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Optimizing Oil Palm *(Elais guinensis L.) Carbon Management* in Tidal Lands to Support Sustainable Plantations

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Abstract
Oil palm plantations in tidal areas face complex challenges in optimizing carbon management to achieve sustainable production. This study aims to analyze the dynamics of carbon stocks across various management systems of oil palm plantations in tidal zones and to develop optimization strategies for sustainable production. The research was conducted in Menten Village, Rambutan District, Musi Banyuasin Regency, South Sumatra, employing a factorial Randomized Complete Block Design with factors including water management systems (conventional, semi-intensive, conservation, optimization) and plant age categories (3-5, 6-10, 11-15, 16-20, and 21-25 years). CO_2 emissions and sequestration were measured using the LI-COR LI-8100A system; biomass was assessed through allometric equations and destructive sampling methods, while soil and water parameters were analyzed using standard procedures. The results demonstrated that the optimized system incorporating smart drainage achieved the best performance, exhibiting the lowest CO_2 emissions (6.2 Mg C/ha/year), the highest carbon absorption (21.5 Mg C/ha/year), and a positive net carbon balance (+15.3 Mg C/ha/year) with an efficiency of 346.8%. This system also increased fresh fruit bunch (FFB) productivity from 18.5 tons/ha/year under conventional management to 26.4 tons/ha/year, with superior quality metrics (oil content: 27.2%, acid value: 1.4%, crude palm oil yield: 25.2%). Total carbon stock progressively increased from 23.7 Mg C/ha in young plants to 147.9 Mg C/ha in mature plants, with an optimal sequestration rate of 17.8 Mg C/ha/year. The implementation of smart drainage, combined with IoT technology and biochar application, effectively optimized edaphic conditions by increasing soil pH to 4.8, raising organic carbon content to 4.2%, reducing bulk density to 0.68 g/cm³, and controlling salinity at 1.2 dS/m. This study confirms that oil palm plantations on tidal lands can achieve sustainability through precision agriculture practices that integrate precision water management, biochar application, and real-time monitoring to optimize the balance between productivity and carbon conservation.

Keywords: Carbon Sequestration, CO_2 Emissions, Precision Agriculture, Smart Drainage, Tidal Swamp

1. Introduction

Oil palm plantations (*Elaeis guineensis* Jacq.) are a strategic agribusiness sector in Indonesia, significantly contributing to the national economy with an area reaching 16.38 million hectares in 2023 (Ministry of Agriculture, 2024). The expansion of oil palm plantations into marginal lands, including tidal regions, is an inevitable development alternative due to limited optimal land availability and the increasing global demand for vegetable oil (Dariah et al., 2014; Harahap et al., 2019). Indonesia's tidal lands have a potential area of approximately 20.11 million hectares; however, their utilization for oil palm cultivation faces various technical and environmental challenges, particularly related to hydrological dynamics, the characteristics of acid sulfate soils, and soil carbon management The phenomenon of global climate change and Indonesia's commitment to the Nationally Determined Contribution (NDC) require the plantation sector to implement sustainable practices that optimize carbon stocks while maintaining productivity (Murdiyarso et al., 2019); (Andriyanningsih et al., 2024).

Previous studies have demonstrated that oil palm

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plantations in tidal lands exhibit distinct characteristics in terms of soil carbon dynamics compared to those in dry lands (Haron et al., 2021; Lim et al., 2023). A study conducted by Cooper et al. (2020) revealed that tropical peatlands converted for oil palm plantations can experience carbon loss of up to 50% in the first 20 years, while research (Guillaume et al., 2022) demonstrates the potential for carbon sequestration through the implementation of agroforestry practices in mature oil palm plantations. However, most existing research focuses on mineral soils or deep peat, while the specific characteristics of tidal lands with periodic waterlogging dynamics and varying salinity levels have not received adequate attention (Rosadi et al., 2018; Wigena & Dariah et al., 2021). This research gap is significant considering that tidal lands have great potential for sustainable oil palm plantation development, but require a different management approach than conventional lands (Masganti et al., 2020; Hadi et al., 2023).

