JEE Journal of Ecological Engineering

*Journal of Ecological Engineering*, 2025, 26(2), 342–349
https://doi.org/10.12911/22998993/197408
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Received: 2024.11.15
Accepted: 2024.12.18
Published: 2025.01.01

# Engineering carbon dynamics and vegetation indices in oil palm plantations: An integrated assessment of carbon stocks, normalized difference vegetation index, and net ecosystem exchange in Riau Province

Eko Jaya Siallagan[1,2*], Yusni Ikhwan Siregar[3], Nofrizal[3], Ujang Paman Ismail[3]

[1] Graduate student Environmental Sciences, Universitas Riau, Indonesia
[2] Indonesian Palm Oil Smallholders' Association, Jakarta, Indonesia
[3] Teaching Staff of Environmental Sciences, Postgraduate Program, Universitas Riau, Indonesia
* Corresponding author's e-mail: ekojayaunri@gmail.com

## ABSTRACT

This research examines carbon dynamics and vegetation indices in oil palm plantations across Riau Province through an integrated analysis of carbon stocks, normalized difference vegetation index (NDVI), and Net Ecosystem Exchange (NEE). Observations were conducted in six districts (Kampar, Siak, Pelalawan, Rokan Hulu, Indragiri Hulu, and Indragiri Hilir) from August 2022 to May 2024, using a nested sampling design focusing on productive oil palmsaged 8–16 years. Results showed significant variations in carbon stocks among districts, with Rokan Hulu and Indragiri Hilir consistently demonstrating the highest carbon storage capacity (41.43–43.46 $tC \cdot ha^{-1}$). NDVI analysis revealed increasing values from 2022 to 2024, with Siak District reaching the highest value (0.81) in 2024. Meanwhile, NEE in all districts showed negative values (-1.64 to -1.82 $gC/m^2/day$), indicating that oil palm plantations serve as net carbon sinks. This research provides a comprehensive understanding of carbon dynamics in oil palm plantation systems and their contribution to climate change mitigation, while highlighting the importance of sustainable management practices in optimizing carbon sequestration.

**Keywords:** carbon sequestration, oil palm, remote sensing, ecosystem flux, biomass accumulation.

## INTRODUCTION

The rapid expansion of oil palm (*Elaeis guineensis* Jacq.) plantations in Southeast Asia, particularly in Indonesia, has sparked intense scientific debate regarding their environmental impacts and role in global carbon cycling (Uning et al., 2020). As the world's largest producer of palm oil, Indonesia has witnessed substantial land-use changes, with Riau Province emerging as a crucial hub for oil palm cultivation, hosting approximately 2.7 million hectares of plantations (Varkkey, 2012). This extensive transformation necessitates a comprehensive understanding of the carbon dynamics and ecosystem functioning within these agricultural landscapes.

Oil palm plants are perennial plants that have the potential to absorb carbon emissions. Soil respiration is the largest component (60–90%) of terrestrial ecosystems that contributes to the release of $CO_2$ into the atmosphere (Murphy, 2024). Soil respiration consists of autotrophic and heterotrophic respiration. These contributions come from two respiration processes: (1) respiration of autotrophic components, such as root respiration and other autotrophic organisms that represent plant activity and the supply of organic compounds to the roots, and (2) respiration of heterotrophic components, specifically the decomposition of organic matter by microbes, which controls the storage and dynamics of nutrients (Condron et al., 2010).

Carbon reserves refer to carbon content stored either on the soil surface as plant biomass, dead plant remains (necromass), or in the soil as soil organic matter (Inoue, 2019). Carbon reserves can be found in living parts (biomass), dead parts (necromass), and in the soil (Supardi et al., 2022). The carbon stored in oil palm plants changes along with plant growth and development.

