**Special Issue:** Agricultural Productivity and Sustainability Improvement in Tropical Region

# Land Suitability Assessment and Soil Organic Carbon Stocks as Two Keys for Achieving Sustainability of Oil Palm (*Elaeis guineensis* Jacq.)

**Didiek Hadjar Goenadi[1,2*], Roy Hendroko Setyobudi[3,4], Erkata Yandri[3,4], Kiman Siregar[5,6], Aris Winaya[7], Damat Damat[7], Wahyu Widodo[7], Ahmad Wahyudi[7], Praptiningsih Gamawati Adinurani[4,8], Maizirwan Mel[9], Ivar Zekker[10], Muhammad Zul Mazwan[7], Devi Dwi Siskawardani[7], Endang Dwi Purbajanti[11] and Ida Ekawati[12]**

*[1]Indonesian Research Institute for Biotechnology and Bioindustry, Bogor 16128, West Java, Indonesia; [2]Indonesian Inventor Association, Special Capital Region of Jakarta 12520, Indonesia; [3]Renewable Energy Graduate School, Darma Persada University. Jakarta 13450, Indonesia; [4]Indonesian Association of BioEnergy Scientists and Technologists (IABEST), Jakarta 10340, Indonesia; [5]Faculty of Agriculture, Syah Kuala University, Banda Aceh 23111, Indonesia; [6]Indonesian Life Cycle Assessment Network (ILCAN), Serpong Tangerang, 15314, West Java, Indonesia; [7]Faculty of Agriculture, University of Muhammadiyah Malang, Malang 65145, East Java, Indonesia; [8]Faculty of Agriculture, Merdeka University of Madiun, Madiun 63133, East Java, Indonesia; [9]Faculty of Engineering – Biotechnology, International Islamic University Malaysia 50728 Kuala Lumpur, Malaysia; [10]Institute of Chemistry, University of Tartu, 50411 Tartu, Estonia; [11]Faculty of Animal and Agricultural Sciences, Diponegoro University, Semarang 50275, Central Java, Indonesia; [12]Faculty of Agriculture, Wiraraja University, Sumenep 69451, East Java, Indonesia.*

**Abstract** | The most efficient oil-producing crop, oil palm (*Elaeis guineensis* Jacq.) is able to generate a higher yield than soybean [*Glycine max* (L.) Merr.], rapeseed (*Brassica napus* L.), and sunflower (*Helianthus* L). Relatively affordable in price, palm oil is in high demand in Asia. Further than a food source, Crude Palm Oil also serves as feedstock for biodiesel – an environmentally friendly renewable energy. In Indonesia, the palm oil industry plays an essential role in the national economy. However, negative issues in oil palm cultivation bring certain apprehension towards its industrial sector in implementing the concept of sustainable development. To overcome this, the sustainable certification has been developed through the Roundtable on Sustainable Palm Oil (RSPO) and Indonesia Sustainable Palm Oil (ISPO) in order to accomplish the global standards for sustainable palm oil. RSPO and ISPO function to minimize the negative effect of oil palm production on the environment and social community. Indonesia's National Team for the Acceleration of Poverty Reduction indicates that oil palm in Indonesia has significantly contributed to at least six out of the 17 sustainable development goals (SDGs). This review addresses 56 references from Google Scholar for the issues on understanding the sustainability from land management's perspective, the land suitability for oil palm, and the strategy for land management to achieve oil palm sustainability. The role of land management technology and the maintenance of soil carbon stocks are emphasized as vital parts of best management practice to achieve conditions in line with SDGs.

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***Correspondence** | Didiek Hadjar Goenadi, Indonesian Research Institute for Biotechnology and Bioindustry, Bogor 16128, Indonesia; **Email:** dhg_rpn@yahoo.com
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## Introduction

Vegetable oils are commodities for public consumption. Considering their wide use by those of lower-income strata, they hold a critical function in social welfare and health. As natural-resource-based products, vegetable oils are facing environmental issues with agricultural practices concerning long-term trade-offs among people, the planet, and prosperity. As internationally-traded commodities, inevitable competition among vegetable oils has driven producers to take all measures to protect their markets which – to some extent – lead to an unfair zone that can become counter-productive in terms of global development to achieve sustainability.

Many definitions of sustainability have been proposed; for the sake of brevity, "sustainable" in this review means "able to avoid natural resource depletion in order to maintain an ecological balance." Although the Sustainable Development Goals (SDGs) and their targets have been agreed upon by most countries globally, the execution varies depending on the internal policy applied in each country. This situation creates gaps in the interpretation and implementation of sustainable practices related to own commodity versus others. Take oil palm (*Elaeis guineensis* Jacq.) as the most efficient oil-producing crop (Goh *et al*., 2016), which will directly or indirectly face attacks and accusations on its sustainability, especially by countries and regions with interests in the competitor crops such as soybean [*Glycine max* (L.) Merr.], rapeseed (*Brassica napus* L.), and sunflower (*Helianthus* L.). (Sharma *et al*., 2012).

