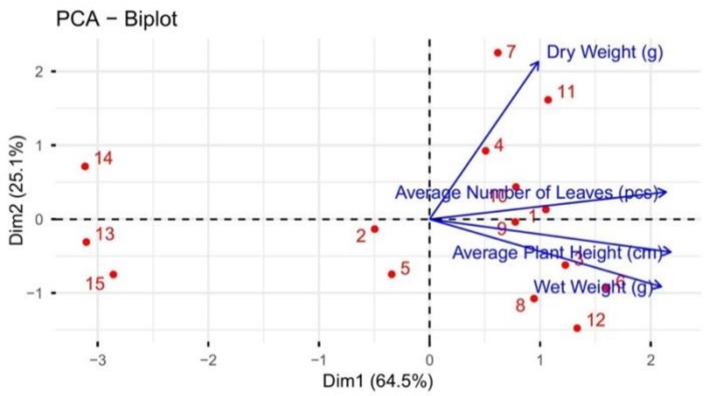

Fig. 2. Principal Component Analysis (PCA) Biplot Showing the Relationship between Nano-POC Treatments and Kale Growth Response Variables

The PCA individuals plot (Fig. 3). further illustrates treatment distribution within the multivariate space. Treatments with partial substitution of AB Mix with nano-POC were generally positioned in regions associated with positive Dim.1 values, indicating balanced and superior overall growth performance. In contrast, treatments involving full substitution (100% nano-POC) tended to cluster away from the positive Dim.1 region, reflecting comparatively reduced multivariate growth responses. The relatively coherent grouping of intermediate substitution treatments suggests greater growth stability across replicates.

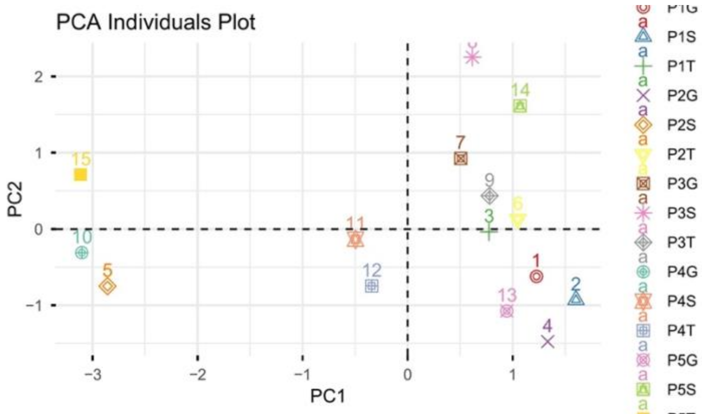

Fig. 3. PCA Individuals Plot in Principal Component Analysis (PCA)

The Pearson's correlation matrix (Fig. 4) complements the PCA results by illustrating strong positive associations among growth variables, particularly between fresh weight and dry weight. These correlations support the interpretation that biomass-related variables strongly influence the principal component structure, reinforcing the dominant role of Dim.1 in capturing overall growth performance.

Fig. 4. Pearson's Correlation Matrix between Growth Variables and Nutrient Solution Parameters in Hydroponically Cultivated Kale

The variable representation quality ($\cos^2$) shown in Fig. 5 confirms that most growth variables were well represented in the first two principal components. Plant height, number of leaves and fresh weight exhibited strong representation in Dim.1, whereas dry weight showed substantial representation in Dim.2. The low contributions of Dim.3 and Dim.4 further support focusing interpretation on the first two components.

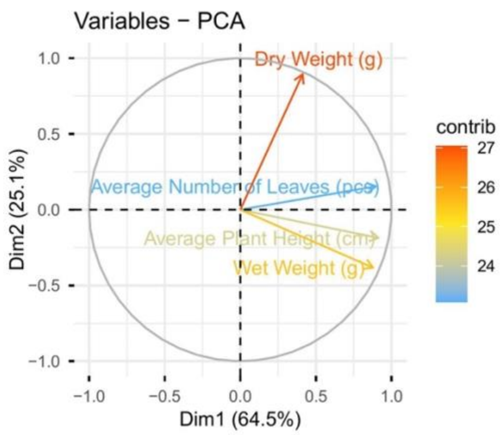

Fig. 5. Variable Representation Quality ($\cos^2$) in Principal Component Analysis (PCA)

The multivariate analysis is consistent with the univariate findings, demonstrating that partial substitution of AB Mix with nano-formulated liquid organic fertilizers produces a coherent and stable growth profile across multiple parameters. The PCA approach therefore provides integrative confirmation that balanced substitution strategies optimize hydroponically cultivated kale performance.

