

Optimizing automatic irrigation volume and duration for pre-nursery oil palm seedlings (*Elaeis guineensis* Jacq.)

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ABSTRACT

Manual irrigation in oil palm pre-nurseries often results in uneven water distribution and inconsistent water volume, which may constrain early seedling growth. This study evaluated the effects of automatic irrigation volume and duration on the vegetative growth of oil palm (*Elaeis guineensis* Jacq.) seedlings in a pre-nursery system. The experiment was conducted in a greenhouse at the Indonesian Oil Palm Technology Institute (ITSI), Medan, from February to May 2025. A factorial completely randomized design was used, consisting of three irrigation volumes (200, 400, and 600 mL per plant per day) and three irrigation durations (20, 30, and 40 min per day), with four replications. A total of 72 D × P Simalungun seedlings were observed for plant height, stem diameter, root length, wet root weight, wet crown weight, dry root weight, and dry crown weight. Data were analyzed using ANOVA followed by Duncan's Multiple Range Test at the 5% level. The results showed that irrigation volume significantly affected shoot dry weight, with 600 mL per plant per day producing the highest mean value. Irrigation duration significantly affected plant height at 8 weeks after planting, as well as root fresh weight, root dry weight, and shoot dry weight at 12 weeks after planting. The 30 min per day duration consistently produced the highest values for plant height (15.16 cm), root fresh weight (1.32 g), dry weight of roots (0.42 g), and Dry Crown Weight (0.89 g). No significant interaction was found between irrigation volume and duration for all observed variables. These findings indicate that irrigation duration is a key factor in automatic irrigation management, and 30 min per day may support more balanced early growth of oil palm seedlings under greenhouse pre-nursery conditions.

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1. INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq) is a plantation crop that produces vegetable oil in Indonesia (Irham et al., 2023). The development of the palm oil industry in Indonesia can be observed from the growth in the area of land used for cultivation. Based on data released by the Directorate General of Plantations (2023), the area of palm oil plantations increased from 14,326,350 ha in 2018 to 16,833,985 ha in 2023. The increase in the area of palm oil plantations requires large

quantities of quality planting materials (Direktorat Jenderal Statistik Perkebunan Kementerian Pertanian Republik Indonesia, 2023).

In the palm oil growth process, seedling quality has a major impact on final productivity. High-quality palm oil seedlings are characterized by optimal vegetative growth and the ability to adapt to diverse environmental conditions. The seedling process needs to be prepared at least one year before planting. One of the main factors affecting seedling quality is the selection of seed varieties, as well as careful care and selection. In seedling maintenance efforts, fertilization and watering play an important role in supporting optimal growth (Sinaga et al., 2023).

Oil palm is one type of plant that requires a large amount of water. In the early stages of oil palm nursery (pre-nursery), water requirements range from 500 to 800 ml per day. Water availability is one of the main limiting factors in oil palm growth. Water deficiency in the growing medium can disrupt the vegetative growth of plants and even potentially cause death (Wagino et al., 2018).

The availability of water in the soil is influenced by various factors, including the amount of rainfall or irrigation water, the soil's ability to retain water, the rate of evapotranspiration (direct evaporation from the soil and through vegetation), the water table level, the organic matter content in the soil, the chemical compound or salt content -salts, and the depth of the soil layer or soil solum (Maharany et al., 2020).

Irrigation management in nurseries is not only related to the total volume of water applied, but also to the duration and uniformity of application. Manual watering is practical for small-scale nurseries, yet it often produces uneven distribution because the delivered volume depends on operator consistency, hose position, and watering time. Automatic irrigation can reduce this variability by controlling both the daily amount and the operating duration, thereby improving the repeatability of water application across seedlings (Darmawan et al., 2022; Fulcher et al., 2012).

Previous studies on oil palm seedlings have shown that water stress affects seedling growth, physiology, and biochemical responses, while studies on nursery irrigation more broadly emphasize that precise scheduling can improve water use efficiency and reduce unnecessary leaching (Knight et al., 2019; Pradiko et al., 2025). Watering during the seedling phase is still often done manually, but this method is ineffective because watering is uneven, resulting in inaccurate water doses that can inhibit vegetative growth (Sukmawan & Riniarti, 2020). Automatic irrigation is the solution needed because it can regulate irrigation times so that water doses are tailored to the needs of the plants.

