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Natural Seed Priming with Coconut Water and Eco-Enzyme Enhances Dormancy Release and Early Seedling Vigor in Oil Palm (*Elaeis guineensis* Jacq.)

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ABSTRACT: Oil palm (*Elaeis guineensis* Jacq.) seed dormancy remains a major constraint to efficient nursery production because it delays germination and reduces seedling uniformity. Although coconut water and eco-enzyme have individually been recognized as natural biostimulants, limited information is available regarding their combined application as seed-priming agents for improving oil palm seed performance. This study evaluated the individual and combined effects of coconut water and eco-enzyme on dormancy release, germination characteristics, and early seedling growth of oil palm. A factorial Completely Randomized Design (CRD) was employed using three concentrations of coconut water (250, 500, and 750 mL L^{-1}) and three concentrations of eco-enzyme (50, 100, and 150 mL L^{-1}). Germination percentage, mean germination time, seedling height, leaf number, and stem diameter were recorded and analyzed using analysis of variance followed by Duncan's Multiple Range Test at the 5% significance level. Both coconut water and eco-enzyme significantly improved germination percentage, accelerated germination, and enhanced early seedling growth. The highest responses were consistently obtained with 750 mL L^{-1} coconut water and 150 mL L^{-1} eco-enzyme. A significant interaction between both biostimulants was observed only for seedling height, indicating complementary physiological effects during early vegetative growth. The findings demonstrate that integrating coconut water and eco-enzyme as natural seed-priming agents provides an environmentally sustainable approach for improving dormancy release and seedling vigor in oil palm while reducing dependence on synthetic plant growth regulators. This study contributes new evidence supporting the integration of renewable biological resources into sustainable oil palm nursery management.

KEYWORDS: coconut water, eco-enzyme, oil palm, seed dormancy, seed priming, biostimulant

INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is one of the world's most productive oil-bearing crops and plays a pivotal role in supporting the global vegetable oil supply. Sustaining high plantation productivity depends largely on the availability of vigorous and uniform seedlings, making successful seed germination a critical prerequisite for commercial nursery production. However, oil palm seeds exhibit pronounced physiological dormancy, resulting in slow and uneven germination that prolongs nursery duration and increases production costs (Manurung, A.I., Bilter A. Sirait and R. Sabrina, 2022; Sirait, B.A., A.I. Manurung, O.M. Samosir, R.G. Marpaung, Nurhayati and C. Manalu, (2021); Sirait, B., A.I. Manurung, E. Panjaitan and L. Siregar, (2020). Consequently, sustainable oil palm cultivation depends not only on improved genetic materials but also on the availability of vigorous and uniform seedlings capable of establishing rapidly under nursery and field conditions. High-quality seedlings constitute the foundation of plantation productivity because early plant vigor strongly influences subsequent vegetative development, flowering, and long-term yield performance (Yarra, R., Jin, L., Zhao, Z., & Cao, H. (2019; Woittiez, L. S., van Wijk, M. T., Slingerland, M., van Noordwijk, M., & Giller, K. E. (2017); Wei, L., Martin, J. J. J., Zhang, H., Zhang, R., & Cao, H. (2021).

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Despite its economic importance, commercial propagation of oil palm remains constrained by prolonged and non-uniform seed germination. Oil palm seeds exhibit a complex dormancy mechanism involving both physical and physiological components. The rigid endocarp restricts oxygen diffusion and water movement, whereas physiological dormancy is regulated by hormonal balance, embryo development, and metabolic activation. Under natural conditions, germination may require several months, resulting in delayed nursery operations, heterogeneous seedling populations, and increased production costs (Backer, R., et al. (2018); Bewley, J. D., Bradford, K., Hilhorst, H., & Nonogaki, H. (2013); Cui, J., Lamade, E., & Tcherkez, G. (2020). These limitations continue to represent one of the principal bottlenecks in commercial oil palm seedling production worldwide. Recent transcriptomic studies further demonstrate that dormancy release is accompanied by coordinated changes in abscisic acid degradation, carbohydrate mobilization, starch metabolism, and cell elongation pathways, highlighting the complexity of the germination process (Backer, R., et al. (2018); Bhardwaj, D., et al. (2014); Bewley, J. D., Bradford, K., Hilhorst, H., & Nonogaki, H. (2013).

Various dormancy-breaking techniques have therefore been developed to accelerate germination and improve seedling uniformity (Cui, J., Lamade, E., & Tcherkez, G. (2020); Nonogaki, H. (2019). Seed germination and dormancy. Conventional approaches include prolonged dry-heat treatment, scarification, embryo excision, and the application of synthetic plant growth regulators such as gibberellic acid (GA_3). Among these methods, controlled heat treatment at approximately 38-40°C remains the most widely adopted commercial practice because it effectively reduces dormancy and increases germination percentage. Nevertheless, these techniques generally require specialized facilities, long incubation periods, high energy consumption, and intensive management. Moreover, increasing global interest in environmentally sustainable agriculture has stimulated the search for biological alternatives capable of reducing dependence on synthetic growth regulators while maintaining high germination performance.

