Environmental Reviews

OPEN ACCESS | Review

A comparative synthesis of environmental sustainability in smallholder oil palm systems in Southeast Asia and Sub-Saharan Africa

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Abstract

Smallholder oil palm (OP) systems are central to rural livelihoods and global vegetable oil supply, yet the evidence base informing their environmental management is heavily concentrated in Southeast Asia (SEA). At the same time, OP cultivation is expanding across Sub-Saharan Africa (SSA), where production systems differ markedly. The uneven distribution of research and the rapid growth of the sector in Africa create a need for careful comparative synthesis to clarify where lessons are transferable and where they are not. This review compares smallholder OP systems in SEA and SSA to examine how contrasting development histories, agronomic practices, and governance shape current and future potential for environmental sustainability. This review synthesises evidence on nutrient management, soil fertility, yield potential, greenhouse gas emissions, crop residue management, and institutional constraints. SEA systems are generally characterised by higher external inputs, established processing infrastructure, and more developed certification and policy frameworks, alongside well-documented challenges related to nutrient losses, soil degradation, and emissions. In contrast, many SSA systems operate under lower-input, resource-constrained conditions, with complex land tenure systems, resulting in distinct productivity and environmental profiles. Rather than assuming a common development trajectory, the review highlights major differences that influence environmental performance across regions. By distinguishing between context-specific challenges and potentially transferable practices, this synthesis provides a clearer evidence base for researchers, policymakers, and practitioners working to improve the sustainability of smallholder OP systems.

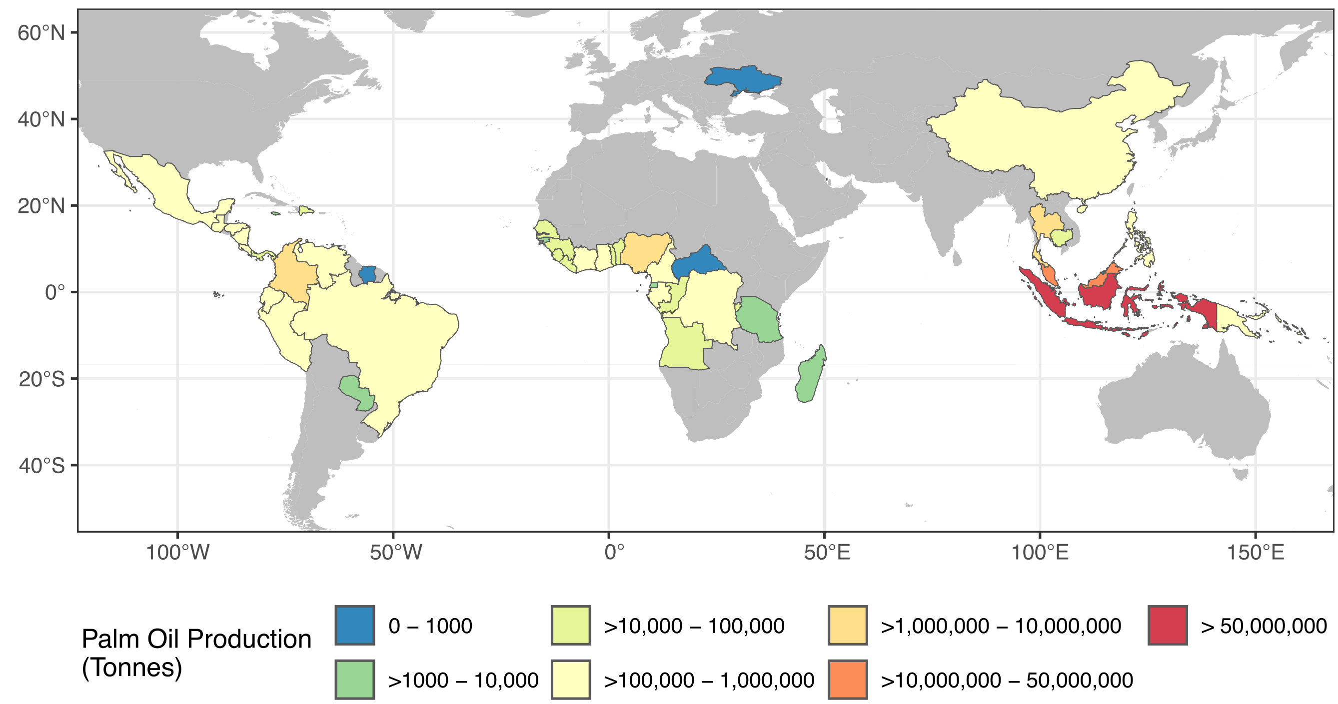
Key words: nutrients, greenhouse gas, nitrous oxide, nitrogen, phosphorus, soil

1. Introduction

Oil palm (*Elaeis guineensis*, OP) has become an important crop in global food, fuel, and cosmetic supply chains, underpinning a vast array of consumer products (Meijaard et al. 2020; Qaim et al. 2020). As of 2022, palm oil (including palm kernel oil) accounted for over 40% of global vegetable oil production, despite OP crops occupying only about 5% of the land used for oil crop cultivation (Descals et al. 2024; Meijaard et al. 2024; FAO 2025). This large yield advantage has driven widespread expansion, particularly in humid tropical regions where the crop thrives. As a result of the environmental and social impacts associated with this expansion (particularly biodiversity loss, peatland degradation, greenhouse gas (GHG) emissions, and land-use conflicts) OP is one of the most contentious crops in debates over tropical land-use and sustainability (Meijaard et al. 2020; Qaim et al. 2020). However, as OP yields 6 to 10 times more oil per hectare than other vegetable oil crops (Murphy 2014), it is recognised that meeting global demand for vegetable oils (from crops such as soy, sunflower, or rapeseed) would require the utilisation of significantly more land, with potential for even more damaging consequences to the environment.

OP is indigenous to the tropical rainforest region of West-Africa, but most scientific and policy attention has been focused on Southeast Asia (SEA) with approximately 90% of global production concentrated in this region as of 2022 (Indonesia and Malaysia accounted for more than 80%) (Fig. 1; FAO 2025). Over 70% of published research on the ecological and socio-economic impacts of OP cultivation has been conducted in SEA (Reiss-Woolever et al. 2021). However, there

Fig. 1. Annual oil palm production in tonnes by country for the year 2022 (FAO 2025).



is growing interest toward OP expansion in Sub-Saharan Africa (SSA), particularly within its native region stretching across the tropical rainforest belt of Sierra Leone and Liberia through Ghana, Nigeria, and Cameroon to the Congo Basin. Across the continent, nearly 6 million hectares in 20 countries are now planted with OP. Despite this rise in OP cultivation (a doubling of oil production between 2000 and 2022; FAO 2025), production remains insufficient to meet local and regional demand, as Africa consumes several times more palm oil than it produces. This results in a heavy dependence on imports (Duguma et al. 2021). As the crop's native range (Henson 2012), Africa holds both cultural and agroecological relevance for OP and significant potential for economic development and food security gains (Pashkevich et al. 2024).

The trajectories of OP industries in SEA and SSA differ significantly, but both regions are now at pivotal points in their OP development. SEA faces intensifying scrutiny over GHG emissions from deforestation and destruction of peatlands and is reaching the end of a major planting wave (carried out in the 1990s onward), with many plantations now entering their replanting phase. Efforts are increasingly focused on raising productivity and reducing environmental impacts within existing land areas. There is a moratorium on new licences for OP plantation in Indonesia (since 2018), and a commitment in Malaysia to maintain current forest cover at or above 54%, essentially making expansion of OP plantations illegal in the region. In SSA, OP cultivation remains dominated by smallholders operating largely outside of formal supply chains. While expansion potential exists, land availability is increasingly constrained by competing land uses, forest conservation efforts, and growing international scrutiny of commodity-driven deforestation (Ordway et al. 2019; Sassen et al. 2022). Ghana is the first country after Indonesia to implement a Forest Law Enforcement, Governance and Trade (FLEGT) licence, essentially making it illegal to deforest for OP expansion without government approval. Other countries in SSA are yet to follow, but there are already many conflicts arising as environmental conservation efforts clash with commercial interests in the region regarding OP expansion (Lyons-White et al. 2025).

A key structural distinction between the palm oil industry in both SEA and SSA lies in the scale and input intensity of production systems. There has been a significant effort in SEA to maximise OP cultivation and palm oil production, and the region now produces almost 90% of global supplies of which 40% are being produced by smallholders. In SSA, by contrast, OP production is overwhelmingly smallholder-driven, with minimal involvement from large multinational producers or commercial investment. These smallholders typically operate with limited access to improved planting material (selectively bred seedlings) or fertiliser markets, and are reliant on artisanal milling (Ayompe et al. 2023). Several government research stations that specialise in OP cultivation (e.g., CSIR-Oil Palm Research (Ghana) and the Nigerian Institute for Oil Palm Research (NIFOR)) provide research, education, and support for smallholders in the region, but are restricted by available funding and geographical constraints.