Based on the above description, the purpose of this study is to determine the effect of dosage and timing of automatic irrigation on the vegetative growth of oil palm seedlings in the Pre Nursery.

2. METHOD

2.1. Place and Time of Research

This research was conducted in two greenhouses at the Indonesian Palm Oil Institute campus in Medan. The research was conducted over a period of three months, from February to May 2025. Environmental conditions were kept comparable among treatments by placing all experimental units in the same greenhouse setting and rotating the position of seedlings periodically. These procedures minimized microclimatic variation among treatments, although temperature and relative humidity were not treated as experimental factors. The greenhouse microclimate was recorded throughout the experiment using a thermo-hygrometer/data logger. Air temperature and relative humidity were monitored daily in the morning, afternoon, and late afternoon. During the experiment, the greenhouse condition was targeted to remain within the tropical nursery range of 27–32°C and 70–85% relative humidity.

2.2. Tools and Materials

The equipment used in this study consisted of three digital timer sockets, nine Hikari Hk P 103 aquarium water pumps, nine PVC (polyvinyl chloride) pipes, each 1.5 meters long, a 10-meter connector, 90 meters of aerator hose, a total of 72 emitters, a total of 3 water containers, a total of 72 baby bags, 1 measuring cup, 1 analytical scale, a 10-meter measuring tape, and 1 caliper. The materials used in this study were D×P Simalungun variety oil palm seedlings, totaling 72 seeds, 72 kg of topsoil, clean water, 16 g of 15-15-6-4 NPK fertilizer, and 16 g of urea fertilizer.

The topsoil was homogenized before use, and coarse roots, stones, and plant residues were removed to reduce variation among nursery bags. Each baby bag was filled with an equal mass of growing medium to maintain comparable rooting volume and water-holding capacity among experimental units. Before treatment application, the automatic irrigation system was calibrated by running each pump and collecting the discharged water from each emitter for the assigned

duration. The collected water was measured using a measuring cup to ensure that the target volumes of 200, 400, and 600 mL plant⁻¹ day⁻¹ were delivered consistently. Emitter uniformity was checked by comparing discharge among emitters within the same treatment line; emitters with visibly inconsistent discharge were cleaned or replaced before the experiment began. This calibration step was important to ensure that observed growth differences reflected irrigation treatments rather than uneven flow rates. The schematic layout of the automatic irrigation system is presented in Figure 1.

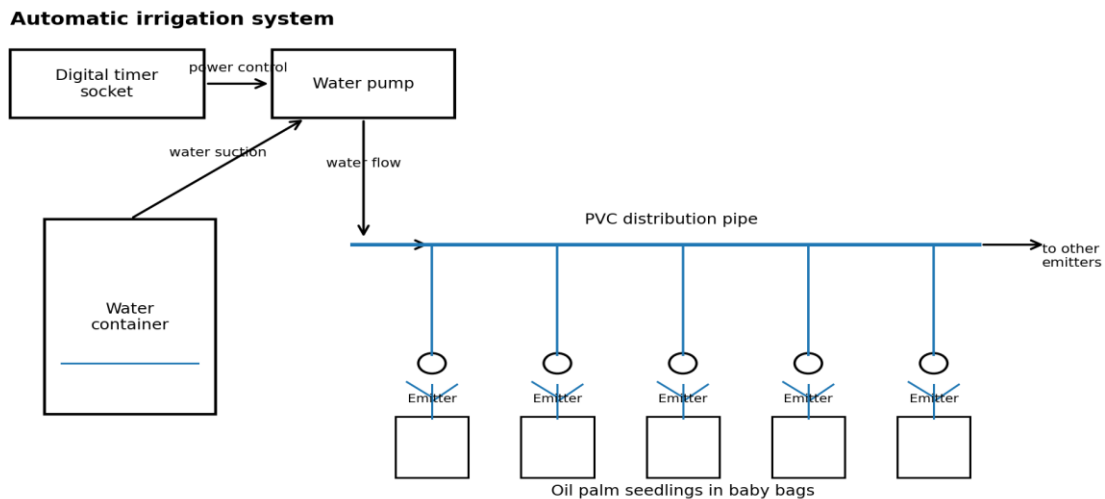


Figure 1. Diagram of automatic irrigation system

2.3. Research Design

Experimental research method using a Complete Randomized Design (CRD) Factorial consisting of two factors and 4 repetitions, namely: The first factor, irrigation volume (D), consists of three levels, namely: D₁ = Irrigation volume 200 ml/day; D₂ = Irrigation volume 400 ml/ day; D₃ = Irrigation volume 600 ml/ day