Although coconut water and eco-enzyme have each been investigated as natural biostimulants in various crop species, studies evaluating their combined application for oil palm seed priming remain extremely limited. Previous research has primarily focused on their independent effects or on conventional dormancy-breaking techniques such as heat treatment and synthetic plant growth regulators. Consequently, it remains unclear whether the hormonal compounds present in coconut water can complement the enzymatic activity and bioactive metabolites supplied by eco-enzyme during dormancy release and early seedling establishment. Addressing this knowledge gap is essential for developing environmentally sustainable seed-priming technologies capable of improving nursery efficiency while reducing reliance on synthetic chemical inputs (Ibrahim, E. A. (2016); Ngin Tan S., J.W.H.Yong, Liya Ge, 2014; Neupane, K. dan Khadka, R., (2019); Paparella, S., Araújo, S. S., Rossi, G., Wijayasinghe, M., Carbonera, D., & Balestrazzi, A. (2015). The application of natural biostimulants during seed priming has recently attracted increasing attention because bioactive compounds may simultaneously regulate hormonal signaling, nutrient utilization, and metabolic processes involved in early plant development (Nonogaki, H. (2019). Among natural biostimulants, coconut water represents an abundant and inexpensive biological resource widely available throughout tropical regions. Coconut water naturally contains cytokinins, auxins, gibberellins, amino acids, soluble carbohydrates, vitamins, antioxidants, and essential mineral nutrients (Prades, A., Dornier, M., Diop, N., & Pain, J. P. (2012). These compounds collectively stimulate cell division, promote embryo growth, enhance enzymatic activity, and facilitate reserve mobilization during seed germination. Previous studies on several horticultural and plantation crops have consistently demonstrated positive effects of coconut water on germination, rooting, vegetative growth, and biomass accumulation. However, its physiological potential for improving dormancy release in oil palm seeds remains insufficiently explored, particularly when integrated with other natural biostimulants.

Another promising biological input is eco-enzyme, a fermentation product obtained from organic fruit and vegetable residues. Besides contributing to organic waste recycling, eco-enzyme contains diverse hydrolytic enzymes, low-molecular-weight organic acids, beneficial microbial metabolites, and soluble mineral nutrients capable of stimulating plant physiological activity (Vama, L., & Cherekar, M. N., (2020). These bioactive constituents may facilitate hydrolysis of stored seed reserves, improve nutrient availability, enhance microbial interactions in the rhizosphere, and promote early seedling establishment (Vama, L., & Cherekar, M. N. 2020; Neupane, K. dan R. Khadka, (2019); Wojtyla, Ł., Lechowska, K., Kubala, S., & Garnczarska, M. (2016). Consequently, eco-enzyme has recently gained attention as an environmentally friendly agricultural input supporting sustainable crop production and circular bioeconomy. Nevertheless, scientific evidence regarding its physiological effects on seed dormancy and germination remains relatively limited compared with conventional plant growth regulators.

The concept of plant biostimulants has evolved considerably during the past decade. Rather than acting solely as nutrient sources or fertilizers, plant biostimulants enhance intrinsic physiological processes that improve nutrient use efficiency, stress tolerance, crop quality, and overall plant productivity. Because coconut water supplies naturally occurring phytohormones whereas eco-enzyme contributes fermentation-derived enzymes and metabolites, simultaneous application of both materials may provide complementary mechanisms during dormancy release and early seedling development (Yong, J. W. H., Ge, L., Ng, Y. F., & Tan, S.

N. (2009). Such integration represents an environmentally sustainable strategy consistent with current efforts to reduce synthetic chemical inputs while improving nursery efficiency.

Although numerous studies have independently investigated coconut water, eco-enzyme, heat treatment, or synthetic plant growth regulators for enhancing seed germination, information regarding the combined application of coconut water and eco-enzyme as natural seed-priming agents for oil palm remains scarce. To date, little is known about whether hormonal stimulation supplied by coconut water can complement the enzymatic and nutritional functions provided by eco-enzyme during dormancy release and subsequent seedling establishment. This knowledge gap limits the development of integrated, biologically based seed-priming technologies for commercial oil palm nurseries (Yarra, R., Jin, L., Zhao, Z., & Cao, H. (2019); Woittiez, L. S., van Wijk, M. T., Slingerland, M., van Noordwijk, M., & Giller, K. E. (2017); Yong *et al*. (2009).

To the best of our knowledge, this study is among the first to investigate the combined use of coconut water and eco-enzyme as natural seed-priming biostimulants for improving dormancy release and early seedling vigor in oil palm. Unlike previous studies that evaluated these materials separately, the present work integrates two renewable biological resources into a single priming strategy and provides new evidence regarding their complementary physiological roles during germination and early vegetative development.