Carbon stocks in oil palm plantations represent a significant component of the terrestrial carbon pool, yet their quantification and temporal dynamics remain subjects of ongoing research (Cooper et al., 2019). The complexity of carbon allocation patterns in oil palm systems, including above-ground biomass, below-ground biomass, and soil organic carbon, presents unique challenges for accurate assessment and monitoring. Recent studies have highlighted substantial variations in carbon sequestration potential across different plantation ages, management practices, and environmental conditions (Komal et al., 2022). Understanding these patterns is crucial for developing sustainable management strategies and evaluating the industry's contribution to climate change mitigation efforts.

The application of remote sensing technologies, particularly the NDVI, has emerged as a powerful tool for monitoring vegetation dynamics and productivity in agricultural landscapes (Vidican et al., 2023). NDVI provides valuable insights into plantation health, biomass accumulation, and phenological changes across spatial and temporal scales. However, the relationship between NDVI values and actual carbon stocks in oil palm plantations remains incompletely understood, particularly concerning age-specific variations and seasonal dynamics (Tan et al., 2012).

Net ecosystem exchange (NEE) measurements offer crucial insights into the carbon exchange between oil palm ecosystems and the atmosphere, providing a direct assessment of their role as carbon sources or sinks (Virkkala et al., 2018). Recent eddy covariance studies in Southeast Asian oil palm plantations have revealed complex patterns of carbon flux, influenced by factors such as plantation age, management practices, and environmental conditions (Gomez et al., 2023). Understanding these dynamics is essential for accurate carbon accounting and developing strategies to optimize the environmental performance of oil palm cultivation.

The integration of carbon stock assessments, NDVI monitoring, and NEE measurements presents an opportunity to develop a more comprehensive understanding of carbon dynamics in oil palm landscapes. This approach is particularly relevant in Riau Province, where diverse plantation ages, management practices, and environmental conditions create a complex mosaic of ecosystem functions (Song et al., 2024). Despite the importance of this integrated approach, few studies have examined these three aspects simultaneously within the same plantation systems.

Furthermore, the relationship between vegetation indices and ecosystem carbon exchange in oil palm plantations remains poorly quantified, particularly in the context of varying management practices and environmental conditions (Alvarez et al., 2024). Understanding these relationships is crucial for developing effective monitoring systems and improving our ability to predict carbon dynamics across large spatial scales. This knowledge gap is particularly significant given the increasing pressure to develop sustainable plantation management practices that optimize both productivity and environmental performance.

This research addresses these knowledge gaps by conducting a comprehensive assessment of carbon stocks, NDVI patterns, and NEE in oil palm plantations across Riau Province. The study employs a multi-scale approach, combining field measurements, remote sensing analysis, and continuous flux monitoring to provide insights into the complex interactions among these parameters. These findings will contribute to our understanding of carbon dynamics in oil palm systems and inform the development of sustainable management practices in this crucial agricultural sector.

The integration of these three components—carbon stocks, NDVI, and NEE—provides a unique opportunity to develop a more nuanced understanding of ecosystem functioning in oil palm plantations. This knowledge is essential for improving management practices, enhancing carbon sequestration potential, and informing evidence-based policy decisions in the oil palm sector (Scriven et al., 2022). Furthermore, the study's findings will contribute to the broader scientific understanding of agricultural ecosystem dynamics and their role in global carbon cycling.

## MATERIALS AND METHODS

### Research procedures

This research was conducted from August 2022 to May 2024 in oil palm plantations across six regencies of Riau Province: Kampar, Siak, Pelalawan, Rokan Hulu, Indragiri Hulu, and Indragiri Hilir (Figure 1). The study employed a