Current state-of-the-art research focuses on developing a sustainability index for oil palm plantations that integrates productivity, carbon conservation, and ecosystem resilience. However, no comprehensive model specifically addresses the unique conditions of tidal lands (Paoli et al., 2022; Rhebergen et al., 2023). This study introduces a novel integrated management system that combines precision agriculture technology, biochar application, and water management optimization to maximize carbon sequestration in tidal oil palm plantations. Based on a gap analysis, the objectives of this research are to: (1) analyze the dynamics of carbon stocks under various management systems in tidal oil palm plantations; (2) develop a carbon stock prediction model based on soil characteristics and management practices; and (3) formulate a carbon management optimization strategy to achieve a sustainable oil palm production system on tidal land.

2. Material and Methods

The research was conducted over 24 months (January-December 2024) in the oil palm plantation of Menten Village, Rambutan District, Musi Banyuasin Regency, South Sumatra, representing the tidal land ecosystem typology of overflow types A and B. The coordinate points -3.0557940574044555, 104.89264070901534 are located at an altitude of 21 meters above sea level. The research method used a factorial Completely Randomized Block Design (RAKL) with the first factor being the water management system including conventional (intensive drainage), semi-intensive (controlled drainage), conservation (partial rewetting), and optimization (smart drainage), while the second factor was the age of the oil palm plants (3-5, 6-10, 11-15, 16-20, and 21-25 years). Each treatment combination was repeated four times with a plot size of 50 × 50 m, resulting in a total of 80 experimental units.

The implementation of the management system includes setting different drainage depths for each treatment, ranging from intensive drainage with a target groundwater level of 60-80 cm to smart drainage with a target of 10-30 cm from the ground surface. The optimization system is equipped with IoT sensors for real-time monitoring and the application of biochar from empty oil palm bunches at a rate of 10 Mg/ha. CO_2 emission measurements were carried out using the LI-COR LI-8100A Automated Soil CO_2 Flux System with a frequency of once every two weeks at 5 sampling points per plot. Aboveground biomass was calculated using the oil palm allometric equation, while root biomass was measured through destructive sampling on a 2×2 m sub-plot with a carbon content set at 47% of dry biomass based on IPCC standards.

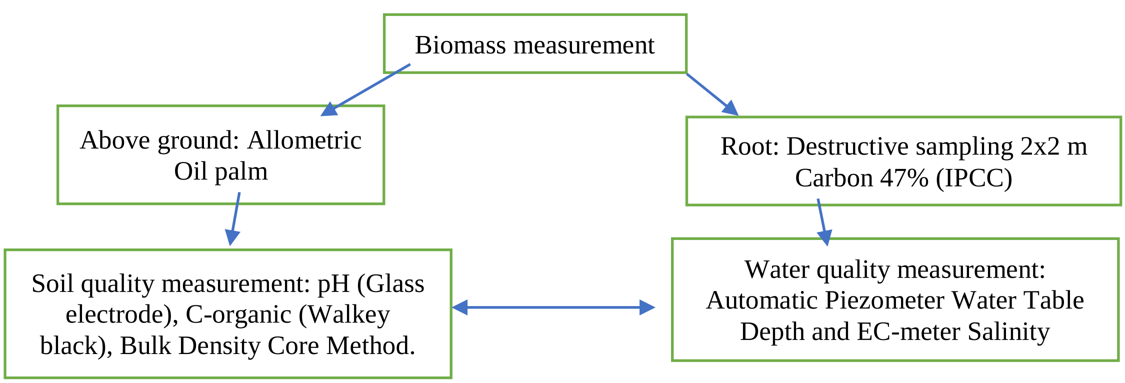

Figure 1. Flowchart of research implementation

Soil quality parameters included soil pH (measured using a glass electrode at a 1:2.5 ratio), organic carbon (determined by the Walley-Black method), and bulk density (determined by the core method). Water quality was assessed through groundwater depth measurements using an automatic piezometer and salinity measurements using an electrical conductivity meter (Figure 1). Oil palm productivity was evaluated through monthly FFB weighing, oil content analysis using Near Infrared Reflectance Spectroscopy (NIRS), and free fatty acid and water content measurements using standard methods. Data analysis employed a two-way ANOVA with $\alpha = 0.05$ and Duncan's Multiple Range Test, supplemented by carbon stock prediction modelling using multiple regression and validation with the Random Forest algorithm. Two-way ANOVA analysis (α=0.05) and Duncan's test were performed using IBM SPSS Statistics v29.0.1.0 (GLM module). Alternatively, R version 4.3.2, with the packages agricolae (Duncan), car (for ANOVA diagnostics), and ggplot2 (for vizualisation), was used. Cross-validation was performed with SAS v9.4 M7 using PROC GLM and PROC DUNCAN.