A study reported by *Tim Nasional Percepatan Penanggulangan Kemiskinan* (Indonesia's National Team for the Acceleration of Poverty Reduction) in 2018 indicates that oil palm in Indonesia has made significant contributions to at least six out of the 17 points of SDGs: to reduce poverty (SDG #1), to diminish inequalities (SDG #10), to aid food security (SDG #3), to support food fortification (SDG #2), to contribute in national economic performance (SDG #8), and to increase renewable energy mix as well as prevent environmental deteriorations (SDG #13) (TNPPK, 2018). After comparing selected vegetable oils (*i.e*., palm, rapeseed, soybean, and sunflower oils) in regards to their impacts on SDGs achievement, Alamsyah *et al*. (2020) found that palm oil was of the highest rate. However, these two studies lack analyses on the current sustainability statuses of those world-leading vegetable oils. Meijaard *et al*. (2020) observed the environmental impact of palm oil in the context then stated that to comply with SDGs, demands on land between agriculture (SDG # 2) and biodiversity (SDG # 15) should be well-balanced.

The Roundtable on Sustainable Palm Oil (RSPO) is the existing voluntary standard of palm oil sustainability, yet its application holds various divergences. Indicated by Van den Homberg (2020) of the International Union for Conservation of Nature Netherlands (IUCN NL) that improving RSPO uptake and the quality of its assurance can support risk mitigation in palm oil sourcing, investing, and lending. He also emphasized that since voluntary standards would not suffice, obligatory application of due diligence and sustainability criteria set by governments should complement. The unions persuaded the EU and governments in producing countries to set high-quality mandatory sustainability requirements that also served as examples and additional tools both in legislation and in implementation. Five minimum criteria adopted as mandatory across the EU policy and regulation – legality, general good business practice, deforestation-free and conversion-free production, respect for rights, and climate-smart and biodiversity-smart agricultural practices – were proposed accordingly.

In addition to RSPO, Indonesia implements Indonesia Sustainable Palm Oil (ISPO) instructed by her Ministry of Agriculture, State Ministry for the Environment, Ministry of Forestry, and National Land Agency. Pertaining both RSPO and ISPO aims to minimize the negative effect of oil palm production on both the environment and social community (Hidayat *et al*., 2018; Norhana *et al*., 2021; Shahputra and Zen, 2018). Going through so many sustainability standards makes it look like a complex set of issues, which calls for a one-shot regulation mechanism. To simplify, sustainability should be about minimizing environmental damage while still producing enough food and feed for the current generation and beyond. The extent of this principle then includes environmental safety, people's welfare, and healthy life (Herry *et al*., 2020). From a land management perspective, these three orientations strongly focus on enabling humanity to manage its environment without permanent damage.

This review discusses the basic capital is supporting agriculture, namely land, particularly in the production of biomass for energy or bio-energy, concerning common sustainability criteria and standards of land utilization for oil palm in Indonesia.

## Materials and Methods

*Understanding sustainability from land management perspective*

Sustainability could be defined as a result of activities that are: (i) not creating environmental damages, (ii) maintaining and/or improving soil fertility, (iii) increasing revenues, (iv) improving farmers' welfare, (v) opening education opportunity, and (vi) providing a better life for growers (Goenadi, 2019). These targeted conditions have been more or less included in the so-called seventeen SDGs of the United Nations declared in 2013 (Björn-Ola and Selin, 2013). As indicated previously, oil palm in Indonesia significantly contributes to at least six of them (TNPPK, 2018).

*Land as a non-renewable resource*

Land, consisting of soils and access to the above atmosphere, is the principal capital for growers. Both components are considered non-renewable but re-usable resources, and to some extent they are challenging to manage, especially concerning climatic factors. As a natural living body, Soils would be fragile when exposed to any anthropogenic damages and under unique ecosystem conditions, such as wetland and peatland areas. Draining wetland areas for land clearing and cultivation endangers the area to fire hazards and accelerated decomposition of organic matter, resulting in greenhouse gas (GHG) emissions to the atmosphere. From a sustainability point of view, these conditions must be avoided. Therefore, it could be assumed that sustainable land management means managing the land without any damages or, in other words, managing the non-renewable resources according to their capacity. Damaging non-renewable resources will create a big disaster sooner or later.

However, we should also appreciate all technology developers who tirelessly dedicate their time to finding the most effective way to minimize the damages while achieving profitable yields. Technologies vary from practical drainage methods to advanced biotechnological approaches, such as genome editing to construct new crop varieties tolerant to various a-biotic restrictions like waterlogging, prolonged drought, or strong-acid soil reaction. Technology is a strategic means to overcome problems regarding crop growth and yield while maintaining repairable damage.