The irrigation volume range was selected to represent three practical water-supply levels for pre-nursery management: a low level that may represent deficit watering (200 mL plant⁻¹ day⁻¹), an intermediate level (400 mL plant⁻¹ day⁻¹), and a higher level approaching the reported daily water requirement range for young oil palm seedlings (600 mL plant⁻¹ day⁻¹). This range allowed the study to evaluate whether a lower volume could still support seedling growth when delivered automatically and uniformly, and whether a higher volume improved biomass accumulation under greenhouse conditions (A. M, 2022; Pradiko et al., 2025).

The second factor, irrigation duration (W), consists of three levels, namely: W₁ = Irrigation duration 20 minutes/day; W₂ = Irrigation duration 30 minutes/day; W₃ = Irrigation duration 40 minutes/day. The irrigation durations were selected to represent short, moderate, and relatively long daily operating times of the automatic system. Duration was examined separately from volume because the same daily water amount may produce different wetting patterns depending on discharge rate and application time. A moderate duration was expected to improve lateral and vertical water movement in the growing medium without creating excessive saturation.

The data obtained from the research results were analyzed statistically using Analysis of Variance (ANOVA), and if the results showed a significant effect, they were followed up with Duncan's Multiple Range Test (DMRT) at a level of $\alpha = 5\%$.

Observation parameters consisted of plant height (cm), stem diameter (mm), root length (cm), wet root weight (g), wet crown weight (g), dry root weight (g), and dry crown weight (g). Plant height and stem diameter were observed every two weeks from 4 to 12 WAP. Plant height was measured from the surface of the growing medium to the highest leaf tip using a measuring tape, while stem diameter was measured at the seedling base using a caliper. Root length and biomass variables were measured destructively at 12 WAP. Root length was measured from the root collar to the longest root. Fresh weights were recorded immediately after harvest using an analytical balance, and dry weights were recorded after plant samples were dried to constant weight. The use of both fresh and dry biomass variables allowed the study to distinguish water-related changes in tissue mass from actual dry matter accumulation.

3. RESULTS AND DISCUSSION

3.1. Plant Height (cm)

Based on the results of the analysis of variance, the automatic irrigation volume has no significant effect on the height of oil palm seedlings in the pre-nursery across all plant ages. The timing of automatic irrigation showed a significant effect at 8 weeks after planting (WAP). The interaction between the automatic irrigation volume and the timing of automatic irrigation showed no significant effect on the height of pre-nursery oil palm seedlings at all ages. The average height of seedlings at 8 WAP are shown in Table 1.

Table 1. Average plant height data (cm) at 8 WAP Observations

Treatment	Observation to 8 WAP
W ₃	13,63 b
W ₁	14,08 ab
W ₂	15,16 a

Note: Numbers followed by the same letter in the same column for each treatment are not significantly different according to Duncan's multiple range test at the 5% level.

Table 1 shows that irrigation duration had a significant effect on plant height at 8 WAP, with the highest plant height (15.16 cm) observed in W₂, corresponding to an automatic irrigation duration of 30 min day⁻¹. This result indicates that a moderate operating duration may provide a more favorable balance between sufficient water distribution and root-zone aeration than shorter or longer durations. The graph showing the increase in plant height at 8 WAP is also presented in Figure 2.

