The potential for climate-smart palm oil production in Ghana and Nigeria:
a scoping review of challenges and opportunities

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Rationale

Palm oil is a vital agricultural commodity in Ghana and Nigeria, supporting livelihoods and contributing to national economies. However, despite its economic importance, the sector faces mounting challenges related to sustainability, climate resilience, and productivity. Smallholder farmers, who account for the majority of production, often operate with limited resources, outdated practices, and weak market access, resulting in low yields and economic vulnerability. At the same time, increasing global scrutiny on deforestation, carbon emissions, and land-use change places pressure on producers to adopt more sustainable practices.

While significant research and investment have been directed toward making palm oil production more sustainable in Southeast Asia, far less attention has been given to West Africa. Many climate-smart innovations, including improved agronomic practices, efficient milling technologies, and sustainability certification schemes, have not been widely adopted in the region. A key challenge is the lack of context-specific research and engagement with smallholder farmers to develop solutions tailored to local environmental, social, and economic conditions. Without better access to knowledge, resources, and financial support, smallholders struggle to transition toward more sustainable and climate-resilient production systems.

This report was developed to address these gaps by identifying opportunities, barriers, and potential pathways for climate-smart palm oil production in Ghana and Nigeria. Through collaboration with a trilateral network between the UK, Brazil, and West Africa, it seeks to facilitate knowledge exchange and support targeted interventions that can improve sustainability, productivity, and climate resilience in the sector. By assessing existing challenges and highlighting areas for action, the report aims to provide a foundation for future research, policy development, and investment in sustainable palm oil production in West Africa.

Contents

1. Introduction

1.1. The global palm oil industry

Palm oil is a versatile edible vegetable oil derived from the fruit of oil palm (OP) trees (*Elaeis guineensis*), which originate from the tropical rainforests of West Africa. Since the 1970s, commercial expansion of OP plantations, particularly in Southeast Asia, has driven a near tenfold increase in global OP cultivation. Indonesia and Malaysia now account for over 80% of global palm oil production [1]. The increasing global demand for palm oil has led to extensive land-use changes, with OP plantations occupying approximately 10% of permanent global cropland [2].

Crude palm oil is commonly used as a cooking ingredient in regions where OP is cultivated, such as Africa, Southeast Asia, and parts of South America. Refined palm oil is widely used in commercial food industries due to its lower cost compared to other vegetable oils and its high oxidative stability, making it ideal for frying and extending shelf life. In 2023–2024, global palm oil production reached 77.5 million tonnes, with Indonesia contributing 57%, Malaysia 26%, Thailand 5%, and a combined 9% from Colombia, Nigeria, Guatemala, and Papua New Guinea [3].

The OP tree is an exceptionally efficient crop, producing high oil yields per hectare year-round. It requires minimal soil management, is semi-drought resistant, and thrives in soils unsuitable for other crops. It yields four to ten times more oil per hectare than alternatives like rapeseed, sunflower, and soybeans (Figure 1). Despite these advantages, OP harvesting remains labour-intensive, necessitating a substantial workforce even on large commercial plantations. This makes OP cultivation attractive in regions with available low-cost labour, providing a steady income for smallholders, particularly in developing nations where OP is a key livelihood source.

The palm oil industry has become a major economic driver in Southeast Asia, contributing 4.5% of Indonesia's GDP and 2.7% of Malaysia's [4], while employing approximately 17 million people in the region. However, the expansion of OP plantations has led to significant negative environmental consequences, including widespread deforestation and biodiversity loss. Since 1990, Southeast Asia has lost 15% of its natural forest cover, with OP plantations accounting for nearly half of this loss [5]. Globally, OP production contributes 5% of tropical deforestation and 2.3% of overall deforestation. In Indonesia and Malaysia, OP plantations were responsible for 39% of tropical forest loss (2.4 million hectares) in Borneo from 2000 to 2018 [6,7]. The clearance of rainforests and peatlands for OP expansion has released substantial carbon emissions, exacerbating climate change [8,9]. Conversion of forests for OP plantations in Malaysia and Indonesia accounts for up to 0.8% of global greenhouse gas (GHG) emissions, nearly half that of the aviation industry [10].

In response, Southeast Asian governments have implemented sustainability measures, including the No Deforestation, Peat, and Exploitation (NDPE) policy and forest moratoriums. Since 2017, deforestation in Indonesia and Malaysia has declined [11], with new OP plantations primarily replacing existing cropland. Nevertheless, global demand for palm oil continues to rise, with vegetable oil demand projected to increase by 46% by 2050 [12]. Given OP's higher oil yield per hectare and economic viability, sustainable palm oil production remains a priority. Expansion is ongoing in Thailand, Papua New Guinea, Myanmar, and the Philippines, as well as in tropical

African nations such as Nigeria, Ghana, Ivory Coast, and Cameroon [13]. While Africa primarily consumes its palm oil domestically, there is growing potential for export markets.