Accordingly, this study aimed to evaluate the individual and combined effects of coconut water and eco-enzyme concentrations on dormancy release, germination performance, and early seedling growth of oil palm (*Elaeis guineensis* Jacq.). We hypothesized that combining both natural biostimulants would produce complementary physiological effects that enhance seed vigor and improve early seedling establishment compared with the application of either biostimulant alone.

Unlike previous studies that investigated coconut water or eco-enzyme separately, this study is the first to evaluate their combined application as natural seed-priming biostimulants for improving dormancy release and early seedling vigor in oil palm.

MATERIALS AND METHODS

Study Site

The experiment was conducted from November 2023-January 2024 at the Experimental Farm and Plant Physiology Laboratory, Faculty of Agriculture, The Methodist University of Indonesia, Medan, North Sumatra, Indonesia. The experimental site is located at approximately 3°35′ N latitude and 98°40′ E longitude, with an elevation of approximately 25 m above sea level. During the experimental period, the average air temperature ranged from 27 to 32°C, while relative humidity varied between 70% and 85%, providing environmental conditions suitable for oil palm seed germination and early seedling establishment. All experimental units were maintained under uniform nursery conditions to minimize environmental variation throughout the study.

Plant Materials

Uniform mature oil palm (*Elaeis guineensis* Jacq.) seeds with good physical quality and without visible mechanical damage were used as experimental materials. Prior to treatment, all seeds were visually inspected to eliminate damaged, cracked, malformed, or diseased seeds, thereby ensuring uniformity of the experimental units.

Fresh coconut water obtained from physiologically mature green coconuts was used as the natural phytohormone source. The coconut water was filtered through sterile muslin cloth immediately after extraction to remove suspended particles before preparing the treatment solutions. Eco-enzyme solution was prepared from fermented fruit and vegetable residues following standard fermentation procedures. The fermented solution was filtered prior to use to obtain a homogeneous liquid suitable for seed priming.

Experimental Design

The experiment employed a factorial Completely Randomized Design (CRD) consisting of two experimental factors.

The first factor was coconut water concentration:

- K1 = 250 mL L^{-1} water
- K2 = 500 mL L^{-1} water
- K3 = 750 mL L^{-1} water

The second factor was eco-enzyme concentration:

- E1 = 50 mL L^{-1} water
- E2 = 100 mL L^{-1} water
- E3 = 150 mL L^{-1} water

The combination of both factors generated nine treatment combinations. Each treatment was replicated three times according to the experimental design used in this study. Experimental units were arranged randomly to minimize positional effects and environmental bias. Seeds were soaked for 30 minutes at room temperature using the treatment solutions. Each experimental unit

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consisted of three oil palm sprouts. This experiment was designed to compare different concentrations of natural biostimulants rather than to compare treated and untreated seeds. Because commercially pre-germinated oil palm sprouts are relatively expensive, an untreated control could not be included and this should be considered when interpreting the results.

Coconut water

The coconut water used for seed priming was obtained from young green coconuts aged 6–7 months, as recommended by previous studies due to their relatively high cytokinin and auxin contents. Fresh coconut water was collected immediately after opening the fruits to minimize oxidation and microbial contamination. Prior to use, the coconut water was filtered through a sterile membrane filter with a pore size of 0.22-0.45 μm to remove suspended particles and reduce microbial contamination before preparing the treatment solutions.

Eco-enzyme

The eco-enzyme used in this study was prepared according to procedures described in previous studies. Based on these reports, a high-quality eco-enzyme is produced using brown sugar (palm sugar, coconut sugar, or molasses), fresh organic waste consisting of vegetable scraps or fruit peels, and water (well water, rainwater, or tap water that has been left to stand overnight to allow chlorine to dissipate). The ingredients are mixed at a ratio of 1:3:10 (sugar : organic waste : water) and fermented for 90 days. The resulting eco-enzyme typically has a pH of approximately 4.0 and is characterized as a dark brown to yellowish-brown liquid with a fresh vinegar-like aroma.

Seed Priming Procedure

Seed priming was performed before sowing by immersing oil palm seeds in the respective treatment solutions according to each treatment combination. Fresh treatment solutions were prepared immediately before use. Following priming, the seeds were removed from the solution, surface-dried under room temperature until free surface moisture disappeared, and immediately sown in the nursery medium. The priming treatment was intended to initiate controlled metabolic activation during imbibition without allowing radicle protrusion prior to planting. Seeds were soaked for 30 minutes at room temperature in treatment solutions of the designated concentrations. The volume of each solution was sufficient to ensure that all seeds were completely submerged throughout the priming period.

Nursery Management

Primed seeds were sown individually in polybags containing a nursery medium prepared according to standard oil palm pre-nursery practices.