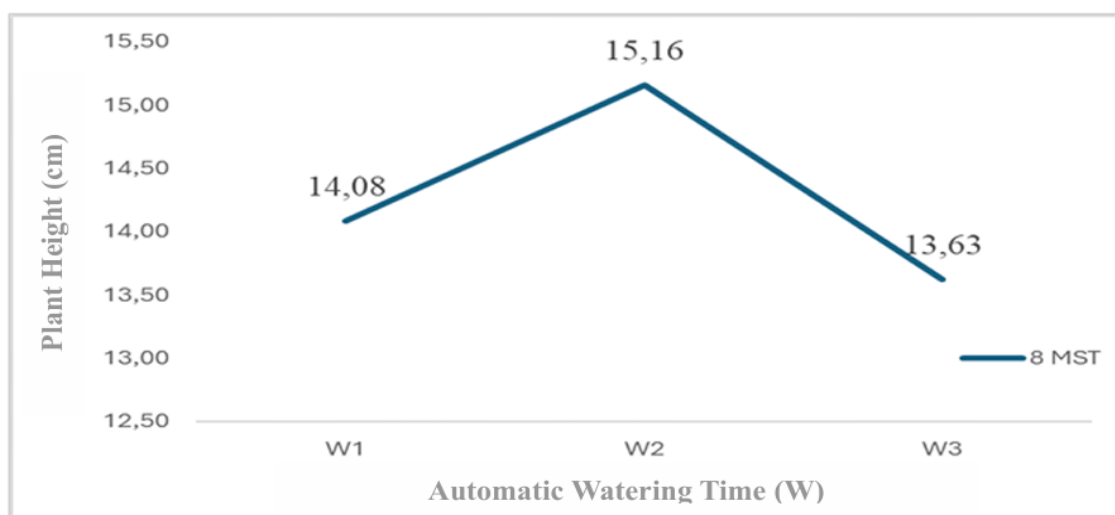


Figure 2. Diagram showing average plant height (cm) at observation 8 WAP

Figure 2 shows that the highest plant height at 8 WAP was recorded in W₂ (30 min day⁻¹), whereas the lowest was recorded in W₃ (40 min day⁻¹). The lower height under the longest duration may be related to excessive wetting of the growing medium, which can reduce air-filled pore space and limit oxygen diffusion to roots. In container and nursery systems, oxygen supply in the root zone is essential for root respiration and nutrient uptake; prolonged saturation can therefore reduce shoot growth even when water is abundant (Yafuso & Fisher, 2017). Table 2 presents the average height data of oil palm seedlings at 4-12 WAP observations.

Table 2. Average plant height data (cm) at observations 4 WAP - 12 WAP

Treatment	Observation to				
	4 WAP	6 WAP	8 WAP	10 WAP	12 WAP
Automatic irrigation volume					
D ₁	5,58	9,91	13,87	16,33	18,81
D ₂	5,99	10,28	14,23	17,15	19,46
D ₃	6,08	10,48	14,77	17,10	19,52
Automatic irrigation duration					
W ₁	5,66	9,85	14,08	16,60	19,22
W ₂	6,14	10,76	15,16	17,68	19,84
W ₃	5,84	10,06	13,63	16,31	18,73
Combination of automatic irrigation volume and Automatic irrigation duration					
D ₁ W ₁	5,06	9,38	13,78	16,26	18,85
D ₂ W ₁	6,05	10,59	14,45	17,56	19,65
D ₃ W ₁	5,86	9,59	14,03	15,96	19,16
D ₁ W ₂	5,93	10,38	14,26	16,66	18,70
D ₂ W ₂	6,06	10,24	15,21	17,68	20,44
D ₃ W ₂	6,44	11,68	16,00	18,70	20,38
D ₁ W ₃	5,74	9,99	13,56	16,06	18,89
D ₂ W ₃	5,85	10,01	13,03	16,23	18,29
D ₃ W ₃	5,85	10,19	14,29	16,65	19,03

Table 2 shows that the highest automatic irrigation volume treatment was found in treatment D₃ (Automatic irrigation volume of 600 ml/day), which was 19.52 cm, while the lowest was found in treatment D₁ (automatic irrigation volume of 200 ml/day), which was 18.81 cm.