3.4.Implications for Sustainable Hydroponic Nutrient Management

The findings of this study demonstrate that nano-POC functions most effectively as a complementary nutrient source rather than a complete substitute for conventional AB Mix in hydroponic kale cultivation. Both univariate and multivariate analyses consistently showed that partial substitution (25–50%) maintained or enhanced plant growth performance, whereas full substitution reduced growth magnitude.

These results highlight the importance of nutrient balance in soilless cultivation systems. Hydroponically cultivated crops require readily available macronutrients in stable concentrations, and maintaining the proportion of inorganic nutrient solution ensures consistent nutrient supply. Meanwhile, nano-POC may enhance nutrient use efficiency through improved nutrient dispersion and potential bioactive effects derived from organic sources.

From a sustainability perspective, integrating nano-POC with conventional nutrient solutions may reduce dependency on fully synthetic inputs while maintaining high productivity. Such an approach aligns with current efforts to improve nutrient efficiency and reduce environmental impacts in controlled-environment agriculture. Rather than replacing synthetic fertilizers entirely, nano-organic formulations may serve as strategic supplements that optimize nutrient dynamics and support sustainable hydroponic production systems.

Future research should evaluate long-term nutrient stability, recirculating system performance and economic feasibility under commercial-scale conditions. Further investigation across different crop species would also strengthen the applicability of nano-formulated organic fertilizers in sustainable hydroponic cultivation.

4. Conclusions

This study demonstrates that partial substitution of conventional AB Mix with nano-formulated liquid organic fertilizers (nano-POC) can sustain kale growth in hydroponic systems. Among the evaluated treatments, the intermediate nano-POC substitution level resulted in the most balanced and consistent growth responses across key morphological and biomass-related parameters. Principal Component Analysis (PCA) supported this finding by showing coherent clustering of the optimal treatment, indicating stable multivariate performance. However, complete replacement of AB Mix with nano-POC reduced plant growth and biomass accumulation, indicating that nano-POC alone is insufficient to fully meet crop nutrient requirements under hydroponic conditions. These findings suggest that nano-POC functions effectively as a complementary nutrient source rather than a full replacement for synthetic fertilizers, highlighting both its potential and its limitations in sustainable hydroponic nutrient management.

Abbreviations

AB Mix	commercial inorganic nutrient solution used in hydroponic systems
ANOVA	analysis of variance
CRD	completely randomized design
DMRT	duncan's multiple range test
EC	electrical conductivity
EM4	effective microorganisms 4
nano-POC	nano-formulated liquid organic fertilizer
PCA	principal component analysis
POC	liquid organic fertilizer
TDS	total dissolved solids
UV	ultraviolet

Data availability statement

The data will be provided upon readers' request.

CRediT authorship contribution statement

Resti Fevria: Conceptualization, Methodology, Resources, Formal analysis, Investigation, Writing – review & editing; **Vauzia**: Writing original draft, Validation, Data curation, Formal analysis, Conceptualization; **Silvy Annisa**: Writing – review & editing, Formal analysis, Resources; **Santi Diana Putri**: Conceptualization, Supervision, Project administration. **Roni Jarlis**: Data curation, Writing – review & editing.

Declaration of Competing Interest

The authors of this manuscript state that they have no conflicts of interest or competing interests.

Declaration of Use of AI in the Writing Process

The author(s) used ChatGPT during the preparation of this manuscript to [e.g., improve grammar, paraphrase text, enhance clarity]. After using the tool, the author(s) carefully reviewed and edited the content and take full responsibility for the content of the publication.

Acknowledgement

The author expresses gratitude to LP2M Padang State University for funding this research. Thanks, are also extended to the Head of the Department of Biology and his team, the Head of the Biology Laboratory and his team, the Dean of the Faculty of Mathematics and Natural Sciences for granting permission to carry out the research, and to everyone who has contributed to its execution.

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