Throughout the experiment, all seedlings received identical management practices including irrigation, weed control, and sanitation. Watering was performed regularly to maintain adequate soil moisture while avoiding waterlogging. No additional plant growth regulators were applied during the observation period to ensure that plant responses resulted exclusively from the experimental treatments.

Observation Variables

Germination Percentage. Seed germination percentage was determined as the proportion of germinated seeds relative to the total number of seeds sown and expressed as a percentage. A seed was considered germinated when the radicle had visibly emerged from the seed coat.

Mean Germination Time

Mean germination time (MGT) was calculated to evaluate the speed of germination. Lower MGT values indicated faster dormancy release and greater physiological seed vigor.

Seedling Height

Seedling height (cm) was measured from the collar region to the tip of the youngest fully expanded leaf using a graduated ruler.

Measurements were conducted periodically until eight weeks after planting.

Number of Leaves

Leaf number was determined by counting fully expanded functional leaves present on each seedling. Only healthy leaves that had completely unfolded were included in the observations.

Stem Diameter

Stem diameter (cm) was measured at the basal stem using a digital caliper with an accuracy of 0.01 mm. Measurements were conducted at the same developmental stage for all seedlings.

Statistical Analysis

All experimental data were subjected to analysis of variance (ANOVA) appropriate for a factorial Completely Randomized Design.Prior to ANOVA, the assumptions of normality and homogeneity of variance were evaluated to ensure the validity of parametric statistical analysis. Whenever significant treatment effects were detected ($P < 0.05$), treatment means were separated using Duncan's Multiple Range Test (DMRT) at the 5% probability level. Regression analysis was additionally performed to describe the response patterns of coconut water and eco-enzyme concentrations for each measured variable and to identify concentration-response trends. Statistical analyses were performed using appropriate statistical software.

Scientific Rationale of the Treatments. The concentration ranges of coconut water and eco-enzyme were selected based on preliminary observations and previous studies indicating that moderate concentrations provide sufficient bioactive compounds without causing osmotic stress or physiological inhibition during seed imbibition. Coconut water primarily supplies endogenous phytohormones, including cytokinins, auxins, and gibberellins, together with soluble carbohydrates, amino acids, vitamins, and mineral nutrients. In contrast, eco-enzyme contributes hydrolytic enzymes, fermentation-derived organic acids, microbial metabolites, and readily available nutrients that may enhance reserve mobilization and early seedling metabolism. The combined application of both natural biostimulants was therefore expected to promote complementary physiological mechanisms during dormancy release and early seedling establishment.

RESULTS AND DISCUSSION

Germination Percentage and Mean Germination Time.

The mean values are presented in Table 1. The results showed that soaking treatments with coconut water and eco-enzyme significantly affected the germination age (days) of oil palm seeds (Table 2), whereas the interaction between the two treatments was not significant.

The analysis of variance demonstrated that both coconut water and eco-enzyme significantly improved the germination performance of oil palm seeds. Increasing concentrations of coconut water consistently enhanced germination percentage, with the highest response obtained at 750 mL L^{-1}. Likewise, eco-enzyme application significantly increased germination percentage, with the highest value recorded at 150 mL L^{-1}. These findings indicate that both natural biostimulants independently promoted dormancy release and improved seed viability during the germination process (Vama, L., & Cherekar, M. N. 2020; Prades, A., Dornier, M., Diop, N., & Pain, J. P. (2012); Ngin Tan S., J.W.H.Yong, Liya Ge, 2014; Cui, J., Lamade, E., & Tcherkez, G. (2020).

The improved germination percentage observed in this study suggests that seed priming successfully activated physiological processes before radicle emergence. Coconut water increased the germination rate by 18.52% compared with the lowest concentration. This response was described by the regression equation $\hat{Y} = 65.43 + 0.04K$ ($R^2 = 0.98$). Likewise, eco-enzyme increased the germination rate by 25.93%, as described by the regression equation $\hat{Y} = 58.02 + 0.26E$ ($R^2 = 0.98$).

The availability of bioactive compounds supplied by coconut water and eco-enzyme likely accelerated these metabolic events, enabling a greater proportion of seeds to complete germination successfully (Paparella, S., Araújo, S. S., Rossi, G., Wijayasinghe, M., Carbonera, D., & Balestrazzi, A. (2015); Prades, A., Dornier, M., Diop, N., & Pain, J. P. (2012); Vama, L., & Cherekar, M. N., 2020.

The mean germination time (days) of oil palm seeds as affected by coconut water and eco-enzyme concentrations is presented in Table 2.