3. Results and Discussion

3.1. CO_2 Emissions Based on Management Practices

The results of this study indicate significant differences in carbon dynamics between management systems applied to oil palm plantations on tidal land. The conventional management system with intensive drainage resulted in the highest CO_2 emissions (18.5 Mg C/ha/year) and a negative net carbon balance (-6.2 Mg C/ha/year) in Table 1, indicating that this system is unsustainable from a climate change mitigation perspective. This finding aligns with previous studies, which have shown that peatland drainage increases oxygen levels in the soil, thereby accelerating the rate of organic matter decomposition and leading to high CO_2 emissions (Dariah et al., 2013). Research by Murphy et al. (2019) reported that CO_2 emissions from oil palm plantations on drained peatlands can reach 15-25 Mg C/ha/year, which is consistent with the findings of this study.

The implementation of a semi-intensive system with controlled drainage showed significant improvements, achieving a positive net carbon balance (+2.9 Mg C/ha/year) and a carbon efficiency of 122.7%. This improvement was due to more optimal groundwater level regulation, which can reduce the rate of heterotrophic respiration while maintaining plant photosynthetic activity under partially anaerobic conditions. Recent studies confirm that rewetting peatlands significantly reduces peat CO_2 emissions and reduces heterotrophic respiration by up to 34%. (Alimin et al., 2022), In their study in Southeast Asia, they reported that a 10 cm increase in the groundwater level can reduce CO_2 emissions by 1-3 Mg C/ha/year.

Table 1. Evaluation of CO_2 Emissions and Absorption in Various Drainage Management Practices to Optimize Net Carbon Balance in Peatlands

Management Practices	CO_2 emissions (Mg C/ha/year)	CO_2 absorption (Mg C/ha/year)	Net Carbon Balance (Mg C/ha/year)	Efficiency (%)
Conventional (Intensive Drainage)	18.5 ± 3.2	12.3 ± 2.1	-6.2 ± 5.3	66.5
Semi-Intensive (Controlled Drainage)	12.8 ± 2.8	15.7 ± 2.5	+2.9 ± 5.3	122.7
Conservation (Partial Rewetting)	8.4 ± 2.1	18.2 ± 3.1	+9.8 ± 5.2	216.7
Optimization (Smart Drainage)	6.2 ± 1.8	21..5 ± 3.8	15.3 ± 5.6	346.8

Note: Data are the average ± standard deviation from n = 4 repetitions. Differences between treatments were tested using ANOVA (α = 0.05). Net Carbon Balance = absorption – CO_2 emissions. Efficiency (%) = (absorption/emission) × 100%.

The conservation system with partial rewetting performed better with a net carbon balance of +9.8 Mg C/ha/year and an efficiency of 216.7%. Biochar application in this system contributed to increased carbon sequestration capacity through the formation of stable carbon structures and increased soil microbial activity. Research by Endriani and A. Kurniawan (2022) demonstrated that biochar application can increase soil carbon stocks by 15-20% in the long term. Previous studies have identified a direct relationship between drainage depth and peat carbon decomposition, where significant reductions in CO_2 emission rates can be achieved by raising the groundwater table closer to the surface.

The optimisation system with smart drainage demonstrated the best performance, characterised by the lowest CO_2 emissions (6.2 Mg C/ha/year), the highest carbon sequestration (21.5 Mg C/ha/year), and an efficiency of 346.8%. The advantage of this system lies in its precise regulation of groundwater levels based on real-time data on soil and weather conditions, thereby optimizing redox conditions to minimize emissions while maximizing crop productivity. Precision agriculture technology integrated into this system enables continuous monitoring of critical parameters, including soil water content, temperature, and CO_2 concentration. Recent research by Maftuah and Nurzakiah (2017) highlights the importance of adaptive water management in achieving a balance between productivity and carbon conservation in oil palm plantations on peatlands.