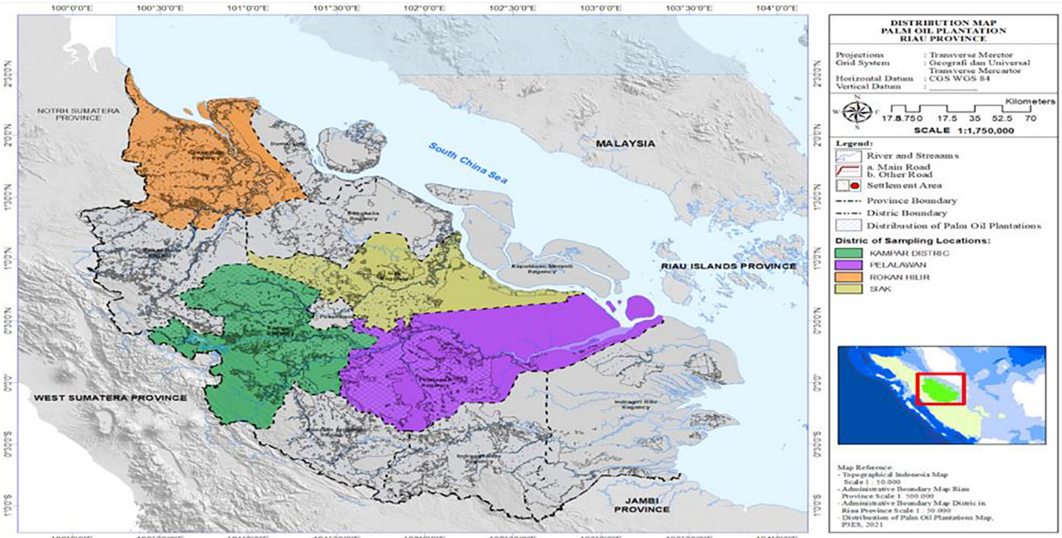


**Figure 1.** Location of oil palm plantation research in Riau

nested sampling design to account for variations in palm age and plantation location.

The study focused on productive oil palms aged 8–16 years (PP8-16). Leaf freshness and greenness were monitored monthly for six months using an RGB color analyzer on fronds 9, 17, and 25. The analyzed parameters included quantification of red, green, blue spectrums, along with Hue, Saturation, and Value measurements, with the RGB color analyzer providing values ranging from 0 to 1023. NDVI measurements were conducted using multispectral data obtained from both drone and satellite imagery. The study specifically examined 8- to 16-year-old oil palms of the PPKS variety. The research equipment included measuring rulers, hoes, hand augers, digital scales, a Haga altimeter, $CO_2$ and $CH_4$ measurement devices, and GPS units.

Visualization process of vegetation index values in QGIS: The Sentinel-2 satellite imagery from the rainy season was selected due to optimal conditions for oil palm growth. Initial processing involved resampling the Sentinel-2 imagery using SNAP software to standardize pixel sizes across all spectral bands. The imagery was then cropped using QGIS 3.28.3 to isolate the study area. Vegetation index analysis was performed using the raster calculator tool in QGIS 3.28.3 to compute band values and vegetation indices. The raster calculator enabled algebraic operations on raster layers, after which the resulting layer was converted to polygons. Zonal Statistics were then applied to extract reflectance values from the study area. Finally, the reflectance values were compiled and exported as a CSV file for further analysis.

### Data analysis

Data were analyzed using one-way ANOVA with a significance level of $\alpha = 0.05$. When significant differences were detected, post-hoc comparisons were performed using Tukey's honest significant difference (HSD) test at a 95% confidence level ($\alpha = 0.05$). All statistical analyses were conducted using Minitab version 22.

## RESULTS AND DISCUSSION

### Carbon stocks of oil palm plantations

Carbon stocks in oil palm plantations comprise carbon stored in aboveground biomass (stems, leaves, and fresh fruit bunches), belowground biomass (roots), and soil organic matter (Malaga et al., 2021). Oil palm biomass typically stores 30–50 tonnes of carbon per hectare, while soil carbon content ranges from 50–200 tonnes per hectare, varying with soil type, palm age, and management practices. Palm age significantly influences carbon stocks, with mature palms accumulating higher carbon content due to increased biomass (Ramos et al., 2018). However, land conversion for oil palm cultivation, particularly on peatlands or in primary forests, often results in substantial carbon emissions. Peatland conversion can release 300–800 tonnes of carbon per hectare through drainage and organic matter decomposition.