The superior performance of coconut water is probably associated with its naturally occurring phytohormones, particularly gibberellins, cytokinins, and auxins. These hormones are known to regulate several critical physiological processes during germination. Gibberellins stimulate the production of hydrolytic enzymes, especially α-amylase, which converts starch reserves into soluble sugars that are readily utilized during respiration. Increased carbohydrate availability provides sufficient energy for embryo elongation and radicle protrusion, thereby improving both germination percentage and seed vigor (Yong, J. W. H., Ge, L., Ng, Y. F., & Tan, S. N. (2009); Wojtyla, Ł., Lechowska, K., Kubala, S., & Garnczarska, M. (2016); Ngin Tan S., J.W.H.Yong, Liya Ge, 2014.

Table 1. Average Germination Percentage of Oil Palm Seeds under Coconut Water and Eco-Enzyme Treatments

Treatment	Germination Rate (%)
K_1	74,07b
K_2	85,19a
K_3	92,59a
E_1	70,37c

E_2	85,19b
E_3	96,30a
K_1E_1	66,67
K_1E_2	66,67
K_1E_3	88,89
K_2E_1	66,67
K_2E_2	88,89
K_2E_3	100,00
K_3E_1	77,78
K_3E_2	100,00
K_3E_3	100,00

Note: Means followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level.

Besides hormonal regulation, coconut water also supplies amino acids, simple sugars, vitamins, and mineral nutrients that may support the resumption of cellular metabolism after seed hydration (Vama, L., & Cherekar, M. N. 2020; Wei, L., Martin, J. J. J., Zhang, H., Zhang, R., & Cao, H. (2021); Woittiez, L. S., van Wijk, M. T., Slingerland, M., van Noordwijk, M., & Giller, K. E. (2017); Wojtyla, Ł., Lechowska, K., Kubala, S., & Garnczarska, M. (2016). These compounds contribute to protein synthesis, ATP production, and cell division, allowing embryos to resume active growth more rapidly. Consequently, higher concentrations of coconut water produced a greater proportion of normal seedlings and a shorter mean germination time within the observation period, as described by the regression equation $\hat{Y} = 13.44 - 0.0007K$ ($R^2 = 0.98$).

Table 2. Mean Germination Time (days) of Oil Palm Seeds as Affected by Coconut Water and Eco-Enzyme Concentrations

Treatment	Germination Time (days)
K_1	13,26a
K_2	13,07ab
K_3	12,89b
E_1	13,44a
E_2	13,22a
E_3	12,56b
K_1E_1	13,50
K_1E_2	13,50
K_1E_3	12,78
K_2E_1	13,50
K_2E_2	13,17
K_2E_3	12,56
K_3E_1	13,33
K_3E_2	13,00
K_3E_3	12,33

Note: Means followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level.

Eco-enzyme also contributed positively to seed germination through a different physiological pathway. Unlike coconut water, which primarily acts through hormonal regulation, eco-enzyme contains fermentation-derived organic compounds, hydrolytic enzymes, and soluble nutrients that may enhance reserve mobilization during the initial stages of germination. The presence of organic acids may facilitate nutrient solubilization, while enzymatic components potentially accelerate the degradation of complex storage compounds into simpler molecules that can be utilized immediately by the developing embryo (Vama, L., & Cherekar, M. N. 2020; Neupane, K. dan R. Khadka, 2019; Cui, J., Lamade, E., & Tcherkez, G. (2020). Increasing eco-enzyme concentration significantly reduced the mean germination time of oil palm seeds, following the negative linear regression equation $\hat{Y} = 13.95 - 0.009E$ ($R^2 = 0.92$). Based on this equation, each 50 mL L^{-1} increase in eco-enzyme concentration shortened the mean germination time by approximately 0.45 days.

Interestingly, no significant interaction between coconut water and eco-enzyme was observed for germination percentage. This finding indicates that each treatment independently enhanced seed physiological activity without producing additional synergistic effects during the earliest phase of germination.

From a physiological perspective, shorter germination time indicates higher seed vigor rather than merely faster emergence. Vigorous seeds generally exhibit more efficient metabolic activation, better membrane repair, and greater capacity to utilize stored food reserves. Consequently, accelerated germination often represents one of the earliest indicators of improved seed quality following priming treatments (Ibrahim, E. A. (2016); Paparella, S., Araújo, S. S., Rossi, G., Wijayasinghe, M., Carbonera, D., & Balestrazzi, A. (2015); . Yarra, R., Jin, L., Zhao, Z., & Cao, H. (2019); Yong, J. W. H., Ge, L., Ng, Y. F., & Tan, S. N. (2009).

Overall, the present findings demonstrate that both coconut water and eco-enzyme effectively enhanced dormancy release and accelerated germination through complementary physiological mechanisms. Coconut water primarily promoted hormonal regulation and embryo activation, whereas eco-enzyme appeared to facilitate metabolic readiness through enzymatic activity and improved biochemical conditions during imbibition. Although both treatments acted independently during germination, their combined application provides a promising biological alternative to conventional chemical growth regulators for improving oil palm seed propagation.