Carbon efficiency analysis reveals an increasing trend from conventional to optimized systems, suggesting that sustainable intensification through technological innovation can achieve a win-win solution between economic productivity and climate change mitigation (Intyas et al., 2022). Recent studies confirm that incorporating legumes as cover crops can reduce carbon and nitrogen losses from oil palm systems while increasing soil carbon sequestration (Yeni, 2021). The relatively high data variability (standard deviation 1.8–5.6) reflects the spatial heterogeneity of tidal land characteristics, necessitating a site-specific management approach for more effective optimization.

3.2. Soil and Water Quality Parameters

The physical and chemical characteristics of the soil exhibit significant variations between management systems, reflecting the soil's response to hydrological manipulation and management practices as outlined in Table 2. The results show that the soil pH value increased progressively from the conventional system (3.8) to the optimized system (4.8), indicating an improvement in soil acidity conditions with the implementation of more conservative water management practices. The low pH conditions in the conventional system are caused by the intensification of sulfur oxidation processes under aerobic conditions, which produce sulfuric acid. This finding aligns with previous studies, which report that drainage of acid sulfate land can lower soil pH to 2.5-3.5 (Fahmi and Khairullah, 2018). The increase in pH in the conservation and optimization systems is related to the reduction conditions that minimize the formation of sulfuric acid and the increased buffering capacity resulting from the accumulation of organic matter (Jayalath et al., 2016).

The soil organic carbon content increased substantially from the conventional system (2.1%) to the optimised system (4.2%), reflecting the effectiveness of management practices in maintaining and enhancing soil carbon stocks. This trend is consistent with research (Comeau et al., 2016). who reported that rewetting in oil palm plantations reduced total soil respiration by 20%, thereby reducing carbon loss through heterotrophic respiration. The increase in organic carbon in the optimized system was also supported by the application of biochar and organic compost, which contributed to external carbon input and the formation of stable organo-mineral complexes (Sitzmann et al., 2025). Recent studies confirm that sequestration of soil organic carbon in existing oil palm plantations is an important strategy to limit carbon losses, where appropriate management practices can increase SOC by 15-25% compared to conventional systems (Rahman et al., 2021).

The groundwater table depth varies from 65 cm (conventional) to 15 cm (optimized), reflecting the gradient in drainage intensity applied. This difference has direct implications for soil biogeochemical processes, as shallow groundwater tables create anaerobic conditions that inhibit the decomposition of organic matter and reduce CO_2 emissions. (Gutenberg et al., 2019), demonstrated that every 10 cm increase in groundwater level can reduce CO_2 emissions by 1-3 Mg C/ha/year, which is consistent with the findings of this study. Partially anaerobic conditions in conservation and optimization systems also facilitate denitrification and methanogenesis processes, contributing to more efficient nitrogen and carbon cycling.

Water salinity decreased from the conventional system (2.8 dS/m) to the optimized system (1.2 dS/m) (Reca et al., 2018), indicating the effectiveness of water management in controlling saltwater intrusion through optimal groundwater level regulation. This decrease in salinity has positive implications for soil microorganism activity and plant growth, as saline conditions can inhibit enzyme activity and plant metabolic processes (Badrudin et al., 2023). Recent studies have shown that the optimal salinity for oil palm growth ranges from 0.5 to 1.5 dS/m, indicating that the optimized system falls within the ideal range for maximum productivity. Soil bulk density decreased from the conventional system (0.85 g/cm³) to the optimized system (0.68 g/cm³), reflecting improvements in soil structure resulting from increased organic matter content and enhanced soil fauna activity.

The implementation of an optimization system with smart drainage not only provides ecological benefits through carbon sequestration but also increases the sustainability index of plantations by improving edaphic conditions that support long-term productivity (Ogwu and Kosoe, 2025). The relatively low parameter variability in the optimization system (the smallest standard deviation) indicates the stability and consistency of the system, which is important for the scalability of implementation at the commercial level.