Managing soil based on its capacity is the basic philosophy of sustainable agriculture. It should be implemented from the beginning of land use – in the stage of land suitability evaluation – involving soil and climatic factors such as air temperature, rainfall, and sunlight. Evaluation on soil characteristics is intended to map the possible conditions that limit the use of land and the growth of plants and, consequently, crop production. Shallow, coarse texture, deficient in organic matter and nutrient contents, strongly acidic reaction, and potentially toxic materials are substantial growth-limiting soil characteristics. For land-use suitability (LUS), McDowells *et al.* (2018) introduced the concept of Productivity within Environmental Constraints (PEC). Three indicators employed in this concept for evaluating land-water systems are productive potential (explaining the natural productive and economic potential of land parcels), relative contribution (illustrating the potential of a land parcel to throw in contaminants – related to other land parcels – to downstream receiving environments), and pressure (describing the contaminant load delivered to a receiving environment compared to the load that ensures that environmental objectives are met). It should be able to supply incorporated information on possible economical, environmental, social, and cultural upshots in every land-use option, thus the concept also serves as a decision-making tool for stakeholders.

Another critical instrument to ensure sustainable agriculture and attain the current global food security goal corresponding to the SDGs is agricultural land suitability analysis (ALSA) for crop production. However, despite the number of review studies addressing land suitability, few of them specifically concentrate on land suitability analysis for agriculture (Akpoti *et al.*, 2019). Since land suitability assessment is indeed indispensable in attempts to increase production as well as arrange a sustainable agricultural system (Taghizadeh-Mehrjardi *et al.*, 2020), ALSA should be capable of controlling the potential negative impacts and keeping it at a minimum to the environment.

*Technology and land sustainability*

The use of land is directly related to the activity of humans. In a case study in Northeastern Thailand, Heumann *et al.* (2013) examined the correlations between the natural environment, built-up area, and social environments related to the common crops of Nang Rong District – cassava, (*Manihot esculenta* Crantz), long grain rice (*Oryza sativa* L.), and jasmine rice (*Oryza sativa* L. var. Thai Hom Mali) as well as fruit. The results indicate that while the natural environment (such as elevation and soils) is often the leading factor in crop similarity, local characteristics (such as local assets and locality conditions or developed environments) are also influential. Moreover, the shape of the land use-environment curves illustrates these relationships' non-continuous and non-linear nature. This method reveals a unique comprehension of non-linear correlations between land and people.

Different regions may utilize divergent methods of agricultural sustainability, and some of them are distinctive to certain areas (Amini *et al*., 2020). But, it is definite that whatever method applied must be founded on social, economic, and ecological sustainability (Chelan *et al*., 2018; Dantsis *et al*., 2010, Dempsey *et al*., 2011; Quintero-Angel and González-Acevedo, 2018). In agriculture, the golden rules of sustainability cover upholding or increasing the environment's natural resources, satisfying food demands, and fostering social welfare; once farmers improve the efficiency of their used inputs, their economic and environmental goals should be within their reach. It is essential to realize that any restraints on production factors are corrigible (Atanda, 2019; Koeijer *et al*., 2002; Praneetvatakul *et al*., 2001). A study showed that optimal electricity consumption and chemical fertilizers contributed significantly to reducing the climate impact in corn (*Zea mays* L.) fodder production (Esfahani *et al*., 2017). One recommended arrangement was to employ different irrigation methods in order to conserve water and reduce power consumption due to groundwater pump operation. The other proposal was to encourage more effective ways of utilizing chemical fertilizers towards farmers. After observing sustainability determinants of rainfed and blue rice cultivation, Roy and Chan (2015) perceived that knowledge, skill, and commodity efficiency were vital to sustaining rice production. Further findings are that applying resource-conservation technology in irrigated rice was helpful in productivity enhancement and natural resources conservation attempts and that improving land productivity was a formative factor in rice sustainability. It is evident then that the understanding of sustainability from land management viewpoints should involve any mitigations of possible degrading soil capacity by using appropriate technologies to maintain land productivity.

## Results and Discussion

*Land suitability for oil palm*

Everest *et al.* (2021) has stated that optimal use of natural resources is crucial for the environment. Also, since land degradation is a significant threat to natural resources, avoiding mistreatment and mismanagement is necessary. Site selection is the first key component to sustainable land use management strategies. Land reduction, deterioration, and deprivation calls for sustainable agricultural practices. To avoid soil degradation, running Land Suitability Analysis (LSA) is one of the best options. Environmental problems will likely arise when land is not managed by its potentials and properties, and LSA helps to plot the optimal land-use opportunities.