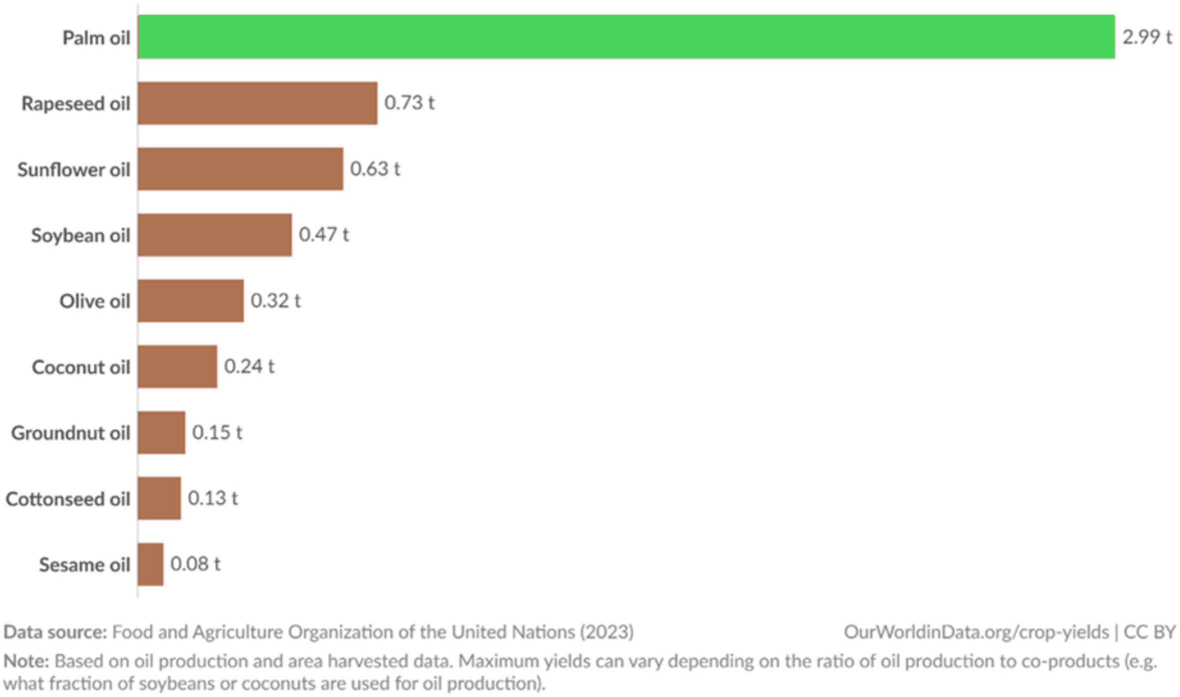

Figure 1 A global analysis of Oil yields (tonnes per hectare) by crop type for 2021 (https://ourworldindata.org/grapher/oil-yield-by-crop).

1.2. The African palm oil industry

In the early 19th century, Africa was the primary source of palm oil in global trade. Nigeria and Zaire (now the Democratic Republic of the Congo) led production until the 1930s when Malaysia and Indonesia surpassed them. Accelerated success of the palm oil industry in Southeast Asia was influenced by the introduction of plants that combined *dura* (thick shell) and *pisifera* (no shell) palm varieties to produce a hybrid known as *tenera*. The rapid expansion of OP plantations in Southeast Asia, aided by the high-yielding *tenera* hybrid, solidified the region's dominance in global palm oil production. African farmers largely rejected *tenera* hybrids due to their higher fat content (compared to the *dura* crop), which altered the taste of crude palm oil used in traditional cooking. Consequently, African nations failed to compete with Southeast Asian producers in the industrial palm oil market.

Currently, nearly 6 million hectares across 20 African nations are dedicated to OP cultivation. However, Africa consumes 15% of global palm oil production while producing less than 5%, necessitating imports of nearly 8 million tonnes in 2020. Expanding palm oil production in West Africa aims to enhance food security, reduce import dependence, and diversify economies reliant on primary exports such as cocoa, gold, rubber, and timber. The region's tropical rainforest belt, spanning Sierra Leone, Liberia, Côte d'Ivoire, Ghana, Togo, Nigeria, Angola, and Congo, presents viable conditions for OP expansion. However, concerns persist regarding deforestation, land-use changes, and the potential exploitation of indigenous communities, particularly in the Congo Basin and West Africa [14,15].

Ghana and Nigeria have made explicit commitments to expanding their palm oil industries. Nigeria's government announced a $500 million investment in 2019 to increase production from 600,000 tonnes to 5 million tonnes annually, aiming for domestic self-sufficiency by 2027. However, challenges remain. Over 80% of palm oil production in these nations is from independent smallholders cultivating traditional *dura* varieties, which are unsuitable for industrial processing and export. Smallholders in Africa achieve some of the world's lowest OP yields—approximately 3 tonnes of fresh fruit per hectare annually [16] —whereas commercial estates yield 10 to 15 tonnes per hectare, approaching global standards of 15 to 20 tonnes [17].

Recent investments in large OP plantations operated by experienced multinational corporations have introduced *tenera* hybrids, targeting both local and international markets. Expanding palm oil production in West Africa will require balancing improved productivity of existing plantations, particularly among smallholders, with responsible expansion into new land. While OP expansion in Africa could lead to deforestation and environmental degradation similar to Southeast Asia, there is a growing emphasis on sustainable practices, leveraging lessons learned to secure access to premium international markets, particularly in Europe.