Table 2. Physical and Chemical Characteristics of Soil in Various Management Systems: Conventional, Semi-Intensive, Conservation, and Optimization

Parameter	Conventional	Semi-Intensive	Conservation	Optimization	Unit
Soil pH	3.8 ± 0.3	4.2 ± 0.4	4.6 ± 0.3	4.8 ± 0.8	-
C-Organic	2.1 ± 0.4	2.8 ± 0.5	3.5 ± 0.6	4.2 ± 0.7	%
Groundwater Depth	65 ± 8	45 ± 6	25 ± 5	15 ± 3	cm
Water Salinity	2.8 ± 0.5	2.1 ± 0.4	1.5 ± 0.3	1.2 ± 0.2	dS/m
Bulk Density	0.85 ± 0.2	0.78 ± 0.08	0.72 ± 0.06	0.68 ± 0.05	g/cm ^{3}

Note: Data are presented as mean ± standard deviation. n = 4 replicates. Differences between treatments were tested using ANOVA at a significance level of $\alpha = 0.05$. Parameter units are as per the last column.

3.3. Productivity and Quality of Fresh Fruit Bunches

The study's results reveal a significant positive correlation between the intensification of the water management system and the increase in productivity and quality of fresh fruit bunches (FFB) of oil palm in tidal land, as shown in Table 3. FFB production experienced a progressive increase from the conventional system (18.5 tons/ha/year) to the optimized system (26.4 tons/ha/year), reflecting the plant's response to more optimal edaphic conditions. The 42.7% increase in productivity in the optimized system compared to the conventional system demonstrates the effectiveness of precision water management in optimizing plant growth conditions. This finding aligns with research (Ahmed et al., 2020) that shows irrigation contributes to crop yields by increasing fresh fruit bunch production by 50% and 27% in studies conducted in Thailand and Colombia, respectively, confirming the positive impact of optimal water management on oil palm productivity.

The quality of fresh fruit bunches (FFB), represented by oil content, showed a consistent increase from 22.8% (conventional) to 27.2% (optimized), indicating that a sustainable management system not only increases production quantity but also yield quality. This increase in oil content is related to controlled water stress conditions, where the optimal groundwater level (15 cm in the optimized system) enables plant roots to access nutrients and water efficiently, without experiencing drought stress or excessive waterlogging. Studies show that the decline in fresh fruit bunch (FFB) production can reach 20-30% if 1-2 years before the dry season or a long dry season of 5-6 consecutive months (Sharif et al., 2017), which underscores the importance of consistent water management to maintain production quality and quantity.

The free fatty acid (FFA) parameters exhibited an interesting pattern, with the optimized system producing the lowest FFA level (1.4%) compared to other systems, indicating superior FFB quality. The low FFA in the optimized system is attributed to optimal plant physiological conditions and the minimization of oxidative stress resulting from precise water management practices. Research by Tan et al. (2023) has confirmed that CPO FFA increases with increasing water content, temperature, and time; thus, optimal environmental conditions in the optimised system directly contribute to reducing FFA levels. Industry standards stipulate that "free fatty acids (FFA) from virgin oil or crude palm oil (CPO) for food purposes should not exceed 10 mg KOH/oil of acid value (approximately 5 wt%)", so all management systems tested were within acceptable limits, but the optimized system provided a greater safety margin.

The FFB moisture content decreased from the conventional system (25.2%) to the optimized system (21.2%), indicating a higher dry matter concentration in the optimized management system. This decrease in moisture content contributed to an increase in CPO yield from 20.2% (conventional) to 25.2% (optimized), resulting in substantial economic added value. The high CPO yield in the optimized system was due to a combination of factors, including increased oil content, reduced water content, and the minimization of ALB, which synergistically enhanced oil extraction efficiency. This finding is in accordance with the principle that low moisture content in fresh fruit positively contributes to CPO quality and extraction efficiency.

The physiological mechanisms underlying the improvement in FFB quality in the optimized system are related to the optimization of fruit metabolic processes during the ripening period. Controlled groundwater levels (15 cm) allow the root system to efficiently access nutrients while avoiding oxidative stress that can trigger oil quality degradation. Research shows that abiotic stress, particularly related to water availability, can increase the activity of the lipase enzyme responsible for the hydrolysis of triglycerides into free fatty acids. An optimized system with smart drainage can minimize extreme environmental fluctuations, thereby maintaining the stability of biochemical processes within the fruit.