*Land use capability to support oil palm*

Oil palm development, which usually involves a considerably large area, beyond doubt requires land assessment. With the current oil palm boom as a highly efficient source of vegetable oil, several non-governmental environmental organizations and consumers have been raising arguments regarding potential ecological damage and global warming issues brought by the commodity; such condition indeed demands an even higher need on one. To top it up, criticisms motivated by competing interests of other central producer countries make oil palm development a significant concern. According to Pirker *et al.* (2016), when employing climatic conditions as land suitability criteria for oil palm, about $1.37 \times 10^9$ ha land – concentrated in 12 tropical countries – is suitable for oil palm and is. Nevertheless, the number is 30 % lower when current land uses for other eligible commodities and protected areas are considered. It was also found that the non-conversion rates of high carbon stock forest (>100 t AGB $ha^{-1}$), the most likely be the main restricting factor for future oil palm expansion, covers two-thirds of the suitable global area for oil palm. Using eight criteria considered to restrict future land availability for oil palm expansion, 234 × $10^6$ ha or 17 % of the appropriate worldwide area left was recorded. Although the limits are far for expanding oil palm, area accessibility and competition with other agricultural commodities are more factors to count. After considering all information, the maximum area available for oil palm expansion is conclusively about 18 % of 234 × $10^6$ ha, which equals approximately 42 × $10^6$ ha.

In practice, oil palm plantation establishment is always and should be based on land capability evaluation. As the parameter of land suitability for agricultural production, Land Use Capability Classification (LUCC) is a basic set of criteria to allow better comprehension in land surveys (Everest, 2017). LUCC assesses land characteristics and sub-parameters – such as climate, soil, topography, and drainage properties – and evaluates as well as classifies the land suitability for various types of cultivated plants. Two orders and eight classes are presented in LUCC classification: ranges I to IV puts land in the first order (suitable for cultivation) and, therefore, capable of producing adapted plants under good management, while V to VIII lays one in the second-order (not ideal for agricultural practices). Further, lands in classes I and II are apt for growing nearly all types of cultivation, and the degree of aptness falls starting class III. Even though lands in class V are improper for cultivation in their current situations, upgrading them to higher classes is attainable through either cultural or chemical improvements or both. Meanwhile, lands in classes VI, VII and VIII are not suitable for cultivation due to inclination and soil shallowness problems; therefore, class VI should function for grazing land and forest, whereas class VII should be under forest cover (Everest *et al.*, 2011). Goenadi (2017) specifically emphasized – and re-emphasized (Goenadi, 2019) – how vital LSA is for oil palm to achieve sustainable production. Evaluating optimum crop growth conditions, soil characteristics, and climatic factors to match targeted new land for oil palm plantation is what it is about. By applying this system, it should be possible to define certain land's class and determine whether any constraining factors are adaptable for oil palm; if they are difficult to change, it would be too expensive – or even impossible – to fix should damage occur. Five classes of land suitability for oil palm listed are: highly suitable, moderately suitable, slightly suitable, temporarily unsuitable, and permanently unsuitable.

*Land suitability assessment for oil palm*

Among vast LSA methods long and widely proposed for oil palm, Paramananthan (2011) has outlined the one based on soils and their environmental conditions that most likely affect oil palm yield. The criteria recorded during soil mapping and land suitability evaluation included climate (rain, temperature, sunshine hours, and wind), topography (slope), hydrology (moisture availability, flooding, and drainage), soil physical and chemical properties, and soil fertility. In addition, six groups of problem soils on which oil palm has been cultivated to date were described based on most potential handicaps present, *i.e.*, (i) poorly-drained non-acid sulfate soils, (ii) acid sulfate soils, (iii) organic soils, (iv) highly weathered soils, (v) sandy soils, and (vi) volcanic ash soils. These classifications are intended to guide planters in managing their land for oil palm without any or with minimum damage to the environment, particularly soil fertility, which must be closely related to the yield. Figure 1 shows how different land suitability classes affect the productivity of oil palm (Sufriadi, 2015). The current author believes that by applying proper technology, the S3 land class could achieve an S1 yield level without any significant damage to long-term soil fertility (indicated by the red arrow in Figure 1). For further references, an integration system used by Pirker and Mosnier (2015), who employed climatic, soil, and topographical factors for global oil palm land suitability assessment, are presented in Table 1, Table 2 and Table 3.

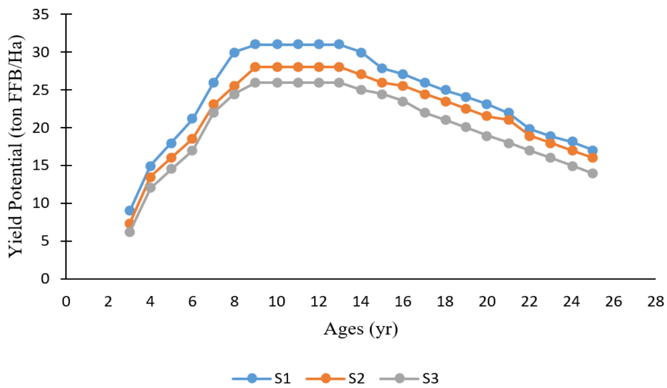


**Figure 1:** *Yield patterns of oil palm on different land suitability classes for oil palm (PPKS, 2010).*

*Strategy for land management to achieve sustainability of oil palm*

The high growth of oil palm cultivation in Southeast Asia has elicited environmental concerns about deforestation and greenhouse gas emissions, despite the fact that valid scientific data currently available