This contrast between high-input, high-yield estates, and low-input, low-yield smallholdings has significant implications for nutrient cycling, productivity, and environmental impacts. In commercial OP estates in SEA, fertiliser regimes are often guided by diagnostics and precision tools. Small-

Table 1. Comparative overview of oil palm production metrics: Southeast Asia versus Sub-Saharan Africa.

Metric/indicator	Southeast Asia	Sub Saharan Africa
Main producing countries	Indonesia, Malaysia, Thailand	Nigeria, Ghana, Cameroon, DRC
Share of global production	∼87% (Indonesia ∼59%, Malaysia ∼23%)	∼4%–6%
Estimated smallholder share	30%–40% (20%–50% of smallholders operate under supported schemes)	70%–90% (very limited support schemes)
Typical farm size	2–10 ha (smallholder); estates 1000s ha	0.5–2 ha
Soil and climate conditions	High rainfall, some peat soils	Variable; many sites with drought risk
Average FFB yield (tonnes ha^{-1} $year^{-1}$)	15–22 (estate); 8–15 (smallholders)	10–15 (estate); 2–5 (smallholders)
Average oil extraction rate	20%–22% (industrial mills)	8%–10% (artisanal mills)
Fertiliser access	Moderate to high	Low
Synthetic fertiliser use (kg N/ha/year)	100–200 (estates); 50–100 (smallholders)	0–80 (typically low or zero)
Use of improved cultivars	Tenera hybrids widespread	Mixed dura/tenera; limited certified use
Land tenure security	Variable; more secure in plasma schemes	Often insecure or informal
Mill access and processing infrastructure	Centralised industrial mills; high density	Artisanal mills common; sparse industrial coverage
Certification participation	Growing (RSPO, ISPO, MSPO); mostly estate-led	Very limited; mostly pilot schemes
Dominant supply chain type	Vertically integrated estates + plasma/outgrowers	Fragmented informal trade
Presence of peatland cultivation	Extensive (esp. Indonesia, Malaysia)	Negligible
Common nutrient sources	Synthetic fertilisers, EFB, POME compost	Subsidised mineral fertilisers, livestock manure, and household waste
Extension and advisory support	Moderate to strong (estate- supported)	Weak, inconsistent
Climate constraints	High rainfall (>3000 mm), flood risk	Rainfall 1200–2000 mm; drought risk
Carbon emissions hotspots	Peat drainage, land clearance, fertiliser N_2O, manure mismanagement, and untreated POME	Artisanal mill waste, land clearance, manure mismanagement, and untreated POME

holder systems, by comparison, often lack the tools, knowledge, labour, and capital to manage nutrients efficiently, particularly in SSA where practices are highly diverse and data are scarce (Tittonell et al. 2008; Onyango et al. 2021; Reiss-Woolever et al. 2025). Land-use change remains the largest source of GHG emissions associated with OP, particularly in SEA where peatland drainage and tropical forest deforestation have historically dominated (Manning et al. 2019; Wan Mohd Jaafar et al. 2020). However, with expansion increasingly restricted by land scarcity, regulatory pressure, and deforestation-free supply chain requirements for exports, future production increases in both SEA and SSA will rely heavily on improving smallholder productivity within existing agricultural lands.

Smallholder farms in West Africa typically achieve only 20%–30% of the fresh fruit bunch (FFB) yields (2–5 tonnes FFB ha^{-1} $year^{-1}$) obtained by commercial estates in the same climactic region, highlighting substantial room for improvement where agricultural management is optimised (Ofosu-Budu and Sarpong 2013; Jaza Folefack et al. 2019). While the productivity of commercial estates growing OP crops in both SEA (15–22 tonnes FFB ha^{-1} $year^{-1}$) and SSA (10–15 tonnes FFB ha^{-1} $year^{-1}$) are reaching the limit of what is possible with modern techniques and understanding, it is in the smallholder sector that improvements must be made (Ofosu-Budu and Sarpong 2013; USDA 2022; Reiss-Woolever et al. 2025). Strengthening the productivity and sustainability of smallholder systems in SSA would primarily help meet regional food security needs while reducing dependence on imports. Beyond this, as production growth in SEA slows due to land constraints and mounting sustainability pressures, West African smallholders could become increasingly central to future global supplies.

This review synthesises current evidence on the environmental sustainability of smallholder OP systems, with a comparative focus on SEA and SSA. Given that much of the existing research is concentrated in SEA, we examine how insights from this region relate to, or diverge from, emerging smallholder systems in SSA. By contrasting differences in agronomic practices, input intensity, governance structures, and environmental constraints, the review aims to clarify where assumptions drawn from Southeast Asian experience may not readily apply to African contexts. In doing so, we provide a differentiated evidence base to inform research and policy seeking to improve the environmental performance and long-term viability of smallholder OP production.

2. Oil palm landscapes

2.1. Plantation structure and cultivar choices

The organisational structure of OP production in SEA and SSA is markedly different, with implications for nutrient management, emissions tracking, genetic diversity, climate resilience, and overall sustainability (Table 1). Palm oil production in SEA is characterised by a dual structure: (i) highly industrialised, vertically integrated large commercial estates with high-input, high-productivity practices (60% of production), and (ii) smallholders who are often semi-integrated or operate within "plasma" (Indonesia) or Federal Land Development Authority (FELDA, Malaysia) schemes. Under these arrangements, companies or government agencies provide seedlings, fertilisers, and technical guidance to smallholders, sometimes in exchange for harvesting rights or sales contracts. Large commercial estates apply mineral fertilisers at recommended rates, invest in mechanisation and waste management infrastructure (industrial milling facilities), and increasingly adopt sustainability certification standards. Many are Roundtable on Sustainable Palm Oil (RSPO)-certified and participate in sustainability audits, which mandate monitoring of fertiliser use, land use change, and GHG emissions. Smallholders in SEA still often apply sub-optimal fertiliser rates (Woittiez et al. 2018*a*; Lim et al. 2023; Reiss-Woolever et al. 2025), but may receive some guidance or inputs through cooperatives, NGOs, or mill-linked partnerships. These schemes improve market access and input security but can also lock smallholders into asymmetric relationships with mill operators, especially when sustainable certification and supply chain traceability is a factor (Bissonnette and Koninck 2017; Watts et al. 2021).

In SSA, OP cultivation is overwhelmingly smallholder-led (Ruml et al. 2022). Farmers often operate on plots of less than 2 ha, frequently within mixed cropping systems involving cassava, maize, vegetables, or cocoa. Unlike SEA, there is minimal mill integration or corporate coordination, and where there is, it is often beset with disagreements between commercial and smallholder interests (Raymond et al. 2014; Ruml and Qaim 2020). Artisanal mills are widespread and tend to have low oil extraction efficiency (less than half the rate of industrial scale extraction methods) and limited environmental oversight, which results in significant quantities of pollution generated from waste materials (Acobta et al. 2023; Ayompe et al. 2023). These structural differences mean smallholders in SSA frequently lack economies of scale and access to credit. As in SEA, initiatives have been setup to help improve value chains for smallholders in SSA, though these vary in magnitude across different regions and are often NGO run, rather than intervention of local governments (e.g., www.acdivoca.org, https://www.solidaridadnetwork.org).

Cultivar choice further differentiates these regions. In SEA, OP cultivation is dominated by high-yielding, hybrid *tenera* varieties derived from controlled crosses of *dura* and *pisifera* parents. These cultivars have a thin shell, yield up to 30% more than the parents and are compatible with estate-scale mechanisation and refinement/processing (Corley and Lee 1992). Breeding programmes, especially those led by national institutions and private companies have delivered genetically improved lines with enhanced yield potential and disease resistance (Ávila-Méndez et al. 2019; John-Martin et al. 2022; Nugroho et al. 2024). National research institutions responsible for the delivery of improved planting materials do exist in SSA but are constrained by funding. Most often, these organisations raise high quality *tenera* seedlings and provide planting materials for smallholder farmers at subsidised prices (Sultan et al. 2025). Where improved seedlings and materials are commercially available, accessibility, distribution, and price are major hinderances (Ayompe et al. 2023). Therefore, SSA smallholders typically cultivate older, unimproved *dura* or mixed *tenera-dura* lines, often sourced from wildings or informal nurseries (Lim 2011; Osei Darkwah et al. 2020). These trees generally have lower oil content and more variable growth habits. While SEA hybrids are optimised for humid, high-rainfall conditions, their performance under the dry-season stress or in degraded soils (common in SSA) remains under-studied and there is a growing need for region-specific breeding programmes that incorporate drought tolerance, nutrient use efficiency (NUE), and adaptability to intercropping or low-input systems. At the same time, breeding programmes and extension services may need to consider consumer preference traits such as oil colour or taste alongside agronomic performance when promoting improved varieties for domestic consumption. Programmes aiming to radically change prevalence of cultivars at the national scale would also need to ensure consistent continuous accessibility to seedlings to compete with the strong temptation of smallholders to replant their own seeds without recourse to its implication on oil yield.