Oil palm plantations function as carbon sinks during their growth phase by sequestering atmospheric carbon dioxide ($CO_2$) through photosynthesis. Carbon stocks in these plantations can be enhanced through sustainable practices, including the incorporation of biomass residues into soil, establishment of cover crops, and avoidance of peatland conversion. These management strategies align with sustainability initiatives, particularly the roundtable on sustainable palm oil (RSPO), which seeks to minimize the carbon footprint and climate impact of oil palm cultivation. While well-managed oil palm plantations can serve as net carbon sinks, significant challenges persist in mitigating emissions from land conversion.

The carbon stock in oil palm plantations across six regencies in Riau Province shows significant variations based on the planting year. In 2022, Rokan Hulu, Indragiri Hilir, and Indragiri Hulu recorded the highest carbon stocks at 41.46 $tC·ha^{-1}$, 41.49 $tC·ha^{-1}$, and 40.44 $tC·ha^{-1}$, respectively, which were statistically different from other regencies. In 2023, the same trend continued, with Rokan Hulu (43.46 $tC·ha^{-1}$) and Indragiri Hilir (42.67 $tC·ha^{-1}$) maintaining the highest carbon stock values, while Kampar, Siak, and Pelalawan showed significant increases compared to the previous year. By 2024, the highest carbon stocks remained in Rokan Hulu (41.43 $tC·ha^{-1}$) and Indragiri Hilir (41.92 $tC·ha^{-1}$), although no significant increase was observed from the previous year. In contrast, Siak and Pelalawan exhibited notable increases, reaching 40.85 $tC\ ha^{-1}$ and 40.94 $tC·ha^{-1}$, respectively. These variations indicate that location and land management practices may contribute to carbon stock accumulation in oil palm plantations, with Rokan Hulu and Indragiri Hilir tending to have higher carbon storage potential compared to other regencies (Table 1).

These findings are consistent with the literature stating that carbon stocks in oil palm plantations depend on above and below-ground biomass, as well as soil organic matter. Guillaume et al. (2021) explained that sustainable management practices, such as returning crop residues to the soil, can increase the soil's capacity to store carbon. In addition, Page et al. (2011) highlighted the importance of avoiding peatland conversion for oil palm plantations, because although plants can sequester carbon during the growing period, significant carbon release can occur due to initial land conversion. Overall, these results suggest that oil palm plantations in Riau have the potential to be significant carbon sinks, especially if supported by sustainable practices as proposed by initiatives such as the RSPO (Ruysschaert and Salles, 2014).

## Normalized difference vegetation index

Vegetation density in satellite image processing can be determined using a density index. The commonly used vegetation density index is the normalized difference vegetative index (NDVI), which utilizes reflectance from near-infrared (NIR) waves and red visible light waves. NDVI is generally used to assess forest ecosystem density. The density of oil palm plantation vegetation can also be determined using NDVI because the structure of oil palm plantations is similar to forests (McMorrow, 2001). NDVI values range from -1 to 1. If a land cover has a positive value and approaches one, it indicates a high vegetation density. In addition to determining vegetation density in an area, NDVI can be used to estimate plant age, biomass, and radiation absorption.

**Table 1.** Carbon stocks of oil palm plantations in six districts of Riau province

| Regency | Planting year | | |
|---|---|---|---|
| | 2022 | 2023 | 2024 |
| Kampar | 38.27 b | 40.04 bc | 40.59 b |
| Siak | 34.49 bc | 35.93 d | 40.85 b |
| Pelalawan | 34.58 bc | 37.36 c | 40.94 ab |
| Rokan Hulu | 41.46 a | 43.46 a | 41.43 a |
| Indragiri Hulu | 40.44 ab | 42.72 a | 40.58 b |
| Indragiri Hilir | 41.49 a | 42.67 ab | 41.92 a |

**Note:** Numbers in the column that share the same lowercase letter do not differ significantly according to the 5% HSD test.