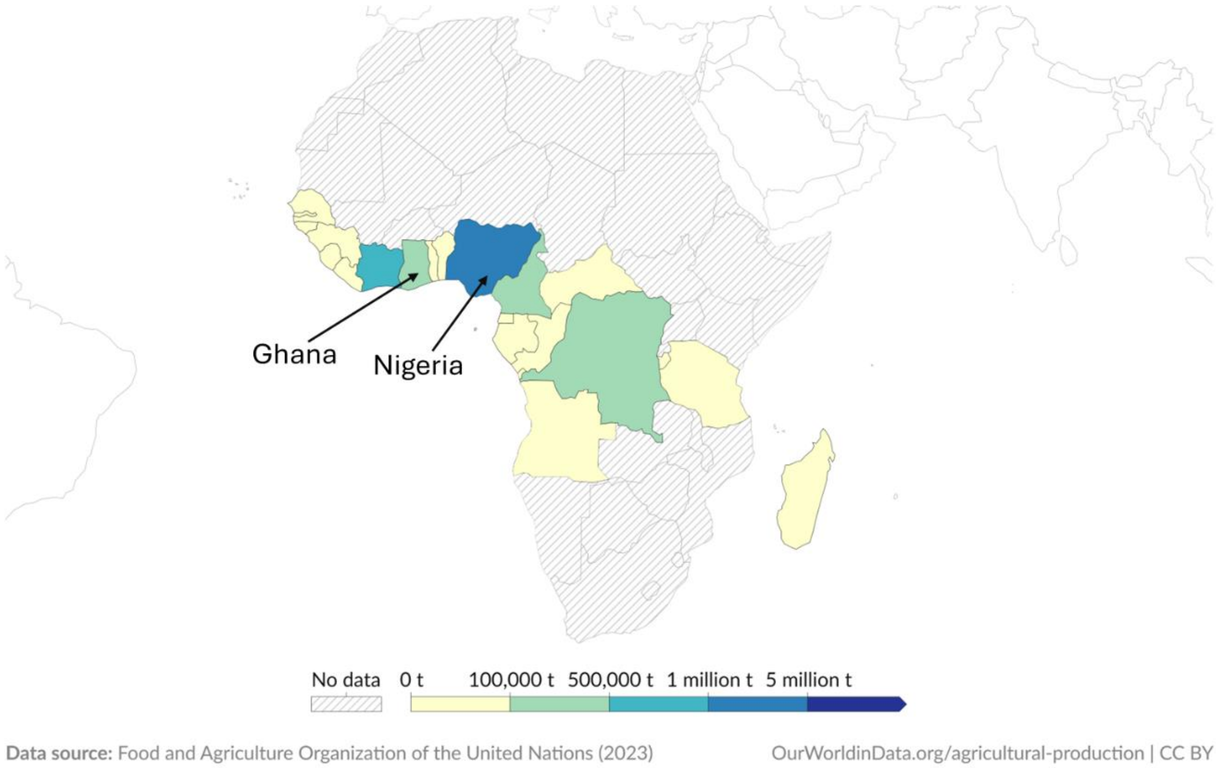

Figure 2 Oil palm production in Africa in 2021 (tonnes) (https://ourworldindata.org/palm-oil).

1.3. Climate-Smart Palm Oil Production

Tropical OP cultivation often involves deforestation and land conversion, resulting in significant carbon emissions. Achieving climate-smart palm oil production requires optimising the entire life cycle, from land use to processing, to minimise greenhouse gas emissions while also considering the practical constraints imposed by social and economic constraints.

Land Use and Deforestation

Expanding OP plantations into natural forests or peatlands carries a high carbon cost, negating climate-smart objectives. Rainforest conversion releases an estimated 174 tonnes of carbon per hectare [18], while peatland drainage can emit over 640 tonnes [19]. In Africa, sustainable expansion should focus on increasing productivity on existing plantations or utilising low-carbon degraded lands rather than converting intact forests.

Crop Management and Fertilizer Use

Sustaining high OP yields requires nutrient inputs, particularly nitrogen, phosphorus, and potassium. However, fertiliser production and application contribute significantly to carbon emissions. Mitigating nitrogen pollution and improving nutrient use efficiency through organic waste recycling and sustainable soil management can enhance climate-smart practices.

Logistics and Transportation

OP cultivation occurs in remote, tropical regions with poor infrastructure. Transporting fertilisers, pesticides, and harvested fruit to mills is energy-intensive, increasing the carbon footprint. Large integrated estates with efficient transportation networks reduce emissions, while smallholders may need support to optimise logistics and access cost-effective processing facilities.

Processing and Waste Management

Palm oil milling consumes substantial energy, with waste products such as empty fruit bunches (EFBs) and palm oil mill effluent (POME) posing environmental challenges. While EFBs can be repurposed as compost or biomass fuel, untreated POME discharge into waterways disrupts ecosystems. Improved waste management practices are essential for sustainable production.

Integration of Climate-Smart Practices

Global perceptions of palm oil are largely negative due to deforestation in Southeast Asia. However, eliminating palm oil entirely could exacerbate environmental issues by increasing reliance on less efficient vegetable oils. Climate-smart palm oil production must balance carbon reduction with socio-economic realities, particularly for smallholders. Large estates have made sustainability strides through economies of scale and technological investment, yet smallholders require targeted support. Lessons from Southeast Asia can inform sustainable development in West Africa, ensuring palm oil expansion aligns with both environmental and economic priorities.

2. Challenges and barriers to climate-smart palm oil

The challenges and barriers to climate-smart oil palm (OP) farming in Africa can be identified from multiple sources. While extensive research exists on the ecological, social, and socioecological impacts of OP cultivation, the majority (>70%) has been conducted in Southeast Asia [20], with only a limited number of studies focused on Africa. As such, caution must be exercised when extrapolating findings across regions. For this report, we conducted a comprehensive literature review and supplemented it with in-person and virtual meetings with key stakeholders in Africa, including OP research institutes, non-governmental organisations (NGOs), smallholder farmers, and government officials. The key challenges and barriers to climate-smart OP farming identified are summarised below.

2.1. Suitable land for Oil Palm farming in West Africa

Oil palm thrives in tropical regions with annual average temperatures above 25 °C and consistent access to moisture in well-drained soils. While the crop is highly adaptable, optimal productivity depends on specific environmental conditions, making soil and climate suitability critical factors in farm placement. A primary climatic limitation for OP farming in West Africa is the annual water deficit [21].