Seedling Height

Seedling height was significantly influenced by both coconut water and eco-enzyme concentrations throughout the observation period. Moreover, unlike the other growth variables, a significant interaction between both treatments was observed, indicating that the response of seedling height depended on the combination of coconut water and eco-enzyme applied.

The interaction effect suggests complementary physiological functions of both biostimulants during early vegetative growth. Coconut water primarily supplied endogenous plant growth regulators, whereas eco-enzyme likely improved nutrient availability and metabolic activity, resulting in greater seedling elongation when both treatments were combined.

Increased seedling height indicates that coconut water remained physiologically active beyond the germination stage and continued to influence cell division and cell elongation during early seedling development (Table 3).

A significant interaction between coconut water and eco-enzyme was observed only for seedling height (Figure1 1). The regression equations are as follows:

K_1 : $\hat{Y} = 14.02 + 0.03\ E$; $R^2 = 0.98$

K_2 : $\hat{Y} = 16.60 + 0.01\ E$; $R^2 = 0.98$

K_3 : $\hat{Y} = 17.30 + 0.01\ E$; $R^2 = 0.94$

Stem elongation requires coordinated regulation of cell division, cell expansion, carbohydrate availability, and nutrient transport. Consequently, simultaneous improvement in hormonal signaling and metabolic support may generate greater responses than either treatment alone (Vama, L., & Cherekar, M. N. 2020; Yong et al. (2009); Prades, A., Dornier, M., Diop, N., & Pain, J. P. (2012).

Table 3. Mean Height of Oil Palm Seedlings (cm) as Affected by Coconut Water and Eco-Enzyme Concentrations at 2, 4, 6, and 8 Weeks After Planting

Treatment	Height of Oil Palm Seedlings (cm)			
	2 WAP	4 WAP	6 WAP	8 WAP
K_1	8,03c	13,08c	14,92c	17,02c
K_2	8,15b	13,98b	15,85b	18,08b
K_3	8,44a	14,46a	16,39a	18,73a
E_1	7,87c	13,05c	14,85c	16,92c
E_2	8,24b	13,83b	15,73b	18,03b
E_3	8,51a	14,65a	16,58a	18,88a
K_1E_1	7,65	11,77f	13,57f	15,47e
K_1E_2	8,10	13,12e	14,92e	17,12d
K_1E_3	8,33	14,37abc	16,27bc	18,47bc
K_2E_1	7,78	13,45de	15,25de	17,35d
K_2E_2	8,23	13,87cd	15,77cd	18,07c
K_2E_3	8,43	14,63a	16,53ab	18,83ab

K_3E_1	8,18	13,93bcd	15,73cd	17,93c
K_3E_2	8,38	14,50ab	16,50ab	18,90ab
K_3E_3	8,75	14,95a	16,95a	19,35a

Note: Means followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level.

From an agronomic perspective, these findings indicate that coconut water and eco-enzyme may be incorporated into environmentally friendly seed priming strategies for oil palm propagation. Their use reduces dependence on synthetic growth regulators while promoting sustainable nursery management through utilization of renewable biological resources. Such an approach is particularly relevant for modern oil palm production systems that increasingly emphasize sustainable agricultural practices and reduced chemical inputs.

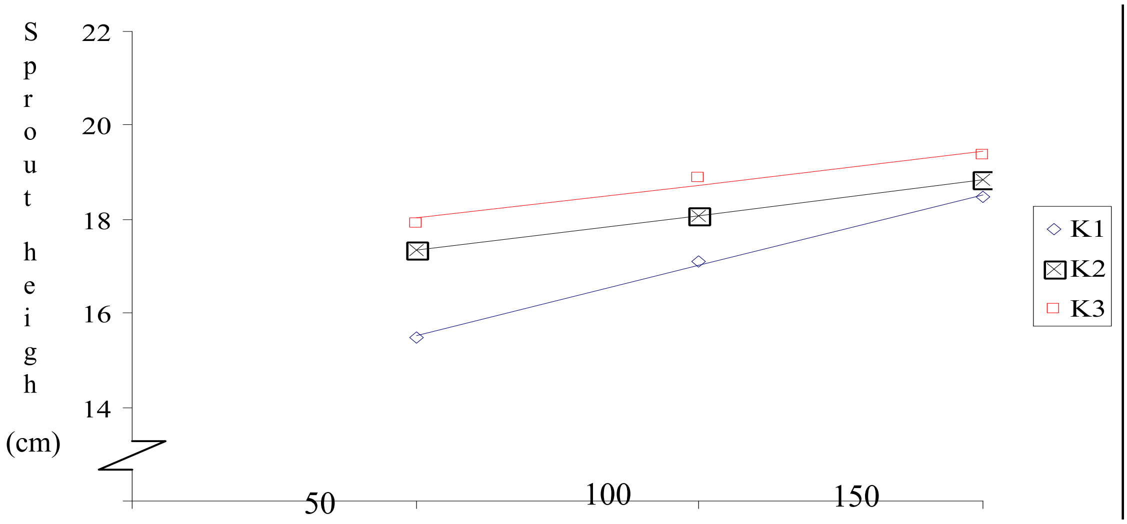

Figure 1. Interaction Effect of Coconut Water and Eco-enzyme Concentration on Oil Palm Sprout Height at 8 Weeks After Planting.