NDVI produces values ranging from -1 to 1, with vegetation areas showing values between 0 and 1, while values below 0 indicate non-vegetation areas (Liu et al., 2019).

Based on the analysis of NDVI data on oil palm plantations in six districts of Riau Province, there was a consistent increase in NDVI values from 2023 to 2024 (Table 2). NDVI values indicate the health of vegetation and canopy density, where this increase reflects improvements in environmental quality or better plant management (Haque et al., 2024). In 2022, NDVI values ranged from 0.67 (Indragiri Hulu) to 0.70 (Siak and Indragiri Hilir). In 2023, the value increased from 0.69 (Kampar) to 0.77 (Rokan Hulu and Indragiri Hulu), while in 2024, Siak Regency showed the best performance with the highest value of 0.81. Siak Regency consistently showed the best vegetation performance throughout the analysis period, while other districts showed a significant increase in NDVI values. This increase may be due to the implementation of sustainable agronomic practices, such as proper fertilization and efficient water management, as well as environmental factors such as favorable rainfall (Lamptey, 2022).

This increasing trend of NDVI indicates that good plantation management and optimal environmental conditions can support the growth of oil palm plants. As a vegetation monitoring tool, NDVI is very useful for identifying differences in productivity levels between regions, as well as an indicator of sustainable land management (Yengoh et al., 2016). Thus, these results can be the basis for strategic decision making in increasing the productivity and sustainability of oil palm plantations.

## Analisis net ecosystem exchange

The analysis of net ecosystem exchange (NEE) in oil palm plantations across Riau Province reveals significant variations between regencies, which can be attributed to differences in plantation size and the average age of the plants. All regencies recorded negative NEE values, indicating that oil palm plantations in the region function as net carbon sinks. The analysis of NEE in oil palm plantations in Riau Province shows that all regencies exhibit negative NEE values, ranging from -1.64 ± 0.05 to -1.82 ± 0.01 gC/m²/day. These negative values indicate that the oil palm plantations act as net carbon sinks. Siak Regency recorded the lowest NEE (-1.82 ± 0.01 gC/m²/day), signifying the highest carbon sequestration capacity, despite having a plantation area of 695.7 hectares and an average plant age of 15 years, which are not significantly different from other regencies. In contrast, Kampar had the highest NEE value (-1.64 ± 0.05 gC/m²/day), with the smallest plantation area (485.4 hectares)

**Table 2.** Normalized NDVI of oil palm plantations in six districts of Riau province

| Regency | Planting year | | |
|---|---|---|---|
| | 2022 | 2023 | 2024 |
| Kampar | 0.68 ab | 0.69 c | 0.81 a |
| Siak | 0.70 a | 0.75 ab | 0.81 a |
| Pelalawan | 0.68 ab | 0.72 b | 0.79 b |
| Rokan Hulu | 0.69 ab | 0.77 a | 0.80 ab |
| Indragiri Hulu | 0.67 ab | 0.77 a | 0.80 ab |
| Indragiri Hilir | 0.70 a | 0.71 bc | 0.80 ab |

**Note:** Numbers in the column that share the same lowercase letter do not differ significantly according to the 5% HSD test.

**Table 3.** Analysis of net ecosystem exchange (gC/m²/day) in oil palm plantations in Riau Province

| Regency | NEE | Plantation area (ha) | Average age of plants (years) |
|---|---|---|---|
| Kampar | -1.64 ± 0.05 | 485.4 | 12 |
| Siak | -1.82 ± 0.01 | 695.7 | 15 |
| Pelalawan | -1.78 ± 0.02 | 575.3 | 13 |
| Rokan Hulu | -1.73 ± 0.05 | 665.2 | 10 |
| Indragiri Hulu | -1.68 ± 0.01 | 505.8 | 17 |
| Indragiri Hilir | -1.72 ± 0.05 | 583.6 | 12 |

and an average plant age similar to that of Indragiri Hilir (12 years) (Table 3). The decline in carbon sequestration capacity in older plants can be explained by reduced photosynthetic rates and increased autotrophic respiration (Xu et al., 2020).