Ghana and Nigeria experience two main seasons: the wet (monsoon) and the dry season. While regional variations in rainfall exist due to geographical influences, the wet season typically spans from March/April to October/September. The most suitable areas for OP cultivation are the rainforest and semi-deciduous forest zones in the south, where rainfall is highest (Figure 3). However, a major barrier to OP expansion is that much of the suitable land is either: (i) protected natural forest under legal conservation, or (ii) already utilised for intensive agriculture or long-term plantation cropping, with crop cycles lasting 10 to 25 years.

Climate change is expected to further challenge land suitability. Modelling projections suggest that drier conditions and reduced rainfall in northern West Africa will negatively impact OP growing conditions, while southern regions should remain viable until at least 2050 [22]. Given that OP plantations have lifespans spanning multiple decades, these projections are increasingly relevant to growers. However, the accuracy of suitability mapping remains uncertain due to the continued development of drought-resistant hybrid palm species, which have yet to be fully characterised for modelling. While commercial OP enterprises may have access to advanced land suitability assessments, smallholder farmers often rely on experience and informal knowledge, increasing the risk of expanding into areas that may become unsuitable within 15–25 years due to climate change.

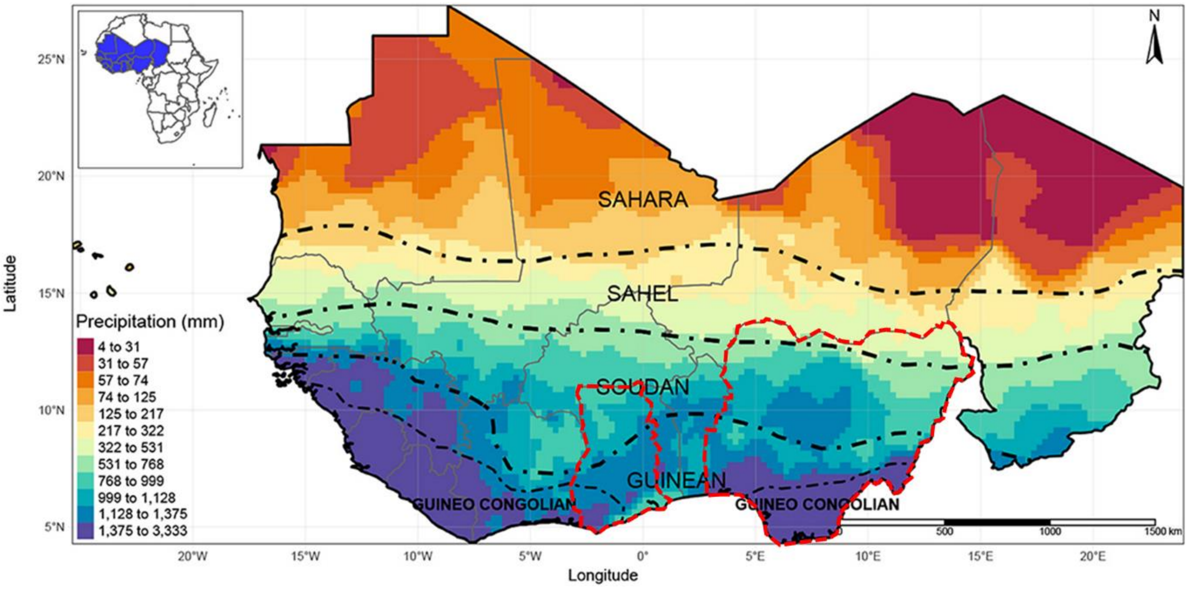

Figure 3 Map of average annual precipitation in West Africa region and bioclimatic zones (Edited from Figure 1 in Houngnibo et al. (2023) [36]; Ghana and Nigeria highlighted (red)).

Although deforestation laws exist in both Ghana and Nigeria to prevent the clearing of natural forests for agriculture or timber, enforcement remains inadequate. Deforestation— driven by plantation expansion, mining, and illegal logging [23,24] —continues at significant rates. Smallholder farmers are often able to access small plots of viable land, but acquiring sufficiently large, contiguous areas for commercial OP estates remains challenging. This limits the development of large-scale, sustainable OP plantations, which require extensive land parcels to ensure economic viability.

2.2. Limitations of subsistence farming

Due to low startup costs, minimal cultivation requirements, and year-round fruit production, OP is an attractive crop for low-income subsistence farmers across tropical regions. In Indonesia and Malaysia, smallholder plantations account for 30–40% of OP cultivation, with large-scale corporate estates dominating overall production. In contrast, smallholder farming is far more prevalent in Ghana and Nigeria, where it accounts for over 80% of total palm oil output [25]. Large-scale plantation farming is a relatively recent development in West Africa and remains uncommon.

Historically, farming in Ghana and Nigeria has been dominated by small-scale subsistence agriculture, where families grow crops primarily for their own consumption and income. Land tenure systems, controlled by local chiefs, often result in fragmented and inconsistently distributed land holdings. These systems generally do not support large-scale farming unless the government intervenes to consolidate land for commercial use.

A typical smallholder OP farm in West Africa covers 1–10 hectares, often reclaimed from degraded forests near rural villages. Farmers typically acquire OP seedlings through government-subsidised programs or donations from local NGOs. However, OP trees require at least three years to bear fruit, leading many smallholders to intercrop with leguminous plants, plantain, or cassava during the early years to supplement income. The lengthy waiting period before first

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harvests exposes farmers to financial vulnerability, particularly in regions where credit access is limited.

Fertiliser application among smallholder farmers is minimal due to prohibitive costs, resulting in significant yield gaps compared to commercial plantations, which benefit from refined fertilisation regimes. Smallholder farms in West Africa typically achieve only 20–30% of the yields obtained by commercial estates, though the output remains sufficient for subsistence farming profitability. Government and NGO programs offer subsidised fertilisers, but bureaucratic hurdles and transportation challenges limit accessibility for many farmers.