**Table 1:** *Palm oil suitability classes thresholds according to climatic factors.*

| Climatic Characteristics | Management | Suitability classes (from perfectly suitable = 5 to not suitable = 0) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 5 | 4 | 3 | 2 | 1 | 0 |
| Annual Precipitation (mm m$^{-2}$) | All | 2 000 to 2 500 | 1 750 to 2 000 | 1 500 to 1 750 | 1 250 to 1 500 | 1 000 to 1 250 | < 4 000 |
| | | 2 000 to 2 500 | 2 500 to 2 875 | 2 875 to 3 250 | 3 250 to 3 625 | 3 625 to 4 000 | > 4 000 |
| Annual Precipitation on well-drained soils (mm m$^{-2}$) | All | < 4 000 | 4 000 to 4 250 | 4 250 to 4 500 | 4 500 to 4 750 | 4 750 to 5 000 | > 5 000 |
| Number of dry months (monthly precipitation) | All | 0 | 1 | 2 | 3 | 4-5 | > 5 |
| Average Annual Temperature (°C) | All | 24.0 to 33.0 | 21.6 to 24.0 | 20.4 to 21.6 | 19.2 to 20.4 | 18.0 to 19.2 | < 18.0 |
| | | 24.0 to 33.0 | 33.0 to 34.0 | 34.0 to 35.0 | 35.0 to 36.0 | 36.0 to 38.0 | > 38 |
| Average temperature of the coldest month (°C) | All | > 15 | | | | | < 15 |

**Table 2:** *Palm oil suitability classes thresholds according to soil factors.*

| Soil Characteristics | Management type | Suitability classes (from perfectly suitable = 5 to not suitable = 0) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 5 | 4 | 3 | 2 | 1 | 0 |
| Pre-dominant soil texture type | Minimum | CL*), SCL, SiCL | SL, SiL, Si | L | C(heavy) LS | S | |
| | Optimal | Same as above | Same as above | Same as above | Same as above | Same as above | |
| Problematic soil properties | Minimum | - | Weathered and leached soils<br>Acid and sulfate soils | Gravelly stony or lateritic<br>High content of organic matter | Deep sandy soils | Poorly drained soils | Saline soils |
| | Optimal | - | - | - | - | - | - |
| Other permanent site properties | Minimum | - | - | - | - | - | Wetlands |
| | Optimal | - | - | - | - | - | Wetlands |

*) *S: sand, Si: silt, C: clay, L: loam*

**Table 3:** *Palm oil suitability classes thresholds according to topography factors.*

| Slope Characteristics | Management | Suitability classes (from perfectly suitable = 5 to not suitable = 0) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 5 | 4 | 3 | 2 | 1 | 0 |
| Slope in degrees | All | < 4 | 4 to 9 | 9 to 13 | 13 to 18 | 18 to 25 | > 25 |
| Elevation a.s.l. (m) | All | < 500 | 500 to 850 | 850 to 1 050 | 1 050 to 1 280 | 1 280 to 1 500 | > 1 500 |

are commonly insufficient to support this argument. Less attention is paid to the possible perturbation of hydrological functions and water quality degradation. Comte *et al.* (2012) conducted a review focusing on (i) the agricultural practices commonly used in oil palm plantations that potentially affect the hydrological process and water quality, and (ii) the hydrological changes and associated nutrient fluxes from plantations.

Regarding the water and fertilizer management recommendations, a number of studies researching agricultural practices are followed by planters (Irina *et al.*, 2012). Their review on hydrological studies in oil palm plantations showed that the major hydrological changes happened within the earliest years after land clearing, which seemed to dissipate as the plants grew bigger, since low nutrient losses were generally reported. Unfortunately, most of those studies were carried out at the plot scale and often focused on one hydrological process at a single plantation site (Irina *et al.*, 2012). Thus, information to evaluate the spatialtemporal fluctuations in nutrient losses throughout the entire lifespan of a plantation is inadequate. Furthermore, only a few studies provide an integrated view of agricultural practices and hydrological processes at a watershed scale that contributes to the nutrient shortfall and consequences for both surface and groundwater quality from oil palm plantations. Therefore, future research efforts need to understand and assess the potential of oil palm plantations to change hydrological functions and related nutrient fluxes by considering agricultural practices and evaluating water quality at the watershed scale.