2.2. Soils, climate, and drought resilience

The environmental conditions under which smallholders operate vary across and within continents, with important consequences for nutrient cycling, GHG emissions, and climate vulnerability. In SEA, soils (particularly in lowland Indonesia and Malaysia) are typically highly weathered and acidic, with low natural fertility and poor nutrient retention. Many commercial OP estates and smallholder plots are located on sandy soils (with low nutrient holding capacity) or former peatlands, which pose substantial environmental risks due to their high carbon density and vulnerability to drainage-induced CO_2 and nitrous oxide (N_2O) emissions (Zhao et al. 2022; Jovani-Sancho et al. 2023). Conversion from forest to OP cultivation can also result in further degradation of soils and carbon losses even when conditions are ideal (Rahman et al. 2018). African soils are more heterogeneous in comparison, including regions such as Ghana's forest-savannah transition or Cameroon's volcanic highlands, which offer fertile soils, but are constrained in productivity by the relatively high rainfall requirements of OP cultivation. Soil degradation from prior land use (shifting cultivation or overgrazing) is also common (Mganga 2022; Slayi et al. 2024). Unlike SEA, soil mapping in SSA is limited, and smallholders seldom receive site-specific recommendations for fertiliser requirements or soil amendments.

It is well documented that OP thrives in tropical regions with annual average temperatures above 25 °C and consistent access to moisture in well-drained soils. While OP is drought resistant to a degree, rainfall strongly influences the productivity of the crop. SEA enjoys more stable annual rainfall (2000–4000 mm year^{-1}) and fewer extended dry periods, though climate variability is intensifying due to climate change (Sentian et al. 2022; Try and Qin 2024). It only takes one extended dry period of approximately 5–6 consecutive months to reduce FFB production by up to 20%–30% for up to 2 years afterwards (Woittiez et al. 2017). In SSA, however, OP production often occurs near or significantly below the species' rainfall threshold (approx. 2000 mm year^{-1}), limiting the viability of OP production to a fraction of available agricultural land and making productivity highly sensitive to dry-season length and drought severity (Gautier et al. 2016; Rhebergen et al. 2016). Climate change is expected to exacerbate these disparities, with many SSA zones of OP production (particularly in Nigeria, Ghana, and Cameroon) facing increasing dry-season intensity and delayed rainfall (Paterson and Chidi 2023). For smallholders who are unable to adapt to changing conditions, this raises the risk of failed seedling establishment, yield decline, or total crop collapse.

Drought resilience strategies are emerging but unevenly distributed. In SEA, estate plantations have begun investing in cover crops, drought resistant cultivars, mulching, and improved water management. Water conservation is also carried out through limited weed control, by simply clearing the area around the OP trees and haul roads and leaving beneficial weeds alone. The presence of the weed *Nephrolepis biserrata* can increase soil water content and the application of soil conservation technologies such as gulud terraces reduces surface runoff and increases infiltration by 60%–90% (Ariyanti et al. 2015, 2016). While most of these techniques are deployed by commercially run plantations only, some smallholders use frond mulches or dig shallow water harvesting pits to improve water retention (Sarkar et al. 2020; Abubakar et al. 2021).

In SSA, adaptation is more often informal, including intercropping for shading, shifting planting dates, or investing in drought-tolerant crops (though limited by availability of subsidised seedlings). Most food production remains rainfed in SSA although irrigation can increase agricultural productivity by over 50% (You et al. 2011). Despite over a decade of national and regional plans promoting irrigation in West Africa, progress has been limited (Redicker et al. 2022). Past efforts have focused on large, state-led, capital-intensive projects aimed at boosting productivity and food security. However, these initiatives often serve political purposes, with greater emphasis on the short-term visibility and prestige of infrastructure development than on long-term performance and sustainability (Redicker et al. 2022).

2.3. Basal stem rot and replanting challenges

Basal stem rot (BSR) is primarily caused by the soil-borne fungus *Ganoderma boninense*. It has become an increasingly serious threat to the OP industry, particularly with successive planting rotations. In the absence of control of *Ganoderma* (which is difficult to achieve) the disease progressively decays the palm's vascular tissue, resulting in frond collapse, yield decline, and eventual palm death. In some replanting areas, *Ganoderma*-related mortality can reduce yield by 50%–80% (Paterson 2019). BSR was initially found to infect older palm trees of more than 25–30 years in age; however, it has progressed to younger palm trees, 10–15 years old, and in the last decade or so, palm trees as young as 1 year were infected by the disease (Zakaria 2023). For smallholders, the implications are serious as they lack capacity for early identification and treatment or the resources for sanitation practices such as stump removal or chemical control (Siddiqui et al. 2021). In SSA, where fewer plantations are from multiple rotations, *Ganoderma* is less widely reported but is an emerging concern, particularly in areas where OP is expanding into previously forested land or where replanting is beginning to occur. As SSA smallholders increasingly adopt monoculture OP systems, the risk of *Ganoderma* establishment and spread may rise, especially in the absence of disease surveillance and effective crop and residue management.

2.4. Supply chain and logistics

Palm oil production involves the transportation and processing of large quantities of heavy organic materials with each hectare of palm oil producing 50–70 tons of biomass waste (Shuit et al. 2009). In SEA (especially Malaysia and Indonesia), supply chains are relatively mature, with centralised mills, organised agrochemical supply chains, and established export infrastructure. Commercial estates often operate their own logistics fleets, and smallholders linked to plasma or other organised schemes benefit from coordinated collection systems, subsidised transport, and guaranteed market access (de Vos et al. 2023). These advantages facilitate just-in-time harvesting, reduced fruit spoilage, and enable the re-distribution of certain residues such as empty fruit bunches (EFB) that holds value as an organic soil amendment (Imam et al. 2025; Kurniawan et al. 2025). Well-structured logistics support traceability of systems, which are increasingly important for accessing sustainability-conscious markets. Certification compliance (e.g., RSPO) is also more feasible within integrated supply chains, where internal monitoring and quality assurance are possible. However, only ~10% of the total biomass within the OP production system is extracted as oil with the remaining ~90% classified as waste residues that remain underutilised (Onoja et al. 2018). This represents an opportunity for the establishment of a circular bioeconomy utilising OP biomass waste streams as a source of nutrients, lignocellulose, and feedstocks for high value biochemicals that could become an additional income source throughout the OP supply chain (i.e., processors, traders, mills, and refiners, growers, and smallholders) (Kahar et al. 2022). However, for certification to benefit smallholders, material processing and sales would need validation of compliance. This would require traceable supply chains, with long-term established partnerships between farmers, millers, transportation, and agribusiness in the region.

In SSA, by contrast, supply chains remain highly fragmented. Transport infrastructure is often poor, with limited vehicle access, and high transaction costs for input delivery and FFB collection (Bromley and Foltz 2011). As a result, smallholders face multiple disadvantages, such as high post-harvest losses due to delayed transport or inadequate storage, poor returns due to inefficient processing and no access to mill-based services (e.g., commercial scale plantations will run their own mills and return composts or treated POME to fields as fertiliser). Most smallholders sell FFB to informal traders or directly to artisanal mills. These mills, while accessible, often have low extraction efficiency and minimal capacity for waste processing. Oil extraction efficiency is a major but often overlooked determinant of productivity and

Table 2. Comparison of fertiliser practices and constraints among smallholders in Southeast Asia (SEA) and Sub-Saharan Africa (SSA).