Nutrient depletion over time can further reduce yields, as smallholders often lack the financial resources to purchase commercial fertilisers to replenish soil fertility [26]. The quality and yield of fresh fruit bunches (FFBs) harvested by smallholders vary considerably. High-quality fruit is able to be processed at industrial mills, which employ efficient extraction and waste recycling techniques. However, low-quality FFBs—determined by manual grading based on visual inspection—are often rejected by these mills, forcing farmers to rely on small artisanal mills. These mills are highly inefficient, potentially wasting up to one-third of oil yields due to low-tech processing methods. Despite their inefficiencies, artisanal mills may offer higher prices for smallholder crops, incentivising farmers to use them over larger industrial mills.

2.3. Certification and sustainability

Efforts to improve palm oil sustainability have been ongoing for decades, with most initiatives focused on Malaysia and Indonesia. The Roundtable on Sustainable Palm Oil (RSPO), established in 2004, remains the primary global sustainability standard for palm oil, promoting environmentally and socially responsible production practices. OP certification frameworks include:

- Roundtable on Sustainable Palm Oil (RSPO) – A global standard for sustainable palm oil production, covering estate plantations, mills, industrial processors, and smallholders.
- International Sustainability and Carbon Certification (ISCC) – Focuses on reducing greenhouse gas emissions and improving traceability within supply chains.
- Indonesian Sustainable Palm Oil (ISPO) and Malaysian Sustainable Palm Oil (MSPO) – National sustainability certification schemes aligned with legal and regulatory requirements.
- EU Deforestation-Free Regulation (EUDR) – Mandates strict due diligence for commodities linked to deforestation, including palm oil, to ensure compliance with post-2020 deforestation restrictions.

While sustainability certification can increase farmer incomes by raising market prices for refined palm oil, achieving certification requires scale, organisation, and investment. Large commercial OP estates in West Africa often achieve certification and demonstrate high sustainability standards, including social programs such as schools and healthcare facilities. However, smallholder reliance on artisanal milling and the inferior quality of their output diminishes the financial viability of certification. Certification costs and compliance requirements—such as commitments to deforestation avoidance and labour rights—may also be prohibitive for smallholders, particularly in lower-income regions [27].

Land tenure complexities in West Africa further hinder certification efforts. The absence of historical land documentation complicates compliance with certification schemes like the EUDR, which require verifiable land-use records. Successful smallholder certification typically involves collective processing facilities where all contributing farmers adhere to sustainability standards. However, auditing and verification processes for certification are expensive, bureaucratic, and time-consuming, posing additional barriers to implementation.

2.4. Governance and Policy Challenges

Despite commitments to poverty reduction and economic transformation, progress in improving smallholder livelihoods in Ghana and Nigeria has been slow. Government initiatives to enhance palm oil productivity have repeatedly failed. Efforts such as the *President's Special Initiative in Oil Palm* (PSI-Oil Palm) in Ghana (2003) and subsequent expansion plans in 2009 collapsed due to political and financial constraints [28]. Political factors influencing OP policymaking include:

1. Short-term political calculations – Government programs prioritise short-term electoral gains, focusing on distributing subsidised inputs like seedlings and fertilisers rather than investing in long-term industry-wide integration.
2. Weak governance structures – Land tenure disputes, inconsistent policies, and lack of leadership hinder OP sector development.

Traditional land management systems further complicate large-scale OP expansion. In many rural areas, community chiefs control land distribution, limiting long-term investments by smallholders due to tenure insecurities. Without clear legal recourse, smallholders are reluctant to invest in soil quality and sustainable practices, further exacerbating industry challenges.

Table 1 A summary of several important challenges that impede efforts to achieve climate-smart production of OP in West African nations such as Ghana and Nigeria:

Challenge	Impact
Limited suitable land for expansion	• Any sizable expansion of OP plantation acreage will likely result in widespread deforestation of high-quality natural forests with a resultant large emission of carbon. • Expansion of high efficiency commercial OP estates (>100 ha) is not feasible (or extremely difficult) in the region as a result of land ownership disputes. • Climate change may lead to decreasing suitability and land availability for crops such as OP in the region over the next few decades.
Smallholder dominance of production	• Palm oil production in the region is dominated by smallholder farmers who are not compensated for practices that improve sustainability. • Smallholder OP yields in Africa are among the lowest in the world. • Small scale of farming, small haulage vehicles and poor road quality results in highly inefficient logistics in terms of harvest/product/fertiliser transport (e.g. fuel usage/milage). • Artisanal milling processes that dominate oil production are very wasteful and pose severe environmental consequences, but are still more profitable for many smallholders than efficient alternatives. • Certification of sustainability not currently viable or beneficial for the majority of smallholders in the region.
Inconsistent governance	• West Africa has a history of short-lived unsuccessful policy efforts to boost palm oil production which have tried and failed to reconcile differences (typically land-ownership disputes) between commercial estates, smallholder farmers and local chiefs. • Parliamentary changes often lead to rapid shift in policies, change in personnel (ministers), or cancellation of projects which require longer-term effort to achieve measurable progress. • Land-ownership laws in the region do not protect smallholders from land seizures, thus long-term investment in land and soil quality is not prioritized in the region.

3. Opportunities for climate-smart palm oil

Achieving climate-smart production of palm oil products in the West African region faces many challenges. However, there are also many opportunities for improvement in the sector which are readily achievable and can benefit stakeholders in the industry as well as improve sustainability and climate credentials for palm oil production. Based on a review of relevant literature, input of expert knowledge, and discussions with stakeholders from the region, we summarise for this report what we believe to be the most effective and pragmatic steps which could realistically improve the uptake and efficacy of climate-smart practices in the West African OP sector.