*Long-term effect of oil palm on soil organic C stocks*

Land under oil palm or other perennial crops should go through a long period per cycle, so long-term effects on soil capacity must be considered due to this type of land use (Guillaume *et al*., 2016; Hsiao-Hang *et al*., 2016). A monoculture in common practice, oil palm limits biodiversity and sources for soil organic matter stocks compared to the natural forest (Vincevica-Gaile *et al*., 2021). A study carried out by Rahman *et al*. (2021) in an oil palm plantation in West Sumatra aimed at establishing the relationships between oil palm management practices and C-organic stock in soils. Comparison made covered three different management practices:

1. Best Management Practices (BMP – cover crops, conventional fertilizer, and composted empty fruit bunches (EFB).
2. Current Management Practices (CMP – cover crops, conventional fertilizer, no EFB return).
3. Smallholder Management Practices (SHMP – no cover crops, conventional fertilizer occasionally and mainly urea, no EFB return).

Figure 2 and Figure 3, shows the fact that different management practices resulted in significant divergences of C-stocks dependent upon the soil depth and management zones (WC = weeded circle, FS = frond stack, IR = interrow, and HP = harvesting path). In addition, their data indicated that FFB production of BMP (27 t $ha^{-1}$) and CMP (26 t $ha^{-1}$) systems were significantly higher than that of SHMP systems (18 t $ha^{-1}$), with a positive linear relationship between SOC and FFB yield.

In an earlier study, Rahman *et al*. (2018) suggested forest conversion to oil palm plantation be associated with SOC stock, showing a decrease of 36 % in upper 30 cm soil and of 42 % in upper 70 cm soil 29 yr after conversion, which corresponds to a total C loss of 18 t $ha^{-1}$ and 33 t $ha^{-1}$ respectively. However, SOC stocks under oil palm plantations were slowly building up during the second rotation. Several other studies have reported that such conversion diminished SOC stock of the upper 30 cm soil, but they mainly assessed the early stages of oil palm life cycle. For example, Guillaume *et al*. (2015) found that SOC stock under a 14 yr-old oil palm plantation was 42 % lower than a forest in Indonesia. On the other hand, in Sarawak, Malaysia, a study evaluating the effects of a change from shifting cultivation to small-scale oil palm plantation found that SOC stocks in the upper 30 cm of the soil were 40 % lower after 15 yr under oil palm (Bruun *et al*., 2013). Moreover, Chiti *et al*. (2014) reported a 28 % SOC loss in the upper 0 cm to 30 cm layer after 25 yr of oil palm plantations in an area converted from primary forests to oil palm plantations in Ghana, contrasting Khasanah *et al*. (2015)'s statement that oil palm plantations in Indonesia could be considered carbon neutral after comparing oil palm plantations of different ages up to 25 yr and finding no disparity between the plantations irrespective of their previous land-use history.

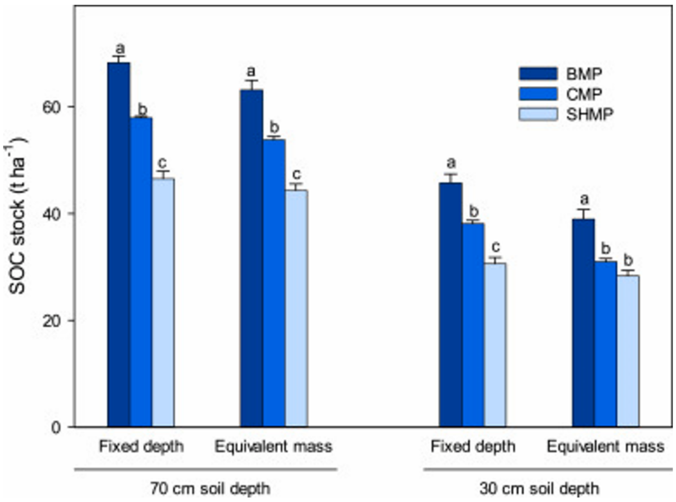


**Figure 2:** *Total SOC stock patterns of upper 70 cm and upper 30 cm soils under three management systems, calculated using fixed-depth and equivalent soil mass approaches regarding relative areas of four management zones. Different letters denote significant differences among management systems ($P < 0.05$) (Rahman et al., 2021).*

Rahman *et al*. (2018) doubted Khasanah *et al*. (2015); it is difficult to justify the carbon neutral claim, as the latter did not refer to original land use, *e.g*., forest or non-forest, when comparing SOC stocks of the plantations. After another look at Rahman *et al*. (2018), it could be estimated that SOC needs more than 60 yr to be back to its original level (Figure 4), and it is a costly consequence. Based on the data provided by Goenadi (2006), biomass generated in a 6 000 ha oil palm plantation was equivalent to 30 t FFB $h^{-1}$ palm oil mill – it amounts to 200 t EFB, 100 t decanted fibers, 70 t palm kernel shell, and 30 t palm kernel cake per day. Another source of plant biomass comes from oil palm frond (OPF), reported to be 10.4 t OPF from routine pruning activity $ha^{-1}yr^{-1}$ and 14.5 t OPF $ha^{-1}$ from replanting activity (MBIC, 2017). These organic matter sources produced in the oil palm areas should be returned to the soils to build up SOC stocks, providing more sustainable land productivity in the long run.