Additionally, the data suggest a trend where NEE tends to decrease (carbon sequestration increases) as plant age increases, as seen in Indragiri Hulu, with an average plant age of 17 years and an NEE of -1.68 ± 0.01 gC/m²/day. However, this trend is not consistent across all regions, indicating the potential influence of other factors, such as land management practices, soil types, and local climatic conditions, on carbon sequestration. Further analysis is needed to link NEE variations to biotic and abiotic factors in each regency, tend to support better carbon management due to the potential for increased biomass and carbon stocks (Guillaume et al., 2018).

Overall, these findings highlight the critical role of oil palm plantations as carbon sinks at the landscape scale. However, the data also suggest that carbon sequestration capacity tends to decline as plant age increases. Therefore, strategies such as replanting older oil palm trees could help maintain carbon sequestration capacity over the long term. Furthermore, the adoption of sustainable agricultural practices to maximize the ecosystem benefits of oil palm plantations is strongly recommended, as supported by existing literature (Lusiana et al., 2023).

### Correlation of carbon stock and NDVI with production oil palm

Correlation between carbon stock and oil palm production: carbon stock, which refers to the accumulation of carbon in plant biomass (including stems, leaves, and roots), is closely related to oil palm productivity. A high carbon stock typically indicates healthy plants with substantial biomass, potentially resulting in higher yields of fresh fruit bunches (FFB). However, this correlation may vary depending on plant age, agronomic management, and environmental conditions. Studies by Kotowska et al., (2015) show that carbon accumulation peaks during the intensive vegetative growth phase (10–15 years), which often coincides with the most productive period. For older plants, productivity tends to decline even though carbon stock remains high, as carbon investment shifts towards maintaining plant structures rather than fruit production.

Correlation between NDVI and oil palm production – the NDVI is an indicator used to assess vegetation health, specifically the ability of leaves to absorb red light and reflect near-infrared light. High NDVI values indicate dense canopies with healthy green leaves, typically associated with high photosynthetic capacity and good productivity. For oil palm, a positive correlation between NDVI and production is commonly observed, particularly in young to mature, productive plants. However, NDVI may become less sensitive to production changes in older plants, where a decline in fruit yields does not always correspond to significant changes in vegetation index values (Glenn and Tabb, 2019).

Link between carbon stock, NDVI, and production – carbon stock and NDVI together provide a more comprehensive picture of the condition of oil palm plantations. Carbon stock reflects total biomass accumulation, while NDVI specifically captures canopy dynamics. When these two indicators are combined, they can identify growth phases of plants that are optimal for production. Research by Abbas et al. (2020) emphasizes the importance of integrating biomass measurements with satellite-based NDVI data to more accurately predict production and the carbon sequestration potential of ecosystems.

## CONCLUSIONS

The research on carbon dynamics and vegetation indices in oil palm plantations across six districts of Riau Province revealed several significant findings. Carbon stock analysis unveiled substantial spatial and temporal variations, with Rokan Hulu and Indragiri Hilir consistently maintaining the highest carbon storage capacity, demonstrating the significant influence of location factors and land management practices on carbon accumulation. NDVI assessment showed a consistent increasing trend from 2022 to 2024 across all districts, with Siak District exhibiting the best vegetation performance, reflecting the successful implementation of sustainable agronomic practices. The negative NEE values across all districts prove that oil palm plantations function as net carbon sinks, although absorption capacity tends to decrease with plant age. The integration of these three parameters provides a comprehensive understanding of oil palm plantation ecosystem functions and their potential in climate change mitigation. This research provides a scientific foundation for developing more effective and sustainable land management strategies in the oil palm plantation sector, while contributing to a better understanding of oil palm plantations' role in the global carbon cycle.

### Acknowledgements

The author would like to thank the APKASINDO and LPPM Universitas Riau to support this research.

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