Feature	SEA Smallholders	SSA Smallholders
Average N application rate	60–150 kg N ha^{-1} year^{-1}; (high variability)	0–80 kg N ha^{-1} year^{-1}; often 0 or <20 kg N ha^{-1} year^{-1}
Timing of application	Irregular; often yield-based	Opportunistic or absent
Guidance sources	Commercial mills, co-ops, peer learning, academic outreach	Peer learning, NGOs (limited)
Common fertilisers	Urea, NPK blends, MOP, rock phosphate	Urea, manures, subsidised minerals (where available)
Major constraints	Cost, over-application or nutrient imbalance, runoff	Cost, logistical access, knowledge, weather

waste generation in smallholder OP systems. In SEA, estate-operated mills typically achieve extraction rates of 20%–23%, supported by modern processing equipment and quality control standards. In contrast, artisanal mills common across much of SSA often operate at efficiencies below 12%, with significant quantities of oil remaining in pressed fibre, sludge, or effluent streams. Even when smallholders operate near commercial mills, they tend to favour the higher sale prices offered by artisanal millers, especially in the low season when local demand is high (Osei-Amponsah et al. 2014). The decentralised, mobile nature of many artisanal mills, which often follow seasonal harvesting flows, further limits the feasibility of waste recovery or treatment infrastructure. These structural barriers directly influence nutrient management outcomes. Limited logistical capability of farmers also constrains the timely application of fertilisers or manure/composts (e.g., rainy seasons where crop growth accelerates), reducing NUE, and increasing the risk of loss via leaching or volatilisation.

In SEA, efforts to increase smallholder independence from estate mills through cooperative-owned mini-mills are being piloted and could offer lessons for SSA, but this often requires investment that is not trivial to local farmers, and thus a system of credit which is difficult to achieve in SSA primarily due to the insecurity of land tenures (Ruml et al. 2022). In many parts of West and Central Africa, land remains under customary ownership, with tribal chiefs or community elders retaining control over access and allocation (Knight 2010). This customary tenure system creates a precarious environment for smallholders, who typically operate under informal or short-term arrangements without formal title or long-term lease agreements. In such contexts, farmers have little incentive to invest in soil fertility improvements, erosion control, or waste recycling, knowing that land rights can be revoked with little notice or compensation. Consequently, OP cultivation under these conditions becomes a short-term extractive activity, with limited emphasis on long-term sustainability or productivity. This insecurity also deters external investment or access to credit, since land cannot be used as collateral nor are returns on investment guaranteed.

Improving supply chain logistics is integral to both economic and environmental performance of smallholder OP producers. Investments in rural roads and cooperative-run collection services could reduce transaction costs and improve market access. Investing in intermediate-scale, village-level mills with basic recovery improvements (e.g., screw presses, FFB driers, and mechanical digesters) could reduce waste volumes while increasing farmer returns, but commercial investment or government support would likely be required to establish and maintain such facilities in the short-term. Digitisation presents new but limited opportunities. GPS-enabled collection tracking, mobile payment platforms, and input ordering apps are increasingly used in SEA and could be adapted for smallholders in the SSA context, provided there is adequate mobile coverage and digital literacy support (Puttinaovarat et al. 2024; Mohamad Zaki et al. 2025).

3. Nutrient and residue management in SEA and Africa

3.1. Fertiliser management

There are distinct differences in the management and application of nutrient fertilisers by smallholder OP farmers in SEA and SSA (Table 2). In SEA, particularly in Indonesia and Malaysia, mineral fertiliser use in OP cultivation is well established. Typical nitrogen (N) application rates on estates range from 100 to 200 kg ha^{-1} year^{-1} (Pardon et al. 2016*a*), supplemented with potassium (K), phosphorus (P), magnesium (Mg), and micronutrients tailored to soil and foliar diagnostics (Sundram 2019; Dassou et al. 2022). These regimes are designed to support high yields (>20 tonnes FFB ha^{-1} year^{-1}) but can result in significant nitrate leaching, runoff, and nitrous oxide (N_2O) emissions if mismanaged (Pardon et al. 2016*b*; Skiba et al. 2020). Smallholders in SEA, while not always formally trained (Retnaningsih et al. 2024), often apply fertilisers based on advice from mills or local cooperatives. However, application is frequently irregular, and rates may fall well below, above or imbalanced relative to agronomic recommendations depending on input affordability and perceived yield response (Woittiez et al. 2018*b*; Lim et al. 2023; Reiss-Woolever et al. 2025). Counterfeit or adulterated fertilisers are also prevalent in the market with smallholders particularly susceptible to unscrupulous traders with NPK fertilisers particularly targeted due to strong demand and relatively high price (Sukarman et al. 2024).

Fertiliser use among smallholders in SSA is extremely variable with typical rates ranging from 0 to 80 kg N ha^{-1} year^{-1}, with many smallholders applying no mineral inputs at all, leading to significant nutrient mining and degradation in soil quality over time (Cobo et al. 2010; Kiboi et al. 2019; Rurinda et al. 2020; Houenou et al. 2025). Constraints include high fertiliser costs, unreliable supply chains, and limited knowledge of nutrient requirements (Krah et al. 2019; Amankwah et al. 2025). The economics of fertiliser use in smallholder

OP systems are heavily constrained by input price in comparison to farm-gate crop prices. In many African countries, fertiliser prices remain prohibitively high due to import dependence and poor distribution infrastructure. For example, urea prices in Africa (2022–2025) range from $470 to $1180 per tonne (Kassouri 2024) often 50%–100% higher than the SEA equivalent. As a result, OP productivity is regularly constrained by nutrient deficiency, particularly of nitrogen (N), phosphorus (P), and potassium (K), and trace elements important for OP cultivation such as boron (B) and magnesium (Mg) (Cobo et al. 2010; Kiboi et al. 2019). Meanwhile, inefficient or poorly timed application (even at low rates) can create "hotspot" emissions, where nutrients are lost to the atmosphere or leach into nearby watercourses (Aini et al. 2015; Dubos et al. 2016).

Improved fertiliser regimes have been found to have the most significant impact on the productivity of smallholder OP farms in West Africa, with all other agricultural practices only having measurable effect after nutrient challenges are addressed. To achieve higher NUE, smallholders require better access to soil testing, improved fertiliser timing, and farmer education on nutrient budgeting, areas where SEA has made some headway but where both regions face significant challenges (Webb et al. 2011; Woittiez et al. 2024). The lack of access to appropriate fertilisers for smallholders in both SEA and SSA is a major constraint that can significantly reduce yield potential and increase pollution as a result of nutrient losses. OP requires significant quantities of K fertiliser, with an NPK ratio of 2:1:4 for mature plants (with sizable contributions of Mg and B). Where ratios in fertiliser blends are not ideal (due to lack of choice), this can result in over-application of some nutrients (particularly N and P) to achieve the desired yield impact (Wottiez et al. 2018*a*, 2018*b*; Lim et al. 2023). Future approaches to improve NUE in smallholder OP cultivation should address all nutrients and not focus solely on N and P pollution, which is often the primary concern for agricultural nutrient losses.

3.2. Utilisation of organic wastes

Organic nutrient sources are a vital but underutilised component of nutrient management in smallholder OP systems. Palm oil waste streams comprise of six main types: Liquid palm oil mill effluent (POME), EFB, palm kernel shells, mesocarp fibres, oil palm fronds, and trunks. Fronds and trunks comprise ~75% of the solid waste and are typically left to decompose in field during regular pruning cycles and at replanting while EFB, mesocarp fibres, palm kernel shells, and POME are generated by the milling process. One ton of processed FFB residue comprises 5% shell, 12% mesocarp fibre, 23% EFB, and 60% POME (Chia et al. 2020).

While environmental accreditations (e.g., RSPO certification) do not have specific guidelines for waste management in OP processing, the overall principles and criteria for sustainable palm oil production encourage practices like composting to minimize environmental impact and improve sustainability. In SEA, there is extensive regulation, testing, and use of by-products such as sludge separated from POME, EFB, and pressed fibre for soil amendment (Loh et al. 2019; Pujono et al. 2021; Azman et al. 2023; Utami and Indrawati 2023). These materials are either applied directly or processed into compost/biofertilizers and returned to the plantation floor, improving soil organic matter, moisture retention, and nutrient cycling.

On large estates, nutrient budgets often include a mixture of both mineral and organic sources, allowing for some substitution of synthetic fertiliser with organic matter, particularly solid organic residues from oil mills (Loh et al. 2019; Mohammad et al. 2021; Imam et al. 2025). However, the primary logistical constraints of using solid and liquid organic materials as nutrient fertilisers in developing countries are the high costs of transportation (materials are typically very heavy in comparison to mineral fertilisers due to high water content) and the possibility of pathogen transfer, which is particularly acute when considering OP cultivation due to prevalence of monoculture farming (and cloned plants). Among SEA smallholders, access to EFB as organic residues is almost impossible unless they are located adjacent to mills with redistribution schemes and biofertilisers derived from mill residues (EFB, treated POME, decanter cake) are not cost competitive. In SEA, waste materials from palm oil mills, are often solely utilised by commercial growers that run the mills. However, frond stacking (where harvested palm fronds (leaves) are arranged in rows to decompose) is common and helps to retain nutrients in the system (Formaglio et al. 2021). Among the generated OP biomass, fronds account for more than 50% of the total biomass grown during OP cultivation and hold significant potential to be utilised for several beneficial activities that improve farmer income and/or the environmental credentials of palm oil production (Ooi et al. 2017).