3.1. Climate adaptation

Agriculture in West Africa is susceptible to the impacts of a changing climate. The gradually shifting rain patterns in the monsoon/rainy seasons in the region is resulting in a deterioration in the suitability of conditions to support OP production in the north of these countries. Deforestation is the primary source of carbon emissions associated with OP cultivation and is driven primarily by the lack of suitable land to expand farming activities. A rising domestic and global demand for palm oil products and a failure to adapt to the climate risks of the future is likely to increase deforestation in the south of West African countries, where rainfall is expected to remain suitable for OP cultivation in the foreseeable future. Domestic governance has been successful at preventing deforestation in Brazil, where a programme launched in 2010 only allowed expansion into already deforested areas [29]. Similar laws have been enacted by Ghana and Nigeria to prevent unsanctioned forest clearance for agricultural or mining purposes, though enforcing these has proven difficult. The threat of changing rainfall patterns caused by climate change is rapidly becoming a real threat for West African nations, and if OP growers in this region cannot adapt to a changing climate, it is highly likely that deforestation in southern regions will accelerate to meet palm oil demand.

To emphasise, efforts to improve OP resistance to drought and water scarcity in the region contributes to climate-smart palm oil production by i) increasing the efficiencies and yields of existing OP cultivation, and ii) by preventing further deforestation and carbon losses from high quality natural forests.

3.1.1. Drought resistant OP hybrids

The breeding of hybrid OP goes back to the early 1900s where controlled pollination efforts were fairly unsuccessful at creating hybrid OP cultivars, frustrated by cross-contamination of pollen and absence of marker genes. By the 1990s, efforts to cross *dura* and *pisifera* palms had resulted in the *tenera* hybrid, improving oil yields by 30% [30]. Since then, advances in biotechnological technologies have transformed conventional plant breeding approaches by introducing novel genotypes for breeding, paving the way for genetic improvement in OP cultivars [31]. Disease resistance is an important area development due to the need to build resistance to diseases that can devastate plantations (e.g. Pestalotiopsis leaf spot or bud rot [32]). For example, crossbreeding between cultivated (African) OP and wild OP (American) is possible, and can improve oil quality and disease resistance, at the expense of lower oil production [33].

Identifying drought-tolerant cultivars has become pivotal to mitigating the detrimental impacts of water stress on growth and productivity [34]. Studies highlight that drought stress on oil palm cultivation has substantial repercussions in terms of yield and crop health [35]. While advancements in drought stress research have been made across the agricultural sector as a whole (e.g. staple crops such as wheat and maize), oil palm remains relatively understudied. There are several factors which slow research into this particular area of research for OP crops:

- OP crops are a long-term investment (>20 years) and new hybrids are unlikely to be utilised at scale before their agronomic performance is fully categorised.
- It takes >9 years to grow OP plants to the point at which yields peak and can be fully compared with other cultivars in terms of agricultural outputs.
- Hybrid OP crops have varying oil quality, which is also altered by environmental conditions and crop management, making comparisons of predicted outputs difficult across regional boundaries.
- Achieving an improvement in performance of one particular aspect of a cultivar such as drought resistance can also come at the cost of another (e.g. disease resistance or productivity). Fully categorising OP cultivars can take many years to achieve in controlled research conditions.

Work on drought resistant cultivars in one continent (such as Southeast Asia) is likely to produce variants that can do well in other tropical regions (such as Africa); however, assumptions that environmental differences in the regions will have no impact on agronomic performance is potentially risky for growers where large long-term investments are made. West Africa is a region in which developing drought resistant OP cultivars is of high importance for the future of the industry. Both Ghana and Nigeria have permanent dedicated research institutes which aim to increase knowledge of OP agronomic practices. The Nigerian Institute for Oil Palm Research (NIFOR) and Oil Palm Research Institute (OPRI) in Ghana both run long-term OP cultivation experiments such as those required to experiment on cultivars. Both institutes have carried out experimentation on the drought resistance of OP cultivars [36,37], though there is still a lack of a

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strong evidence base to suggest which OP cultivars are best for the long-term needs of OP growers in the West African region.

The development of drought resistant OP cultivars that can perform better in the challenging dry and warm seasons across the tropical belt of West Africa would have a major impact on the lives of OP growers in the region. Yield losses due to water limitation in OP crops can be over 50% depending on conditions [38], and in some cases, entire fields can die off after extreme weather events such as heatwaves. The ability for improved OP hybrid cultivars to survive and thrive in drier conditions would significantly reduce demand for land in forested areas in higher rainfall regions in the south of West Africa and also improve smallholder yields in the region. However, it remains a challenge for smallholder farmers to get access to these improved cultivars for planting.

3.1.2. Oil palm modelling

Advancement in remote sensing (e.g. satellite imagery) and Geographic Information Systems (GIS) has enabled the assessment of suitable areas for OP cultivation on a global, regional and local scale. Remote sensing and GIS can offer effective techniques for estimating how suitable large areas are for OP cultivation without the need for direct measurements in the field. Area suitability assessments are important in the planning process before OP is planted as they provide a viable basis for making effective decisions as to where to farm to obtain optimum growth and promote sustainable agricultural land-use. Paired with knowledge of mills, road access, availability of labour and other relevant metrics, (e.g. access to roads, fertilisers or prevalence of pests and disease), suitability maps can evolve beyond agronomic conditions to inform growers of economic and social factors that may impact decision making. Long-term climate models can also predict the impact that climate change may have on a particular region and the resulting impact that may have on OP cultivation over the medium to long-term (10 – 50 years).