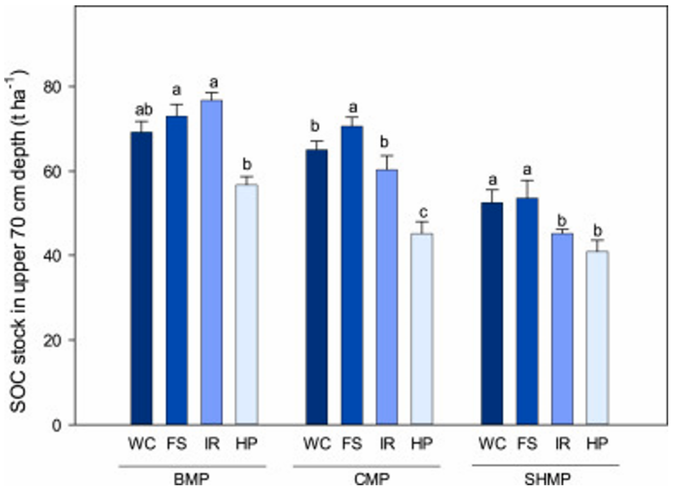


**Figure 3:** *SOC stock patterns in four management zones at different depths under three management systems (WC = weeded circle, FS = frond stack, IR = interrow, and HP = harvesting path). Different letters indicate SOC stock significance (P < 0.05) of upper 70 cm in different management zones per management system (*Rahman *et al.*, 2021*).*

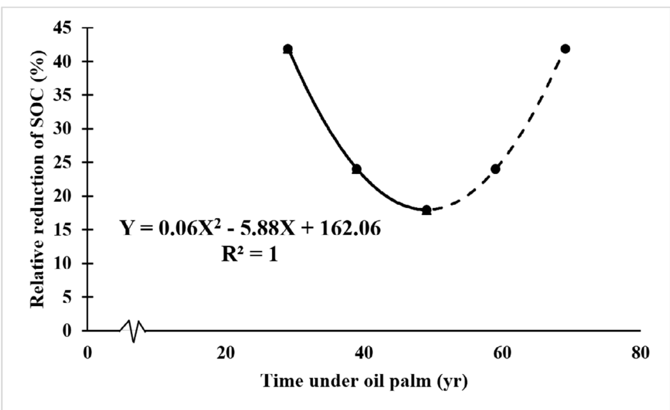


**Figure 4:** *Pattern of SOC reduction and presumed recovery during oil palm planting cycles (data extrapolated from (*Rahman *et al.*, 2021*).*

Similar studies carried out in the Amazon area by Frazao *et al.* (2013) suggested that SOC can be maintained over time with proper oil palm management in northern Brazil. However, land-use conversion to oil palm may involve significant C-debts. Conversing native rainforest shows SOC losses to be insignificant (or there may even be a small gain). Still, there is a hefty loss of above-ground biomass, on the order of 136 mg C $ha^{-1}$ during the first 50 yr of the process from land conversion to biodiesel production (Fargione *et al.*, 2008). On the contrary, conversing pasture can result in significant SOC losses, although this may be largely compensated by the increase of above-ground biomass C stocks in oil palm. Soil C stocks and changes after oil palm has been reported to be 41.4 mg $ha^{-1}$ during the first 12 yr of planting compared to pasture. These features on soil carbon stocks under oil palm production in Amazon provide valuable information to use in the Life Cycle Assessment (LCA) of oil palm biodiesel production.

Specifically, regarding the LCA of oil palm biodiesel in Indonesia, Kiman *et al.* (2019; 2020a) have conducted studies and demonstrated positive impacts. Furthermore, even Kiman *et al.* (2020b) reported a positive value of LCA on electricity production from biomass power plant system through biomass from palm oil mill.

*The critical factor in achieving oil palm sustainability*

Based on the above discussion, it could be outlined that managing the land for oil palm to achieve sustainability will involve some key factors. Among others, the application of composted EFB will be of top priority in combination with conventional complete chemical fertilizer (Goenadi, 2006). Crop residue maintenance in BMP may also help in improving soil quality and yields. While the present study suggests that applying organic amendments and inorganic fertilizers is advantageous, reducing inorganic fertilizers may affect yield. Upcoming long-term studies should focus on soil macronutrient and micronutrient dynamics concerning yield stability in BMP and potential carbon sequestration in several oil palm rotations (Rahman *et al.*, 2021). Intensive socialization of BMP to smallholders needs to be carried out to ensure they take this opportunity to improve their yield and SOC stocks simultaneously. It is undoubtedly not limited to sustaining palm oil production but also involving alternative biomass sources to provide additional values towards the whole oil palm economy and make it beneficial to all humankind. To achieve this ultimate goal, prospective technologies will comprise the conventional ones and biotechnology. Table 4 indicates various oil-producing crops that offer some application for bio-energy sources, including biodiesel (Dyer *et al*., 2012). In addition, some pyrolytic technology recommends using crop biomass – including EFB and OPF – as biochar feedstocks for low C emission soil organic matter inputs (Goenadi, 2020).