Leaf Number

Both main factors significantly affected leaf formation throughout the experimental period, whereas their interaction remained non-significant. Seedlings treated with 750 mL L^{-1} coconut water produced the highest number of leaves at eight weeks after planting, averaging 2.22 leaves, compared with 1.83 leaves under the lowest concentration. Similarly, eco-enzyme application at 150 mL L^{-1} resulted in the highest leaf production (2.28 leaves), exceeding that observed under lower concentrations.

Regression analysis further demonstrated positive linear relationships between increasing concentrations of both biostimulants and leaf number, indicating that leaf development responded proportionally within the concentration range evaluated. For coconut water, the regression equation was $\hat{Y} = 1.65 + 0.0008K$ ($R^2 = 0.98$), whereas for eco-enzyme, the regression equation was $\hat{Y} = 1.48 + 0.005E$ ($R^2 = 0.94$).

This response is closely associated with the hormonal composition of coconut water. Cytokinins stimulate mitotic activity within the shoot apical meristem, resulting in increased production of new cells. Auxins promote cell elongation and vascular differentiation, whereas gibberellins stimulate internode elongation through increased cell expansion. The combined action of these endogenous hormones likely contributed to the superior shoot growth observed in the present study.

Table 4. Mean Number of Leaves of Oil Palm Seedlings as Affected by Coconut Water and Eco-Enzyme Concentrations at 2, 4, 6, and 8 WAP

Treatment	Number of Leaves			
	2 WAP	4 WAP	6 WAP	8 WAP
K_1	1,22b	1,50b	1,67b	1,83c
K_2	1,28b	1,61b	1,83a	2,06b
K_3	1,56a	1,78a	1,89a	2,22a
E_1	1,00c	1,11c	1,44b	1,72c
E_2	1,33b	1,78b	1,94a	2,11b
E_3	1,72a	2,00a	2,00a	2,28a
K_1E_1	1,00	1,00	1,17	1,50
K_1E_2	1,17	1,50	1,83	2,00
K_1E_3	1,50	2,00	2,00	2,00
K_2E_1	1,00	1,00	1,50	1,67
K_2E_2	1,17	1,83	2,00	2,17
K_2E_3	1,67	2,00	2,00	2,33
K_3E_1	1,00	1,33	1,67	2,00
K_3E_2	1,67	2,00	2,00	2,17
K_3E_3	2,00	2,00	2,00	2,50

Note: Means followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level.

Unlike seedling height, leaf number and stem diameter responded independently to both treatments. This observation suggests that leaf initiation and stem thickening are regulated by developmental processes that are less dependent on synergistic hormonal interactions. Instead, both coconut water and eco-enzyme individually provided sufficient physiological stimulation to improve vegetative performance.

Stem Diameter

Stem diameter responded significantly to increasing concentrations of coconut water and eco-enzyme throughout the observation period. However, no significant interaction between both factors was detected. The largest stem diameter was obtained at 750 mL L^{-1} coconut water (0.40 cm) and 150 mL L^{-1} eco-enzyme (0.41 cm) (Table 5).

Linear regression analysis revealed a positive relationship between treatment concentration and stem diameter, indicating continuous improvement in stem thickening with increasing concentrations of both natural biostimulants within the tested range. For coconut water, the regression equation was $\hat{Y} = 0.36 + 0.00006\ K$ ($R^2 = 0.96$), whereas for eco-enzyme, the regression equation was $\hat{Y} = 0.34 + 0.0005E$ ($R^2 = 0.98$).

Overall, both treatments consistently enhanced vegetative growth characteristics, demonstrating their effectiveness in improving early seedling vigor of oil palm.

Leaf production represents one of the most important indicators of seedling quality because leaves constitute the principal photosynthetic organs responsible for carbohydrate production. Increased leaf number enlarges the photosynthetically active surface, thereby improving assimilate production for subsequent plant growth. Consequently, seedlings possessing more leaves generally accumulate greater biomass and exhibit stronger field establishment after transplanting.

The positive linear responses observed across treatment concentrations suggest that neither coconut water nor eco-enzyme produced inhibitory effects within the concentration ranges evaluated. Instead, increasing concentrations continuously enhanced vegetative growth, indicating that the selected treatment range remained within the beneficial physiological threshold for oil palm seedlings.