Large scale (1-25 km grid scale) land surface models (e.g. CLM, JULES, CABLE) are typically more suited to crops with seeding and harvest cycles that occur seasonally (e.g. cereals, rice, maize), with less focus placed on perennial tree crops like OP, but advances are being made in this area of research [39]. Localised models that predict agronomic performance can also be used to predict the agronomic success of palm oil crops (e.g. The Agricultural Production Systems sIMulator (APSIM) [40]). Area suitability assessments for OP farming are still relatively simplified in terms of input parameters. Rainfall, temperature, elevation, soil type, slope (steepness), sunlight hours and land-use history are the primary parameters uses to determine how well OP crops will perform in a given region (Figure 4) [21, 41, 42, 43]. Improving models that can predict the agronomic success of OP crops would have a significant impact on the West Africa OP industry. Up-to-date suitability maps could identify suitable areas where OP can grow that may have been missed by farmers as well as modelling future climate risk and where it is not beneficial to expand production. By incorporating different hybrids into these models, planting of different cultivars could be optimised to suit regional weather patterns.

Without accurate suitability maps, long-term data collection of agronomic metrics (e.g. yield and harvest quality) are required to identify trends in data and predict best practice. This data is difficult to obtain from smallholders in Africa and is only possible to collect several years after crop seeding, which is essentially too late to provide effective decision making prior to planting. Improving accuracy of suitability maps will require still data collection for validation purposes, which is severely limited in West Africa in current literature [40]. Increasing the quantity and quality of agronomic data/metrics from the West Africa region would greatly improve modelling efforts in the region in terms of accuracy and the range of future scenarios which could be explored which includes both changes in climate and management activities.

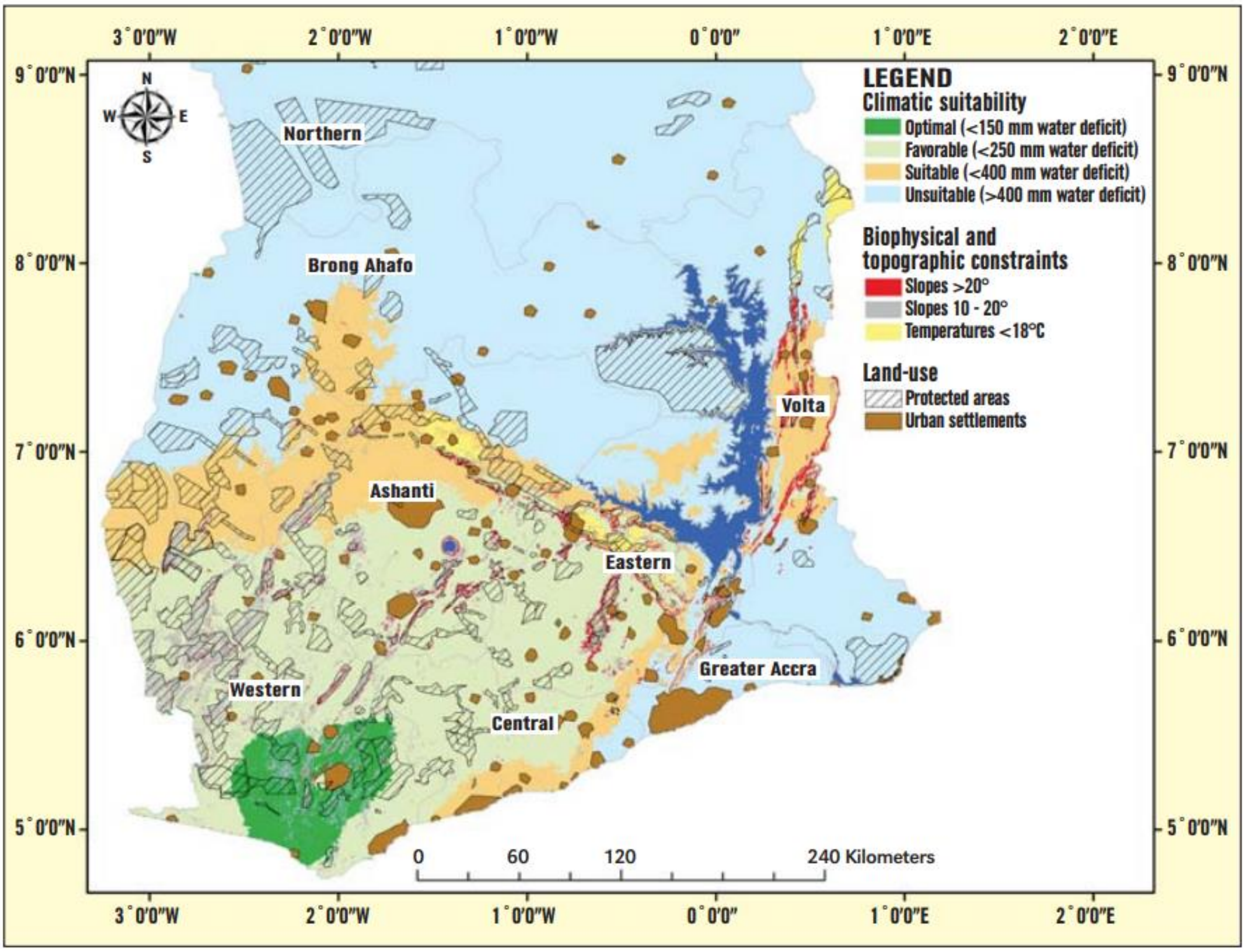

Figure 4 Map of southern Ghana showing suitable and available areas with potential for expansion in oil palm production, after excluding biophysical and topographical constraints and urban settlements and protected areas (Figure 1 in Rhebergen et al., 2016 [43]).