**Table 4:** *Current and potential feedstocks for biofuel production.*

| Source Fuel Type | Fuel Type |
|---|---|
| Corn | Ethanol |
| Sugarcane | Ethanol |
| Soybean | Biodiesel |
| Rapeseed | Biodiesel |
| Perennial plants on degraded lands | Ethanol/syngas/electricity |
| Crop residues (*e.g.*, corn stover) | Ethanol/syngas/electricity |
| Sustainably harvested forest materials | Ethanol/syngas/electricity |
| Double crops/mixed cropping systems | Ethanol/biodiesel/syngas/electricity |
| Municipal and industrial wastes | Ethanol/biodiesel/syngas/electricity |
| Recovery of oils from food industry | Biodiesel |
| Algae | Biodiesel |

Dyer *et al*. (2012) believe that significant challenges remain regarding the use of biofuels as sustainable alternatives to fossil fuels, such as the relatively high cost of biofuel production, competition with food-related practices (*e.g*., arable land and water usage), and the sheer differences in market size between agriculture and energy sectors.

Offering creative approaches to answer some of the most troublesome problems in regards of biofuels, biotechnology will undoubtedly play an essential role in its further development. For example, one of the main challenges is that the current agricultural practices are unable to deliver sufficient quantities at low enough prices to meet the vast demand. This problem could be handled, in part, by engineering crops to yield a much larger amount of carbon and energy contents. Application of advanced biotechnology approaches, such as genome editing and molecular docking, will undoubtedly open wider opportunities to develop and sustain oil palm cultivation for oil and biomass production. These issues become interesting when related to the analyses made by Hinkes (2019) and a solution offered by Mutsaers (2019). Referring to two significant policies (the European Parliament Resolution on palm oil and deforestation of rainforests and the EU's revised Renewable Energy Directive II), the EU outlines palm oil as a "forest-risk" and "high ILUC-risk" commodity, which contradicts its previous support for palm oil-based biofuels. The governments of Indonesia and Malaysia then acknowledge it as a "palm oil prohibition" and "crop discrimination," leading to a potential "trade war." Palm oil sustainability has been contested between palm oil-producing and palm oil-consuming countries for decades. The former pointed out how those policies had provoked the dispute even further. Conversely, the latter tried to provide a solution – since the oil palm expansion trend is inevitable – by having so-called degraded lands employ the superiority of perennial crops over speargrass [*Imperatacylindrica* (L.) P.Beauv.]. A well-established oil palm crop will then keep the grass at bay due to its intolerance for shade, and degraded land can regain its productive capacity, allowing smallholders to preserve their livelihood. Instead of ecological failure, oil palm should be regarded as a restorer. It is indicative that various parties, following their interests, have differently overviewed oil palm sustainability.

## Conclusions and Recommendations

Controversies on long-term oil palm sustainability that have been around in the last decades stem from how superior it is compared to other vegetable oil-producing crops due to its ability to be food and energy feedstock. Since the topic is anticipated by all soil scientists – including environmentalists – its land use for massive agricultural production must follow the basic standard of land exploitation. From the perspective of land management, questions on oil palm's sustainability in the future have been responded to worldwide by copious research that as long as cultivated following standard measures to avoid permanent disruption of soil capacity and to support economic returns, it is sustainable. Two important mandatory guidelines for sustainable oil palm to follow are LSA and soil C stocks maintenance and/or improvement. The growing appeal of economic opportunity to use oil palm biomass – both as bio-energy and as a higher-added value product – needs to be handled wisely by considering all potential trade-offs to the land use. Ignoring the needs of soils for organic matter inputs would end in disaster for future oil palm business as it, along with the broader economy, potentially drifts away from SDGs.

## Novelty Statement

Two important mandatory guidelines for sustainable oil palm to follow are LSA and soil C stocks maintenance and/or improvement. The growing appeal of economic opportunity to use oil palm biomass as bio-energy and as a higher-added value product needs to be handled wisely by considering all potential trade-offs to land use. Ignoring the needs of soils for organic matter inputs would end in disaster for future oil palm business as it, along with the broader economy, potentially drifts away from SDGs.

## Author's Contribution

**DHG:** Designed and implemented the study, elaborated the data analysis, performed literature search and analysis, and manuscript preparation.
**RHS:** Performed literature search, manuscript format, manuscript review, and manuscript revision.
**EY and KS:** Elaborated on the intellectual content and manuscript review.
**AW and DD:** Elaborated on the intellectual content and study supervision.
**WW, AW, PGA, MM, IZ, EDP and IE:** Performed literature search and manuscript review.
**MZM and DDS:** Turnitin and Grammarly check
All authors have read and approved the final manuscript.

*Conflict of interest*
The authors declare that there is no conflict of interest regarding the publication of this article.

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