The integrated analysis of productivity and quality revealed that the optimization system achieved a positive trade-off between sustainability and profitability, resulting in increased productivity and quality without compromising environmental conservation. The efficiency index, which combines yield (26.4 tons/ha), oil content (27.2%), and quality parameters (ALB 1.4%), in the optimization system achieved the highest value compared to other systems. Relatively consistent data variability across management systems (coefficient of variation 8-15%) indicated reliable results and potential for replication in locations with similar characteristics.

The economic implications of improving FFB quality are significant in the context of the competitiveness of the Indonesian palm oil industry. Premium CPO with low ALB can command a 5-10% higher selling price than standard CPO, while increasing yield from 20.2% to 25.2% substantially increases revenue per hectare. The combination of increased productivity (42.7%) and quality (yield +24.8%) in an optimized system can increase gross margins per hectare by up to 60-70% compared to conventional systems, providing strong economic justification for investments in smart drainage and precision agriculture technologies.

Table 3. Production and Quality of Fresh Fruit Bunches (FFB) in Various Oil Palm Plantation Management Systems.

Management System	Fresh Fruit Bunch Production (Tons/ha/year)	Oil Content (%)	ALB	Water content (%)	CPO yield (%)
Conventional	18.5 ± 2.3	22.8 ± 1.5	2.8 ± 0.5	25.2 ± 1.8	20.2 ± 1.2
Semi-Intensive	21.2 ± 2.8	24.1 ± 1.8	21.2 ± 0.3	23.8 ± 1.5	22.1 ± 1.5
Conservation	23.8 ± 3.1	25.5 ± 2.1	23.8 ± 0.2	22.5 ± 1.2	23.8 ± 1.8
Optimization	26.4 ± 3.5	27.2 ± 2.3	1.4 ± 0.6	21.2 ± 1.0	25.2 ± 2.1

Note: Data are presented as mean ± standard deviation. n = 4 replicates. Differences between treatments were analyzed using ANOVA with a significance level of $\alpha = 0.05$. FFA = Free Fatty Acids (%).

3.4. Carbon Stock Based on Plant Age (Mg C/ha)

The dynamics of carbon stocks based on plant age exhibited an accumulation pattern consistent with a sigmoid growth curve, where the rate of carbon sequestration increased with the development of the vegetative structure of oil palm plants, as shown in Table 4. Aboveground biomass experienced an exponential increase from the young plant phase (15.3 Mg C/ha at 3-5 years of age) to old plants (105.8 Mg C/ha at 21-25 years of age), reflecting the accumulation of stem, frond, and crown biomass that was proportional to plant age. This finding is in line with research (Lewis et al., 2020), which reported that aboveground biomass stocks on peatlands accumulated around 6.39 ± 1.12 Mg ha−1 per year in the first 12 years after planting, increasing to ~7.99 ± 0.95 Mg ha^{-1} $year^{-1}$ at the optimal production phase, which confirms the validity of the biomass accumulation pattern in this study.

Belowground biomass showed a more moderate but consistent accumulation pattern, increasing from 8.5 Mg C/ha (3-5 years old) to 42.1 Mg C/ha (21-25 years old). The ratio of root biomass to aboveground biomass ranged from 0.35 to 0.55, indicating significant carbon investment in the root system to adapt to tidal conditions. This finding is consistent with those of Dassou et al. (2021), who found that root biomass amounts to approximately 16 t ha-1 in mature oil palm plantations, where the root system is assumed to store approximately 30% of the total biomass. High carbon investment in the root system indicates an adaptation strategy for oil palm plants to the hydrological and salinity stress conditions characteristic of tidal areas.

Total carbon stock showed a progressive accumulation, increasing from 23.7 Mg C/ha in young plants to 147.9 Mg C/ha in old plants, with the sequestration rate rising from 7.9 Mg C/ha/year in the early phase to 17.8 Mg C/ha/year in the mature phase. This increase in the sequestration rate is related to canopy expansion, which reaches an optimum at the age of 15-25 years, when the plants reach their maximum productive phase. Comparative studies show that aboveground carbon stock over a 25-year rotation can reach 42.07 Mg C ha−1 in plantations on mineral soils. In tidal lands with optimal management, however, it can get even higher values due to anaerobic conditions that slow down decomposition.