Although the interaction between irrigation volume and duration was not statistically significant, the combination means provide useful descriptive information. The highest mean plant height at 12 WAP was observed in D₂W₂ (400 mL plant⁻¹ day⁻¹ combined with 30 min day⁻¹), whereas the lowest mean was observed in D₂W₃ (400 mL plant⁻¹ day⁻¹ combined with 40 min day⁻¹). These descriptive trends support the interpretation that duration, rather than volume alone, influenced the wetting pattern and aeration status of the growing medium. Najihah et al. (2019) reported that water availability affects seedling height, photosynthesis, and assimilate formation, while Sirait et al. (2023) found that watering frequency significantly affected oil palm seedling height at 8 to 12 WAP.

3.2. Stem Diameter (mm)

Based on the results of the analysis of variance, it shows that the automatic irrigation volume has no significant effect on the diameter parameter of oil palm seedlings in the pre-nursery at all plant ages. The timing of automatic irrigation also showed no significant effect on all plant ages. The interaction between the automatic irrigation volume and the timing of automatic irrigation showed no significant effect on the diameter of pre-nursery oil palm seedlings at all plant ages. The average stem diameter data for observations at 4 WAP – 12 WAP are shown in Table 3.

Table 3. Average stem diameter data (mm) in Observations 4 WAP - 12 WAP

Treatment	Observation to				
	4 WAP	6 WAP	8 WAP	10 WAP	12 WAP
Automatic irrigation volume					
D ₁	2,57	3,19	3,71	4,77	5,65
D ₂	2,86	3,57	4,17	5,16	6,04
D ₃	2,80	3,38	3,98	4,92	5,83
Automatic irrigation duration					
W ₁	2,66	3,25	3,82	4,76	5,61
W ₂	2,88	3,53	4,10	5,15	6,05
W ₃	2,69	3,36	3,93	4,93	5,85
Combination of automatic irrigation volume and automatic irrigation duration					
D ₁ W ₁	2,39	2,99	3,44	4,48	5,31
D ₂ W ₁	2,88	3,51	4,15	5,13	6,03
D ₃ W ₁	2,73	3,24	3,86	4,69	5,50
D ₁ W ₂	2,53	3,28	3,81	5,04	5,80
D ₂ W ₂	3,01	3,59	4,19	5,21	6,06
D ₃ W ₂	3,10	3,73	4,31	5,20	6,29
D ₁ W ₃	2,80	3,31	3,88	4,79	5,83
D ₂ W ₃	2,69	3,61	4,16	5,14	6,03
D ₃ W ₃	2,59	3,16	3,76	4,86	5,71

Table 3 shows that the highest automatic irrigation volume treatment was in treatment D₂ (Automatic irrigation volume of 400 ml/day), which was 6.04 mm, while the lowest was in treatment D₁ (automatic irrigation volume of 200 ml/day), which was 5.65 mm. The highest automatic irrigation treatment was found in treatment W₂ (30 minutes of automatic irrigation per day) at 6.05

mm, while the lowest was found in treatment W_1 (20 minutes of automatic irrigation per day) at 5.61 mm.

The interaction effect was not statistically significant, the combination data for stem diameter should be interpreted descriptively. The highest mean stem diameter was observed in D_3W_2 (600 mL plant⁻¹ day⁻¹ and 30 min day⁻¹), whereas the lowest was observed in D_1W_1 (200 mL plant⁻¹ day⁻¹ and 20 min day⁻¹). This pattern suggests that adequate water supply combined with moderate duration may support stem thickening, but the absence of statistical significance indicates that stem diameter was relatively less sensitive to the treatments during the 12-week pre-nursery period. Bayona-Rodríguez and Romero (2024) stated that adequate water availability contributes to oil palm growth, particularly during early vegetative development.

3.3. Root Length (cm)

Based on the results of the analysis of variance, it shows that the automatic irrigation volume has no significant effect on the root length parameter of pre-nursery oil palms at 12 WAP. The timing of automatic irrigation also showed no significant effect on plants aged 12 WAP. The interaction between the automatic irrigation volume and timing showed no significant effect on the root length of pre-nursery oil palm seedlings aged 12 WAP.