In SSA, interest in organic nutrient sources is growing, particularly due to the high cost of and lack of availability of mineral fertilisers (for all crop types). Poultry manure, goat droppings, and composted household waste are frequently used, especially in peri-urban and mixed farming contexts (Ndambi et al. 2019). However, processing capacity is limited, and few farmers have the infrastructure to safely compost or sanitise organic waste. This raises concerns about pathogen transmission, inconsistent nutrient content, and volatilisation losses (particularly ammonia (NH_3)) from unprocessed manures (Bouwman and Van Der Hoek 1997; Ndambi et al. 2019). Manure management is also constrained logistically, and the majority of livestock manures produced in SSA are left to rot or burnt (sometimes as fuel for cooking or heating) instead of application back to high intensity agricultural soils (Ndambi et al. 2019; Okorogbona and Adebisi 2012).

3.3. Integration with livestock and legumes

Livestock integration offers another potential pathway for circular nutrient management in smallholder OP systems, without the need for haulage or treatment of manures. In SEA, some plantations have begun experimenting with silvopastoral systems, allowing cattle or sheep to graze under mature palms. This can provide mutual benefits: reduced understorey management (reduction in herbicide use), the return of manures to soil and supplemental income for farmers (Nobilly et al. 2023; Tohiran et al. 2023). Silvopastoral agroforestry has also been trialled in SSA with positive impacts (Oyelami and Osikabor 2022). While mixed agricultural systems have many potential benefits for smallholder farmers, there are also significant practical hurdles (Bremer et al. 2022). Controlling livestock herds across relatively small parcels of land without fencing or defined borders can lead to complications regarding ownership and arguments over crop damage. Young OP plants are susceptible to trampling, while mature plants will significantly reduce understorey growth as limited light will penetrate the canopy of a dense planting regime. For smallholders, system integration would require strong guidance on stocking densities, manure handling, and rotational grazing. Despite the promise of benefits of livestock integration, effective systems remain underexplored in both SEA and SSA. More research is needed to evaluate tradeoffs, including emissions intensity, nutrient availability, and food safety risks. Poor management practices, such as overstocking, could in theory result in poor rotational grazing and exacerbate soil compaction, reduce infiltration, and limit crop nutrient uptake (Raisa et al. 2024). Additionally, the presence of livestock in plantations may alter pest and disease dynamics but can also lead to improvements in soil health (Al-Saedi et al. 2025).

Leguminous cover crops play a critical yet underutilised role in improving nutrient cycling and soil health in OP systems. Species such as *Mucuna bracteate*, *Pueraria javanica*, and *Calopogonium mucunoides* are commonly used in OP plantations for their nitrogen-fixing capacity with symbiotic bacteria (rhizobia), rapid ground coverage, and weed suppression benefits (Wawan et al. 2019; Drewer et al. 2021*a*; Sumaryanto et al. 2024). These legumes can contribute between 40 and 150 kg N ha^{-1} $year^{-1}$ depending on species and site conditions, thereby reducing the need for synthetic N fertilisers (Pipai et al. 2023). In addition to nutrient inputs, leguminous cover crops protect against erosion by maintaining ground cover during heavy rains, reduce surface runoff losses, and help retain soil organic matter. Despite these benefits, adoption among smallholders remains inconsistent due to seed availability, limited awareness, and perceived competition with OP nutrient availability and alternative food or cash crops that are integrated with young OP plants (pineapple, banana, vegetables, etc.). In the context of SSA, leguminous intercrops such as cowpea or peanuts offer the additional advantage of household food security or marketable yields while improving soil fertility (Sprent et al. 2009; Fukah et al. 2024). There is also evidence that inter-cropping with nitrogen-fixing trees improves growing conditions for crops; offering shade, improving soil pH and nutrient availability and increasing soil carbon uptake (Kaba et al. 2018; Sauvadet et al. 2020). Integrating legumes into fallow cycles or early-stage plantation establishment can help regenerate soil fertility on degraded land. Future extension and research programmes should focus on identifying locally adapted legume species (Snapp et al. 2019), developing simple sowing and rotation protocols, and bundling legume seed distribution with replanting or composting initiatives. Other non-leguminous crops also offer the potential for improved yields and environmental benefits. Increasing understory diversity can have a positive impact on soil fertility and groundwater availability and encourage the presence of biopesticides that prevent pests and diseases (Nahlunnisa and Kwatrina 2023). Greater integration of legumes and other cover crops offers a relatively low-cost and sustainable step toward improving nutrient availability (primarily N) in both SEA and SSA.

4. Greenhouse gas emissions and nutrient cycling

4.1. Sources of greenhouse gases in OP cropping

Three major processes dominate GHG emissions in OP cultivation: (i) land-use change including peatland drainage and deforestation (Gunarso et al. 2013; Ramdani and Hino 2013Drewer et al. 2021*b*), (ii) the application of nitrogen-based fertilisers leading to the release of N_2O (Rivera-Méndez et al. 2017; Skiba et al. 2020), and (iii) the anaerobic decomposition of organic wastes (particularly POME) which generate methane (CH_4) (Rajani et al. 2019; Acobta et al. 2023). In SEA, these sources have been well-documented, especially in large commercial OP estates. For instance, CH_4 emissions from untreated POME in open lagoons are a major concern in Indonesia and Malaysia, with mitigation strategies including covered anaerobic digesters, biogas recovery systems, and flaring (which is illegal in some regions, but still widely practiced) (Chan and Chong 2018; Choong et al. 2018; Rajani et al. 2019). Fertiliser-driven N_2O emissions are also significant, with reported emission factors typically ranging from 0.5% to 2.6% of applied nitrogen, depending on soil characteristics, rainfall patterns, and fertiliser placement (Sakata et al. 2014; Skiba et al. 2020; Chen et al. 2024). These figures are derived mostly from estate settings, which are subject to sustainability certification schemes and have the infrastructure to support emissions monitoring. By contrast, emissions data from smallholder OP systems in SEA are far less comprehensive (Hassler et al. 2017; Jovani-Sancho et al. 2023). Research and measurement efforts have historically concentrated on estate operations, which are more uniform and accessible to researchers and regulators but may overestimate emissions per hectare in a smallholder context (Agusta et al. 2022). This leaves a critical gap in understanding, especially given that smallholders account for up to 40% of palm oil production in the region and often manage their land under less structured, lower-input conditions.

In SSA, the knowledge gap is even wider. Most GHG assessments rely on extrapolations from SEA or employ Tier 1 IPCC default values, which do not account for regional variation in climate, soil types, cropping systems, or management intensity (Hickman et al. 2011; Acobta et al. 2023). Fertiliser use among smallholders in SSA is generally low, but emissions are not necessarily negligible (Lemarpe et al. 2023). Poorly timed applications of small amounts of synthetic N or unmanaged poultry manure, especially during periods of intense rainfall or on poorly drained soils, can lead to high emissions (Lemarpe et al. 2021). Emissions of methane (CH_4) from POME are particularly understudied in African contexts. The dominant processing method in much of West and Central Africa is artisanal milling, which typically lacks any form

Environ. Rev. **34:** 1–19 (2026) | dx.doi.org/10.1139/er-2026-0039

Table 3. Key emission sources and nutrient pollution pathways in Southeast Asia and Sub-Saharan African smallholder oil palm systems.