From a practical perspective, vigorous seedlings possessing greater height, more leaves, and larger stem diameter are highly desirable in commercial nurseries because these characteristics are closely associated with successful field establishment and long-term plantation performance. The use of coconut water and eco-enzyme therefore offers considerable potential as environmentally friendly biostimulants capable of improving both biological quality and production efficiency (Vama, L., & Cherekar, M. N. (2020); Bewley, J. D., Bradford, K., Hilhorst, H., & Nonogaki, H. (2013); Cui, J., Lamade, E., & Tcherkez, G. (2020); Ngin Tan S., J.W.H.Yong, Liya Ge (2014).

Taken together, these results indicate that coconut water and eco-enzyme function through complementary physiological pathways. Coconut water predominantly enhances hormonal regulation and developmental signaling, whereas eco-enzyme supports metabolic activation and nutrient utilization. Their combined application therefore represents a promising seed-priming strategy for producing vigorous oil palm seedlings while reducing dependence on synthetic plant growth regulators.

Table 5. Mean Stem Diameter (cm) of Oil Palm Seedlings as Affected by Coconut Water and Eco-Enzyme Concentrations at 2, 4, 6, and 8 WAP

Treatment	Stem Diameter (cm)			
	2 WAP	4 WAP	6 WAP	8 WAP
K_1	0,26b	0,32b	0,34c	0,37c
K_2	0,27b	0,33b	0,36b	0,39b
K_3	0,29a	0,35a	0,37a	0,40a
E_1	0,26c	0,31c	0,33c	0,36c
E_2	0,27b	0,33b	0,36b	0,39b
E_3	0,29a	0,36a	0,38a	0,41a
K_1E_1	0,24	0,30	0,32	0,35
K_1E_2	0,26	0,32	0,34	0,37
K_1E_3	0,28	0,34	0,36	0,39
K_2E_1	0,25	0,31	0,33	0,36
K_2E_2	0,27	0,33	0,36	0,39
K_2E_3	0,29	0,36	0,38	0,41
K_3E_1	0,28	0,34	0,36	0,39
K_3E_2	0,29	0,35	0,37	0,40
K_3E_3	0,30	0,37	0,40	0,43

Note: Means followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level.

Limitations of this study include the use of only one oil palm variety, evaluation only at the nursery stage, the absence of field performance assessment, and the lack of measurements of endogenous hormone levels and α-amylase activity.

PRACTICAL IMPLICATIONS FOR SUSTAINABLE OIL PALM NURSERY

The practical significance of this study extends beyond improving germination performance under experimental conditions. Uniform and rapid germination is one of the most important determinants of successful oil palm nursery management because it directly affects seedling quality, nursery duration, labor efficiency, and production costs.

Application of coconut water at 750 mL L^{-1} together with eco-enzyme at 150 mL L^{-1} offers a simple, low-cost, and environmentally friendly priming strategy that may improve nursery efficiency without increasing dependence on synthetic growth regulators. The use of renewable natural resources may also reduce production costs in regions where coconut water and organic wastes are readily available.

From a sustainability perspective, eco-enzyme utilization contributes to organic waste recycling and supports circular agricultural systems. Instead of being discarded as household waste, fruit residues can be converted into value-added agricultural biostimulants. Such an approach simultaneously addresses environmental concerns and improves agricultural productivity, thereby contributing to sustainable oil palm cultivation.

Moreover, stronger early seedling growth may increase field establishment success following transplantation. Seedlings possessing greater stem diameter, more leaves, and vigorous root systems generally exhibit higher survival rates and improved adaptation after planting. Therefore, integrating natural seed priming into commercial nursery practices has the potential to improve both biological performance and economic efficiency.

STATEMENT ON THE USE OFARTIFICIAL INTELLIGENCE.

In writing this article, the author used artificial intelligence-based tools in a limited and responsible manner, solely to assist with grammar checking and editorial clarity. All scientific content, including the formulation of the research problem, conceptual framework, research design, data collection and analysis, interpretation of results, and conclusions, is entirely the result of the author's own thinking, analysis, and academic responsibility.

CONCLUSION

Natural seed priming using coconut water and eco-enzyme effectively enhanced dormancy breaking and early seedling growth of oil palm. Coconut water primarily promoted germination through hormonal stimulation and activation of physiological metabolism, whereas eco-enzyme improved metabolic activity through enzymatic processes and increased nutrient availability. Although both biostimulants independently enhanced most growth variables, their interaction significantly promoted seedling height, indicating complementary physiological functions during early vegetative development.

These findings demonstrate that natural biostimulants represent a promising alternative to synthetic growth regulators for oil palm seed propagation. Beyond improving germination and seedling vigor, the combined utilization of coconut water and eco-enzyme supports environmentally sustainable nursery management through the use of renewable biological resources and organic waste valorization.

Future studies should investigate the biochemical mechanisms underlying seed priming responses, including hormonal dynamics, antioxidant activity, enzyme regulation, and gene expression associated with dormancy release. Evaluation under field nursery conditions and economic feasibility analyses are also recommended to facilitate wider adoption in commercial oil palm production systems.

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