Table 4. Average root length data (cm) at Observation 12 WAP

Treatment	Observation to 12 WAP
Automatic irrigation volume	
D_1	25,59
D_2	25,91
D_3	27,70
Automatic irrigation duration	
W_1	27,40
W_2	26,13
W_3	25,67
Combination of automatic irrigation volume and automatic irrigation duration	
D_1W_1	25,20
D_2W_1	29,99
D_3W_1	27,00
D_1W_2	25,14
D_2W_2	24,76
D_3W_2	28,48
D_1W_3	26,43
D_2W_3	22,98
D_3W_3	27,61

Table 4 shows that the highest automatic irrigation volume treatment was found in treatment D_3 (automatic irrigation volume of 600 ml/day), which was 27.70 cm, while the lowest was found in treatment D_1 (automatic irrigation volume of 200 ml/day), which was 25.59 cm. The highest automatic irrigation treatment was found in treatment W_1 (automatic irrigation duration of 20 minutes/day), which was 27.40 cm, while the lowest was found in treatment W_3 (automatic irrigation duration of 40 minutes/day), which was 25.67 cm.

Because no significant interaction was detected, root length combination means are presented as descriptive trends rather than statistical treatment superiority. The highest mean root length was observed in D_2W_1 (400 mL plant⁻¹ day⁻¹ and 20 min day⁻¹), whereas the lowest was observed in D_2W_3 (400 mL plant⁻¹ day⁻¹ and 40 min day⁻¹). These results suggest that root elongation may respond differently from biomass accumulation: under moderate water supply, shorter application duration may encourage roots to explore the medium, while prolonged wetting may reduce oxygen availability and suppress elongation. Intara et al. (2018) the oil palm root system adapts to soil moisture and forms a surface root network that plays a role in capturing and regulating water availability in the plant's root zone.

3.4. Wet Root Weight (g)

Based on the results of the analysis of variance, it shows that the Automatic irrigation volume has no significant effect on the wet weight parameter of oil palm seedlings in the pre-nursery at 12 weeks after planting (WAP). The timing of automatic irrigation showed a significant effect at 12 weeks after planting (WAP). The interaction between the automatic irrigation volume and the timing of automatic irrigation showed no significant effect on the wet weight of palm oil seedlings in the pre-nursery at 12 weeks after planting (WAP). The average wet weight data are shown in Table 5.

Table 5. Average wet root weight data (g) at Observation 12 WAP

Treatment	Observation to 12 WAP
W ₃	1,03 b
W ₁	1,11 ab
W ₂	1,32 a

Note: Numbers followed by the same letter in the same column for each treatment are not significantly different according to Duncan's multiple range test at the 5% level.

Table 5 shows that irrigation duration significantly affected root fresh weight at 12 WAP. The highest root fresh weight (1.32 g) was obtained under W₂ (30 min day⁻¹), indicating that moderate irrigation duration supported better root biomass formation than either shorter or longer durations. Table 6 presents the average wet weight of oil palm seedling roots at 12 WAP.

Table 6. Average wet weight of roots (g) at 12 WAP Observation

Treatment	Observation to 12 WAP
D ₁	1,12
D ₂	1,17
D ₃	1,17
Automatic irrigation duration	
W ₁	1,11
W ₂	1,32
W ₃	1,03
Combination of automatic irrigation volume and automatic irrigation duration	
D ₁ W ₁	1,05
D ₂ W ₁	1,16
D ₃ W ₁	1,11
D ₁ W ₂	1,30
D ₂ W ₂	1,23
D ₃ W ₂	1,43
D ₁ W ₃	1,00
D ₂ W ₃	1,11
D ₃ W ₃	0,96

Table 6 shows that the highest Automatic irrigation volume treatment was found in treatments D₂ and D₃ (automatic irrigation volume of 400 ml/day and automatic irrigation volume of 600 ml/day), which was 1.17 g, while the lowest was found in treatment D₁ (automatic irrigation volume of 200 ml/day), which was 1.12 g.

Although the interaction was not statistically significant, D₃W₂ (600 mL plant⁻¹ day⁻¹ and 30 min day⁻¹) produced the highest descriptive mean root fresh weight (1.43 g), whereas D₃W₃ produced the lowest mean (0.96 g). This finding reinforces that a larger water volume is not always beneficial when the application duration is too long. A 30-min duration may allow more uniform wetting without maintaining prolonged saturation, while a 40-min duration may increase the risk of root-zone hypoxia and reduce root activity. Carr (2011) explains that rhizosphere aeration conditions greatly determine root respiration and water absorption; excessive watering duration risks water saturation, thereby reducing soil oxygen and inhibiting root development. Yafuso and Fisher (2017) highlighted that adequate air porosity and avoidance of overwatering are essential for healthy root growth in container systems.