Emission/loss pathway	Description	Southeast Asia (SEA)	Sub-Saharan Africa (SSA)
GHG emissions			
Land-use change	CO_2 and N_2O emissions from forest or peatland conversion	Major historical driver; includes peat drainage and forest conversion	Deforestation ongoing; widespread use of slash- and-burn
Synthetic fertiliser use	N_2O from nitrification and denitrification; NH_3 volatilisation	Widespread on estates; N_2O emissions range from 0.5% to 2.6% of applied N	Limited use; emissions may still occur due to poor timing, poorly quantified
Organic waste (POME)	CH_4 from anaerobic decomposition of untreated mill effluent	Common from industrial lagoons; biogas systems increasingly used	Artisanal mills discharge POME untreated; CH_4 emissions likely high but unquantified
Biomass burning	CO_2, CH_4, and N_2O from fire clearing and residue burning	Controlled burning utilised less; residue often mulched or composted	Slash-and-burn common for land clearing; residues often burned in field or left to rot
Residue decomposition	CH_4 and N_2O from unmanaged fronds, EFB, or manures	Some structured return of fronds, EFB; emissions depend on treatment	Decomposition unmanaged; EFB and manures often discarded or burned
Nutrient loss/pollution			
Leaching and runoff	N, P, and K losses into water bodies due to over-application or heavy rainfall	High in estates on sandy soils or with poor timing; mitigated with precision application	Limited synthetic input, but nutrients still leach from manures or compost
Volatilisation (NH_3)	Gaseous N losses after surface urea application	Common without rain incorporation	High losses likely if urea or poultry manure left exposed
Soil erosion	Nutrient and topsoil losses from rainfall or mechanical disturbance	Controlled with cover crops and terraces in estates	Significant on slopes and in cleared areas; ground cover usually minimal
Nutrient mining	Depletion of soil nutrients due to low input and continuous harvest	Mitigated through regular fertilisation; still present for smallholders	Widespread; major cause of low yields and land extensification
POME discharge to water bodies	Nutrient and organic loading of streams and rivers	Treated in many large mills; potential for water pollution if untreated	Often untreated; high BOD/COD; localised water pollution from mill waste

of wastewater treatment or containment. POME is often discharged directly into waterways or onto surrounding land, where it decomposes anaerobically and emits CH_4. Unlike industrial mills in SEA, which are regulated and incentivised to install methane recovery systems, artisanal processors in SSA operate informally and with little oversight. The diffuse and decentralised nature of these systems poses challenges for both monitoring and mitigation but likely contributes significantly to GHG emissions in palm oil production as well as pollution of watercourses in SSA (Arthur and Glover 2012; Acobta et al. 2023).

In addition to these process emissions, land-use change remains a critical driver of emissions in both regions. In SEA, conversion of forests and peatlands to OP plantations has historically resulted in large carbon losses (Gunarso et al. 2013; Ramdani et al. 2013). In SEA, high-input estate systems on peatlands are particularly emissions-intensive (Nur Usmani et al. 2025). Although expansion is now restricted by land scarcity and sustainability policies, legacy emissions and ongoing peat oxidation remain major concerns. In SSA, where OP expansion is still unfolding, the primary concern is deforestation linked to new plantation establishment. Smallholder-driven land clearance is often carried out through slash-and-burn practices, which release substantial quantities of CO_2, CH_4, and N_2O. These fires also contribute to localised air pollution and degrade soil organic matter, undermining long-term soil fertility (Daniel-Tang and Yap 2020). Although widely practiced for reasons of affordability and tradition, slash-and-burn is poorly accounted for in formal emissions inventories (large uncertainties), despite its significance in shaping the carbon balance of smallholder systems (Ichoku 2020; Bruun and Hepp 2023).

4.2. Nutrient cycles and pollution

In both SEA and SSA, nutrient losses occur through multiple, overlapping pathways including leaching, surface runoff, volatilisation, soil erosion, and mismanagement of crop waste (Table 3). Understanding how these processes operate in different OP systems is central to designing more sustainable and efficient fertiliser and waste management strategies; however, the actual uptake of applied nutrients is rarely quantified in OP studies. Fertiliser application rates are often calibrated to maximise yields, and NUE estimates are difficult to establish for perennial crops with continuous manually harvested fruits and lifespans covering several decades. Modelling efforts are often preferred to measurements, but opportunity for validation is limited (Pardon et al. 2016*a*; Pardon 2017).

In the high-input, estate-based production systems of SEA, fertilisers are applied routinely, often based on diagnostic testing and production targets. However, these nutrients are still subject to substantial losses, particularly in plantations with sandy soils, steep slopes, or high rainfall (Jaya et al. 2019). Leaching losses of nitrate-N and potassium are common in well-drained soils, especially when fertilisers are applied during the onset of heavy rains (accounting for up to 80% of N losses; Pardon et al. 2016*b*). Nutrient losses (mostly N and P) through leaching and surface runoff not only reduce fertiliser efficiency but also pose risks to groundwater quality and downstream ecosystems (Comte et al. 2012; Sham et al. 2024). In SEA, estate plantations often implement soil erosion control measures, including leguminous cover crops, contour bunds, and terracing, to reduce the loss of applied fertilisers (Satriawan et al. 2017*a*, 2017*b*). These interventions help retain soil structure and reduce nutrient-rich runoff into adjacent waterways. Riparian buffer zones, where strips of intact forest vegetation are retained along the banks of rivers and streams, can also reduce chemical losses and associated negative impacts on freshwater ecosystems (Chellaiah and Yule 2018; Luke et al. 2018; Deere et al. 2022).

However, even in well-managed systems, heavy rainfall events can overwhelm protective infrastructure, resulting in episodic but substantial nutrient transport. In smallholder contexts, these challenges are magnified. Many smallholder plots are established on marginal or previously forested lands with minimal investment in erosion control. In SSA, leaching and runoff are also present, though less studied (Omoti et al. 1983). In Tropical regions where OP is grown, ground cover is frequently sparse and runoff during storm events (intense rainy seasons) can carry away not only applied fertiliser but also the thin upper layer of topsoil where most nutrients are held (Ebabu et al. 2023; Assaye et al. 2025). This is a particularly acute risk in newly established plantations, where the absence of mature canopy and ground vegetation can create highly erosive conditions if no measures are taken (e.g., the planting of groundcover crops such as legumes). In marginal acidic soils such as peatlands, high rainfall combined with high tides causes flooding that can result in significant nutrient losses even where fertiliser application is relatively low (Bakri et al. 2025).

In both SEA and SSA, surface application of urea is the most common method of N fertilisation, especially among smallholders. Without incorporation into the soil or rainfall to wash it in, urea rapidly hydrolyses and emits NH_3 into the atmosphere, which can account for the loss of over 30% of applied N in tropical conditions (Zheng et al. 2018; Selvarajh and Chng 2021; Soares and Cantarella 2023). Controlled release fertilisers can slow nutrient losses, though use of these is limited due to cost and availability (Bah et al. 2014). Among smallholders, the risk of NH_3 volatilisation is particularly high, as fertilisers (when used) are often applied without regard for timing, placement, or form. Livestock manures can also contribute to NH_3 volatilisation if left exposed, especially under high temperatures and low humidity which are common in Africa (Beaudor et al. 2025). These losses of NH_3 not only reduce NUE but also contribute to indirect N_2O emissions and air quality issues.

An overlooked nutrient loss pathway is the discharge of organic wastes such as POME. POME is a colloidal mixture of water, oil, and fine suspended matter generated in large quantities during the milling process with the production of 1 tonne of crude palm oil uses 5–7.5 tonnes of water, of which 50% ends up as POME (Mohammad et al. 2021). The high biological and chemical oxygen demand (COD) of POME necessitate pre-treatment typically in anaerobic open ponds prior to discharge. In Asia, large industrial mills often treat POME through closed anaerobic digesters, capturing some of the CH_4 produced during fermentation/composting and reusing the nutrient-rich sludge as fertiliser (Mohammad et al. 2021; Awoh et al. 2023; Bandara et al. 2025). The nutrient content of POME is relatively high; however, the logistical challenges of transporting POME (high water content) and the toxicity of untreated POME (very high biological oxygen demand (BOD) and COD) mean that only a fraction of the nutrients are typically recycled. Some POME is currently used for domestic and international biodiesel production; however, efforts may be better rewarded by optimising the recovery of nutrients from currently underutilised POME to provide a low-cost nutrient source for smallholders. In many SSA settings, where artisanal mills dominate, POME is released untreated into nearby streams or directly onto land nearby milling activities. This practice leads to substantial nutrient losses as well as causing severe localised water pollution. The high BOD of POME creates anaerobic conditions in receiving water bodies, damaging aquatic ecosystems (Meena et al. 2023). Despite the potential value of POME as a fertiliser or compost input, its use in SSA is negligible due to a lack of infrastructure, awareness, and regulatory enforcement.