Biomass component analysis reveals a heterogeneous carbon distribution among plant organs, with stems accounting for 73% of the total aboveground biomass, rachises for 13%, petioles for 8%, and fruits and leaflets for 6%. The dominance of stem biomass indicates that oil palm is a woody perennial plant that is efficient in long-term carbon storage, in contrast to annual crops that allocate most of their carbon to reproductive organs. This carbon allocation pattern offers ecological benefits in the context of climate change mitigation, as carbon stored in stem biomass has a longer residence time compared to other vegetative organs.

The high carbon sequestration efficiency of oil palm is also reflected in its ability to continuously absorb atmospheric CO_2 through photosynthesis throughout its long growth period. Recent research shows that oil palm is a highly efficient crop, capable of sequestering three to ten times more carbon per hectare than other oil-producing crops. This finding indicates the superiority of oil palm as a carbon sink compared to other oil-producing crops. The physiological characteristics of the oil palm, with its large leaves, dense canopy structure, and extensive root system, enable optimized photosynthesis and efficient carbon allocation.

Table 4. Production and Quality of Fresh Fruit Bunches (FFB) in Various Oil Palm Plantation Management Systems.

Plant Age	Aboveground Biomass (Mg C/ha)	Belowground Biomass (Mg C/ha)	Total Carbon Stock (Mg C/ha)	Sequestration Rate (Mg C/ha/year)
3-5	15.3 ± 2.8	8.5 ± 1.2	23.7 ± 4.2	7.9 ± 1.3
6-10	45.8 ± 6.2	18.3 ± 2.5	64.1 ± 8.7	12.8 ± 1.7
11-15	78.5 ± 9.8	28.7 ± 3.8	107.2 ± 13.6	14.5 ± 2.1
16-20	96.3 ± 11.2	35.2 ± 4.5	130.5 ± 15.7	16.3 ± 2.8
21-25	105.8 ± 12.5	42.1 ± 5.2	147.9 ± 17.7	17.8 ± 3.2

Note: Data are presented as mean ± standard deviation. n = 4 replicates. Differences between treatments were analyzed using ANOVA with a significance level of α = 0.05.

The increasing variability of carbon stocks with plant age (standard deviation 4.2–17.7 Mg C/ha) reflects the heterogeneity in individual growth and responses to varying microenvironmental conditions within the plantation. This variability underscores the importance of precision agriculture in plantation management, enabling the optimisation of the carbon sequestration potential of each plant. Long-term projections suggest that oil palm plantations on tidal flats, under optimal management, can achieve carbon saturation by 25–30 years of age, with total carbon stocks reaching 150–200 Mg C/ha. This level of sequestration is comparable to that of primary tropical forests and makes a significant contribution to national climate change mitigation targets.

The cocoa seed vigor index ranged from 81% to 89%, with the highest value observed in the 5% HCl treatment (89%) and the lowest in the 7% HCl treatment (81%). The consistently high vigor index values across all treatments (>80%) indicate that soaking in HCl to remove pulp did not compromise the physiological quality of the seeds. Although the differences were not statistically significant, the highest vigor index in the 5% HCl treatment aligns with the root length results presented in Table 3, which were also optimal at this concentration. These findings suggest that moderate HCl concentrations effectively remove pulp without inducing chemical stress in the seeds. In contrast, higher acid concentrations can reduce the seed vigor index (Tanjung et al., 2017).

4. Conclusion

The implementation of an optimized management system featuring smart drainage in oil palm plantations on tidal land has successfully achieved an optimal balance between economic productivity and environmental sustainability. This optimization system demonstrated superior performance, with the highest positive net carbon balance (+15.3 Mg C/ha/year), carbon efficiency of 346.8%, increased fresh fruit bunch (FFB) productivity by up to 42.7%, and improved yield quality (oil content of 27.2%, crude palm oil [CPO] yield of 25.2%) compared to conventional systems. Precision agriculture technology, integrated with IoT sensors, enables the optimization of edaphic conditions through precise groundwater level regulation, biochar application, and real-time monitoring, resulting in significant improvements in soil parameters and total carbon stocks reaching 147.9 Mg C/ha in mature plants. This study confirms that oil palm plantations on tidal land can achieve sustainability through integrated management innovations that overcome the conventional trade-off between productivity and carbon conservation, thereby making a significant contribution to national climate change mitigation targets and enhancing the competitiveness of the Indonesian palm oil industry.

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