3.5. Wet Crown Weight (g)

Based on the results of the analysis of variance, the automatic irrigation volume has no significant effect on the wet crown weight in the pre-nursery at 12 WAP. The timing of automatic irrigation also showed no significant effect on plants aged 12 WAP. The interaction between the Automatic irrigation volume and timing showed no significant effect on the wet weight of pre-nursery oil palm seedlings at 12 WAP. The average wet crown weight data at 12 WAP are shown in Table 7.

Table 7. Average wet crown weight data (g) at 12 WAP Observation

Treatment	Observation to
	12 WAP
Automatic irrigation volume	
D ₁	2,48
D ₂	2,70
D ₃	2,86
Automatic irrigation duration	
W ₁	2,55
W ₂	2,93
W ₃	2,57
Combination of automatic irrigation volume and automatic irrigation duration	
D ₁ W ₁	2,36
D ₂ W ₁	2,73
D ₃ W ₁	2,55
D ₁ W ₂	2,58
D ₂ W ₂	2,70
D ₃ W ₂	3,50
D ₁ W ₃	2,51
D ₂ W ₃	2,66
D ₃ W ₃	2,54

Table 7 shows that the highest automatic irrigation volume treatment was found in treatment D₃ (automatic irrigation volume of 600 ml/day), which was 2.86 g, while the lowest was found in treatment D₁ (automatic irrigation volume of 200 ml/day), which was 2.48 g. The highest automatic irrigation treatment was found in treatment W₂ (30 minutes of automatic irrigation per day) at 2.93 g, while the lowest was found in treatment W₁ (20 minutes of automatic irrigation per day) at 2.55 g.

The effect of the interaction between the automatic irrigation volume treatment and the highest automatic irrigation duration on the wet weight parameter of the canopy was 3.50 g, which was found in the D₃W₂ treatment, namely the automatic irrigation volume treatment of 600 ml/day and Automatic irrigation duration of 30 minutes/day. Meanwhile, the lowest was 2.36 g, which was found in treatment D₁W₁, namely automatic irrigation volume treatment of 200 ml/day and Automatic irrigation duration of 20 minutes/day. Franca et al. (2024) showed that proper irrigation scheduling can increase wet crown yield.

3.6. Dry Root Weight (g)

Based on the results of the analysis of variance, it shows that the automatic irrigation volume has no significant effect on the dry weight parameter of oil palm seedlings in the pre-nursery at 12 weeks after planting (WAP). The automatic irrigation duration shows a significant effect at 12 weeks after planting (WAP). The interaction between the automatic irrigation volume and the Automatic irrigation duration had no significant effect on the dry weight of pre-nursery oil palm seedlings at 12 weeks after planting (WAP). The average dry root weight at 12 WAP are shown in Table 8.

Table 8. Average dry root weight (g) at Observation 12 WAP

Treatment	Observation to
	12 WAP
W ₃	0,28 b
W ₁	0,30 b
W ₂	0,42 a

Note: Numbers followed by the same letter in the same column for each treatment are not significantly different according to Duncan's multiple range test at the 5% level.

Table 9 presents the average dry weight of oil palm seedlings at 12 WAP.

Table 9. Average dry weight of roots (g) at 12 WAP Observation

Treatment	Observation to	
	12 WAP	
	Automatic irrigation volume	
D ₁	0,31	
D ₂	0,34	
D ₃	0,35	
	Automatic irrigation duration	
W ₁	0,30	
W ₂	0,42	
W ₃	0,28	
	Combination of Automatic irrigation volume and Automatic irrigation duration	
D ₁ W ₁	0,28	
D ₂ W ₁	0,31	
D ₃ W ₁	0,33	
D ₁ W ₂	0,40	
D ₂ W ₂	0,38	
D ₃ W ₂	0,49	
D ₁ W ₃	0,26	
D ₂ W ₃	0,33	
D ₃ W ₃	0,25	

Table 9 shows that the highest automatic irrigation volume treatment was found in treatment D₃ (automatic irrigation volume of 600 ml/day), which was 0.35 g, while the lowest was found in treatment D₁ (automatic irrigation volume of 200 ml/day), which was 0.31 g.