Beyond POME, the management of other crop residues can play a role in either exacerbating or mitigating nutrient losses in organic wastes. In SEA commercial estates, fronds and EFB are typically returned to the field or composted, recycling significant quantities of nutrients and organic matter back into the soil. While palm trees live for several decades, eventually oil palm trunks (OPT) need to be felled and resown. Felled OPT is one of the most abundant biomass products in OP cultivation. The management of OPT is difficult for several reasons. Removing materials from soils can cause significant nutrient depletion, but if left to rot, the trunks become a breeding ground for pathogens and pests (Pulingam et al. 2022). In commercial estates in SEA, OPT is generally chipped and mulched and incorporated into the soil to prevent the spread of pathogens and retain key nutrients in soils. OPT can also be incorporated into low quality timber products such as plywood or turned into biochar. Biochar application to soil is proposed as a method to reduce nutrient leaching and emissions of N_2O and NH_3, as well as improving soil health (Huat Kong et al. 2014; Uttran et al. 2023). However, managing large quantities as biomass or biochar requires access to machinery, logistics, and labour that smallholders cannot always afford (Keck and Hung 2018). Currently, due to the large quantity of mass and the relatively short lifespan of untreated OPT, most smallholders in SEA and SSA tend to utilise the materials as an alternative fuel source, and burn OPT for cooking or heating, thus losing out on any beneficial nutrient recycling or improvement to soil health, but save on fuel costs. The economic importance of fuel costs should not be understated when considering smallholder wellbeing in all OP cultivating regions. Utilisation of materials such as OPT as fuel in the home is a significant trade-off that prevents willingness to incorporate materials back into the soil.

Logistical constraints (especially for transporting processed organic waste from centralised mills) severely constrains the ability of smallholder farmers to follow best practice regarding nutrient cycling during OP cultivation. Among SEA smallholders and in SSA more generally, residue management is often informal or opportunistic. This results in practices that mine nutrients from soil and cause significant soil degradation over time. Degraded soils are a defining feature of many smallholder OP landscapes in SSA, often shaped by past land use, deforestation, and long histories of nutrient mining. Unlike the weathered but more organically rich soils of SEA plantation areas, SSA OP fields frequently lack the buffering capacity to retain applied nutrients, increasing susceptibility to leaching, and low fertiliser efficiency (Kihara et al. 2020; Atoloye 2024). This makes baseline soil fertility a major limiting factor for sustainable intensification. Additionally, the biological dynamics of SSA soils (reduced microbial activity and poor soil structure) mean that conventional fertiliser response curves may not apply (Kihara et al. 2020; Cowan et al. 2022). Site-specific trials and participatory soil testing approaches are needed to refine fertiliser recommendations and close the persistent yield gap between commercial and smallholder cultivation. Without improved understanding of soil dynamics and locally adapted fertility strategies, even modest investments in inputs risk being economically ineffective and environmentally damaging.

4.3. Soil carbon sequestration

Sequestering carbon in existing OP systems is a critical strategy to restore or reverse carbon emissions resulting from agricultural conversion of forests. In SEA, the soil organic carbon (SOC) content of OP soils is often extremely low, especially those on mineral soils (typically ~2%) (Golicz et al. 2024; Guillaume et al. 2016). Smallholder OP soil can be especially carbon poor due to sub-optimal nutrient and residue management, for example, smallholder OP SOC stocks in Indonesia were shown to be ~19% lower than their commercial counterparts following business-as-usual management, and ~31% lower than plantations employing more sustainable practices (Rahman et al. 2021). This highlights a significant potential for soil and overall ecosystem carbon sequestration in smallholder OP systems in SEA if alternative management practices can be adopted. As SOC is a key indicator of overall soil health, improving soil carbon storage offers multiple co-benefits by simultaneously improving soil fertility, structure, and resilience which can in turn support crop productivity (Tao et al. 2017; Lorenz et al. 2019).

Management practices that increase SOC in OP systems largely follow those of circular nutrient management and include application of organic OP residues (typically EFB, fronds, and POME), as well as OP waste composted with other agricultural waste products e.g., livestock manure (Rahman et al. 2021; Supriatna et al. 2022). There is growing interest in SEA in the use of biochar as a soil amendment to improve soil carbon storage and health in OP systems (Zakaria et al. 2023). Biochar presents opportunities for smallholders to engage in collaborative carbon credit models by partnering with biochar producers; however, the feasibility of such models for applying biochar at scale across smallholder OP systems has not yet been demonstrated. The availability of raw materials by which to generate biochar is also limited in the smallholder context as materials are often burned as fuel, and alternatives would need to be sought to carry out basic cooking and water heating activities (at increased cost). Carbon credit schemes may offer incentives for smallholder farmers to adopt more sustainable practices that improve both soil carbon storage and wider ecosystem health. However, such schemes rely on verification protocols that are not optimised for the spatially heterogenous conditions that are present in both SEA and SSA smallholder soils (Law et al. 2009; Rahman et al. 2018). OP systems require sampling regimes tailored to this spatial variation for accurate quantification and detection of change in SOC over time (Nelson et al. 2015). Moreover, high labour and analytical costs associated with spatially intensive soil sampling required by existing verification protocols can be prohibitive for smallholders (for example Verra's VM0021 Soil Carbon Quantification Methodology, https://verra.org/), constraining benefits to rural livelihoods and adoption of sustainable practices. The development of robust and affordable soil carbon assessment methodologies appropriate for smallholder OP systems is essential to develop, demonstrate, and incentivise best practice for enhancing soil carbon sequestration.

5. Socioeconomic dimensions

Global demand for palm oil is likely to continue to increase for the foreseeable future. As OP cultivation requires tropical conditions and is not automation friendly (manual labour intensive), it is likely that the developing world will be the primary source of any increase in palm oil productivity. Smallholders will be at the forefront of future efforts to boost OP productivity, and these farmers are significantly more susceptible to socioeconomic factors than commercial scale producers. Sustainable intensification of existing smallholder plantations represents a key opportunity for scaling palm oil supply. Factors including access to agricultural inputs and optimum cultivars, technical knowledge, access to tools and machinery, land tenure arrangements, and market participation will shape how smallholder OP farmers can and will engage with nutrient and GHG emissions management.

In SEA, smallholders often benefit from more structured support systems, particularly in countries like Malaysia and Indonesia. Public-sector extension services, commercial mill partnerships, and outgrower schemes (e.g., plasma models) provide avenues for input provision, technical training, and residue management advice (Alwarritzi et al. 2015; Adiprasetyo et al. 2019; Siahaan et al. 2020; Petri et al. 2023; Reis-Woolever et al. 2025; Tjilen et al. 2025). These connections help facilitate uptake of fertilisers, composting, cover crops, and other soil-enhancing practices. In Malaysia, the FELDA programme has historically (since the 1950s) enabled smallholders to access agronomic support and structured replanting cycles (Abazue et al. 2015). The Nucleus Estate Smallholder (NES) programme is the Indonesian equivalent (Jelsma et al. 2024). However, this support is uneven and often excludes independent smallholders who remain detached from formal supply chains, specifically those operating in more remote regions.

In contrast, most smallholders in SSA operate without consistent technical assistance. Despite commitments to poverty reduction and economic transformation, government initiatives which have aimed to enhance palm oil productivity have repeatedly failed (Asante 2023). Access to inputs such as mineral fertilisers, improved planting material, and composting infrastructure is sporadic and often cost-prohibitive. Public extension services typically operate with stretched resources, and private sector engagement is concentrated around a few large commercial estates. As a result, nutrient use among smallholders is often based on personal experience, peer advice, or ad hoc experimentation. The impacts of the recent collapse of USAID and reductions in overseas development aid from large donors (such as Germany, France, and the United Kingdom) in the SSA region are yet to be fully realised, but many of the NGO activities promoting agronomic support for OP cultivation in the West African region are likely to decline in the medium to long-term.

Land tenure is another critical dimension. In SEA, many smallholders operate on titled land or through secure tenancy agreements. While land disputes do occur, the legal frameworks governing land ownership tend to support long-term investment in perennial crops. In SSA, however, land tenure is often governed by customary systems where tribal chiefs or local elites allocate land through informal agreements. Farmers are therefore disincentivised from investing in long-term soil fertility improvements, composting, or residue management if their access to land is not guaranteed (Chavula and Turyasingura 2022). This leads to extractive farming behaviours, where land is used intensively for short-term gains rather than sustained productivity. Without formal land titles, farmers are typically unable to use land as collateral, limiting their eligibility for loans or sustainable agricultural financing. This inhibits adoption of improved nutrient management practices or investments in infrastructure (e.g., composting, irrigation, or soil erosion controls). In both SEA and SSA, smaller and more marginalised farmers (particularly women and migrant farmers) face additional constraints related to intra-household decision-making, labour availability, and exclusion from co-operative structures (Perelli et al. 2024).