The effect of the interaction between the automatic irrigation volume treatment and the highest automatic irrigation duration on the dry root weight parameter was 0.49 g, which was found in the D₃W₂ treatment, namely the automatic irrigation volume treatment of 600 ml/day and automatic irrigation duration of 30 minutes/day. Meanwhile, the lowest effect was 0.25 g, found in treatment D₃W₃, which was an automatic irrigation volume of 600 ml/day and an automatic irrigation duration of 40 minutes/day. This indicates that watering with a larger volume and longer duration can increase root dry weight, while watering with a lower volume and shorter duration can decrease root dry weight. Filho et al. (2021) found that root deficit can decrease root dry weight and that watering duration is a determining factor.

3.7. Dry Crown Weight (g)

Based on the results of the analysis of variance, irrigation volume, irrigation duration, and their interaction did not significantly affect shoot dry weight of pre-nursery oil palm seedlings at 12 WAP. Nevertheless, the treatment means showed a consistent descriptive tendency in which W₂ (30 min day⁻¹) and D₃W₂ (600 mL plant⁻¹ day⁻¹ combined with 30 min day⁻¹) produced the highest shoot dry weight values. The average dry crown weight data at 12 WAP are shown in Table 10.

Table 10. Average dry crown weight data (g) at observation 12 WAP

Treatment	Observation to	
	12 WAP	
	Automatic irrigation volume	
D ₁	0,67	
D ₂	0,73	
D ₃	0,88	
	Automatic irrigation duration	
W ₁	0,69	
W ₂	0,89	
W ₃	0,70	
	Combination of Automatic irrigation volume and Automatic irrigation duration	
D ₁ W ₁	0,63	
D ₂ W ₁	0,74	
D ₃ W ₁	0,70	
D ₁ W ₂	0,73	
D ₂ W ₂	0,74	
D ₃ W ₂	1,20	
D ₁ W ₃	0,65	
D ₂ W ₃	0,73	
D ₃ W ₃	0,73	

Table 10 shows that the highest effect of the interaction between automatic irrigation volume and automatic irrigation duration on the dry weight parameter was 1.20 g, which was found in treatment D₃W₂, automatic irrigation volume of 600 ml/day and automatic irrigation duration of 30 minutes/day. while the lowest was 0.63 g in treatment D₁W₁, which was the automatic irrigation

volume of 200 ml/day. This shows that watering with a larger volume and longer duration can provide stable water availability so that photosynthesis, nutrient absorption, and biomass formation run optimally, while watering with a low volume and short irrigation time can cause plants to experience water stress, thereby reducing biomass accumulation. Sezen et al. (2023) found that increasing the volume of water in irrigation enhances vegetative growth and dry weight of plants up to an optimal point.

4. CONCLUSION

Automatic irrigation duration was the most consistent factor influencing the early growth of oil palm seedlings in the pre-nursery. The 30 min day⁻¹ treatment significantly increased plant height at 8 WAP, root fresh weight, and root dry weight compared with the other irrigation durations. This duration produced the highest plant height (15.16 cm), root fresh weight (1.32 g), and root dry weight (0.42 g). Irrigation volume did not significantly affect most growth parameters in the available analysis, although 600 mL plant⁻¹ day⁻¹ produced the highest mean values for several biomass traits. No significant interaction was observed between irrigation volume and irrigation duration for all measured variables, indicating that the two factors acted independently under the conditions of this study. Therefore, an automatic irrigation duration of 30 min day⁻¹ can be recommended as the most promising scheduling option for supporting balanced vegetative and root biomass growth of oil palm seedlings in greenhouse pre-nursery conditions. The combination of 600 mL plant⁻¹ day⁻¹ and 30 min day⁻¹ produced the highest mean biomass values, but it should be interpreted descriptively because the interaction effect was not statistically significant.

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