Other less visible factors also constrain progress in improving the environmental credentials of smallholder OP growers. The availability of affordable labour is a major constraint for such a labour-intensive crop. The majority of labourers in the commercial Malaysian palm sector (>80%) are migrants from Indonesia with others from Philippines, Bangladesh, India, Nepal, and Myanmar (Crowley 2020). Smallholder farmers typically require family to help carry out farming to avoid the need to pay external help, but a major issue faced by smallholders in SEA is that younger generations are increasingly moving away from rural areas into cities, leaving their elders to tend to the plantations. This is global trend, but the implications are severe for the management and harvesting of a crop that cannot be readily automated. Additional activities that could improve sustainability often require time and effort, luxuries that ageing smallholder farmers can seldom afford. Thus, even when beneficial activities are identified, uptake can remain limited or slow due to limitations in labour availability.

Another consideration for smallholders is the target to which they will sell their product. While the vast majority of palm oil produced in SEA is heavily refined for export, market dynamics in African OP systems are shaped by consumer preferences. Smallholders in SSA are producing palm oil almost exclusively for local consumption in regions where naturally red oil from *dura* palms is highly valued for its colour and flavour. These preferences reflect deeply rooted cultural norms but create economic disincentives for adopting high-yielding, certified planting material (*tenera* cultivars). One serious problem faced in the SSA market is that street traders may adulterate pale oil from *tenera* varieties with Sudan dye (synthetic red colourants banned in many countries due to their carcinogenic properties) to enhance the visual appeal of palm oil sold in informal markets to meet consumer expectations (Andoh et al. 2019; Nyorkeh et al. 2024). This practice not only endangers public health but undermines trust in oil quality and safety.

6. Recommendations for research and practice

6.1. Research priorities

Despite growing interest in the environmental impacts of OP cultivation, smallholder systems (especially in SSA) remain significantly underrepresented in empirical research. Most GHG emission estimates from smallholder OP systems rely on default IPCC Tier 1 factors or extrapolations from estate-based data in SEA, failing to reflect the specific agronomic contexts of smallholders in SSA. Regional specific emission factor data for N_2O and CH_4 emissions under real-world smallholder practices would significantly enhance the accuracy of national inventories and inform mitigation planning. Similarly, nutrient cycling remains poorly understood across smallholder systems in both SSA and SEA. Particular gaps exist in the fate of nutrients from livestock manure and compost, as well as the dynamics of micronutrients that may limit yields. Integrated crop–livestock-OP systems, warrant targeted research to assess both nutrient contributions and emissions trade-offs.

Climate variability and long-term shifts in rainfall and temperature patterns are increasingly affecting OP viability. Satellite-based suitability mapping and agro-climatic zoning are emerging tools to inform more strategic plantation planning and climate adaptation. Remote sensing platforms and geospatial models can identify areas at risk of drought, heat stress, disease, or flooding, while also mapping soil constraints and deforestation hotspots. Integrating such tools into land-use planning frameworks could prevent inappropriate expansion and promote climate-resilient development. More participatory versions of these tools, accessible through mobile apps or cooperative-led mapping, could empower smallholders to plan planting or replanting in more adaptive ways. As rainfall patterns become increasingly erratic and temperature thresholds tighten, climate-informed land-use decisions (potentially supported by satellite data) could help safeguard OP productivity and sustainability.

Participatory trials co-designed with farmers could increase the relevance and adoption of sustainable practices. Partnerships involving agribusiness, cooperatives, and research institutes should be scaled to support technology development and dissemination. In addition, long-term comparative trials examining the yield, emissions, and profitability of mixed farming practices (e.g., intercropping, silvopastoral, and legume integration) would help inform policy and extension recommendations. It is clear that investment is needed in low-cost monitoring and advisory tools suitable for smallholder systems, such as mobile data collection, low-cost methods for GHG flux and carbon stock assessments, and visual diagnostic aids to boost data collection and allow for the expansion of experimental agronomic research into the smallholder domain.

6.2. Recommendations for practice

The greatest advantage that commercial OP growers have over smallholders is the vertical integration of palm oil production. Owning and managing each step of oil production allows for decisions to be made that improve the overall process, rather than individual actors doing what is best for themselves. This integration of processes over a relatively close geographic network provides ample opportunity to maximise logistical efficiencies and utilise economies of scale. A major bottleneck in nutrient recycling and emissions mitigation lies in the logistical challenge of managing organic waste streams, particularly POME, EFBs, and OPTs. To replicate the effectiveness of commercial growers (highly effective in both SEA and SSA), smallholders would require the development of community-based logistics systems that process oil, organised at the village or cooperative level which could improve decentralised waste handling and input redistribution. In both SEA and SSA contexts, the development of small-scale, cooperative-run mills with composting hubs or modular biodigesters could enable the safe conversion of local waste into valuable fertiliser inputs at the village or town scale. The development of small-scale palm oil processing industries that can be built by cooperatives or local governments can also increase farmers income by regulating fair prices and significantly reduce the cost of transporting fruit and resulting spoilage that comes from delayed processing.

Strengthening cooperative structures is one of the most effective mechanisms for scaling innovations in palm oil production. Cooperatives can coordinate bulk composting, manage shared resources such as fermentation tanks or small-scale digesters, and facilitate access to cover crop seeds and training. Legal recognition, leadership development, and operational capacity-building are essential to enhance the effectiveness of such organisations. Simple investments in small-scale transport equipment (e.g., hand carts, trailers), training in hygienic handling, and cooperative governance could prove essential. These decentralised systems can transform waste from a pollution burden into a local asset, supporting both environmental goals and smallholder resilience.

Improving organic nutrient access is an opportunity that can develop from better local scale interactions. Partnerships between OP farmers and local waste generators (such as poultry producers, food vendors, and municipal services) could create a stable supply of organic feedstocks for composting or biogas generation. While compost can improve yields and soil health over time, short-term returns may be lower unless productivity benefits are captured over multiple seasons and likely require continued supplementation with inorganic fertilisers to maintain levels of production. Extension programmes should emphasise these trade-offs and tailor recommendations to farmer resource levels and cropping goals. Organisations such as APKASINDO (a professional organisation of OP farmers authorised and fostered by the government in Indonesia) can be established at the national scale with the purpose of educating farmers with providing knowledge and skills, but also legal information and the means by which to interact and collaborate to improve livelihoods. Practical training on composting and cover crop integration (delivered through farmer field schools or lead farmer models) can demonstrate the benefits of organic matter recycling for soil fertility, weed suppression, and water retention. These practices also complement intercropping strategies where food security or land availability is a concern. Peer-to-peer learning through farmer exchanges, on-farm demonstrations, and regional visits have proven effective in building trust and confidence. Such approaches foster ownership of innovations and accelerate diffusion across heterogeneous farming landscapes.

7. Conclusion

Smallholder OP systems in SEA and SSA are distinct in their development trajectories as both regions are confronting similar pressures: the need to improve yields and livelihoods, while reducing GHG emissions and minimising environmental impacts. In SEA, decades of plantation intensification have delivered high yields but at notable environmental cost, meanwhile, smallholders in SSA are driving a new wave of OP expansion. This presents a pivotal opportunity: SSA systems could avoid the damaging legacy of SEA if supported to adopt lower-input, circular, and locally adapted models from the outset. Improving NUE is central to this transition. SSA struggles with persistent under-fertilisation and degraded soils. Interventions show promise in improving smallholder productivity and sustainability in both regions, but success hinges on context-specific adaptation. Additionally, a major bottleneck remains the lack of empirical data (especially in SSA) on pollution streams and therefore further research is needed to generate important data to inform appropriate systems management strategies. Strengthened smallholder cooperatives, group certification models, and peer-led training are all enablers of circularity and emissions reduction. However, these models require investment in governance, legal recognition, and shared infrastructure, especially in SSA contexts where tenure insecurity and fragmented land systems remain key barriers to long-term planning. Ultimately, smallholders are not peripheral to the sustainability of the global palm oil sector and with the right support systems in place across research and governance, they can transition toward a more sustainable future.

Acknowledgements

We acknowledge funding from NERC National Capability Science: International award "Options for Net Zero Plus and Climate Change Adaptation" (Grant Ref: NE/X006247/1) and NERC Seedcorn "Addressing environmental impacts of oil palm expansion in Liberia/Africa" (Grant Ref: NE/Y003136/1).
Declaration of generative AI and AI-assisted technologies in the manuscript preparation process: During the preparation of this manuscript, the authors employed ChatGPT (GPT-4o; OpenAI) to assist in collation of contributions from multiple international co-authors, structuring and refining discussions to achieve conciseness and coherence. The tool was used solely to aid language refinement and synthesis of author input. All content used in the manuscript was subsequently reviewed, edited, and verified by the authors to ensure accuracy, originality, and intellectual integrity. The authors take full responsibility for the content and interpretations presented in this work.

Article information

History dates

Received: 23 February 2026
Accepted: 9 June 2026
Version of record online: 22 July 2026

Copyright

Data availability

This paper does not report data.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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