3.1.3. Water management, storage and irrigation

Although irrigation in Africa has the potential to boost agricultural productivities by at least 50%, food production on the continent is almost entirely rainfed [44]. Despite its low coverage of crop area (~4%), irrigated agriculture in sub-Saharan Africa contributes around 25% to the total value of agricultural outputs across the region [45]. It is estimated that only 1.6 and 12.6% of the areas with irrigation potential have been equipped with irrigation in Ghana and Nigeria, respectively [46]. Oil palm productivity is sensitive to water availability and those in water scare regions are particularly sensitive to periods of drought [47]; thus, irrigation efforts could result in a substantial increase in yield, especially in areas where rainfall is limited (e.g. northern regions in Ghana and Nigeria). Irrigation efforts have environmental impacts of their own, particularly in areas where large water deficits occur. However, there is large scope to increase irrigation in West Africa without significant detrimental impact on environmental flows, especially when the correct infrastructure is deployed (e.g. water storage facilities [48]).

National and regional development plans emphasising the role of irrigation development and expansion have been in effect for over a decade in West Africa, but progress has been slow [49]. Efforts to improve irrigation efforts have been hampered by several factors, with overestimation of benefits and inefficient long-term maintenance being key determinants of the failure of past developments. Historically, irrigation development initiatives in West Africa have been dominated by large, capital-intensive irrigation projects controlled by the state to raise agricultural productivity, to enhance food self-sufficiency, and to tackle rural poverty. In this context, irrigation projects often also fulfil a symbolic political purpose. Whether the infrastructure performs long-term matters less than the prestige and public image and publicity governments hope to achieve over the short-term from building the infrastructure [49].

Large scale irrigation schemes are costly investments. Where smallholder farmers do not see benefits, efforts to maintain systems typically fail because of costs and labour requirements. To improve the success rate of irrigation schemes in West Africa, more consultation with local villagers and smallholders should be carried out to assess the needs of the local community. By performing local-scale cost benefit analysis, smaller more strategically refined irrigation efforts could better target certain crops (such as OP) and result in improved yields and potential for the expansion of OP into areas deemed unsuitable due to lack of predicted rainfall. Irrigation is a powerful way in which to improve the success rate of palm oil production for smallholders but is also complex in terms of crop needs and technicalities of water flows and availability. Where irrigation rapidly increases crop growth and yields, nutrient demand will also increase and needs to be met with additional fertiliser application or the impact of irrigation may not be realised [50].

Further irrigation trials are required at the plot to village-scale to identify the best practices to adopt at the smallholder level when it comes to implementing irrigation equipment. The key to increasing sustainable long-term irrigation efforts for smallholders in West Africa is to find the right system for localised conditions which profit those who invest in the system. Where the rewards are tangible, smallholders will naturally invest time and money into maintaining systems without dependence on local governments or external support.

3.2. Soil and nutrient management

Management of soil and nutrient flows (e.g. nitrogen, phosphorus, potassium and other essential trace elements) are of high importance in any agricultural system in terms of environmental and economic sustainability, as well as having the potential to significantly alter climate impacts of farming. Improving nutrient flows in agricultural systems can be achieved by optimising fertiliser application to suit the needs of crops. Large scale commercial OP estates often have better nutrient management than smallholder farms as they can afford to apply imported mineral fertilisers, supplemented with locally generated recycled crop waste (see section 3.3.2.). It is recognised that given the poor natural endowments of African soils and often poor nutrient management (long-term nutrient mining caused by crop production), that substantial increases in inorganic fertiliser would be necessary to restore and maintain the fertility of soils and enhance their productivity [51]. However, commercial fertiliser costs are beyond the reach of most smallholder farmers and improved nutrient management does not guarantee increased profitability (fertiliser costs can exceed harvest sales in low-income markets).

Fertiliser subsidy schemes operate in many developing countries where the costs of commercial mineral fertilisers are prohibitive for poor smallholder farmers. This requires governments to pay for and arrange the distribution of fertiliser products to farmers at significantly reduced costs. All governments in West Africa (including Ghana and Nigeria) currently apply fertiliser subsidy schemes to some extent, which account for the majority of mineral fertilisers applied by smallholder farmers in the region. Subsidy schemes in the region have also benefited from significant development aid funding, from organisations such as USAID, West Africa Fertilizer Program (WAFP), and the African Development Bank. However, current subsidy schemes are still small in relation to the full fertiliser potential requirements of farmers (curtailed by costs) and options to improve fertiliser practices for smallholders are extremely limited. Common issues associated with fertiliser use faced by smallholder farmers in Western Africa include:

Access and knowledge barriers:

- Lack of fertiliser availability (physical access)
- Lack of adequacy of available fertiliser to crop needs (e.g. nutrient ratio of blends)
- Lack of knowledge regarding fertiliser use (e.g. timing/rates/NPK ratio)
- Inability to access subsidy schemes

Economic barriers:

- High transport costs
- Lack of credit to purchase fertilisers
- Lack of crop insurance
- Limited market access to sell harvest
- Low output prices of crops
- Volatility of harvest prices

Increasing quantity and access to subsidised mineral fertilisers in the region is one way in which productivity could increase; however, it may come at great expense to governments. A reliance of domestic agricultural outputs on imported fertiliser can result in severe consequences if fertiliser costs exceed that which a government can maintain. For example, the economic crisis in Sri Lanka resulted in a sudden mandatory shift to organic farming when imported mineral fertilisers for subsidy schemes became too expensive, which devastated the farming community and the nation as a whole which had come to rely heavily upon their availability [52]. The recent trend towards reducing or cancellation of development aid programs (e.g. USAID and UK AID Budget) is one such threat that may have a significant impact on fertiliser subsidy schemes in West Africa in the coming years. Access to subsidised fertilisers can also lead to overuse [53] and increased pollution (air pollution and contaminated water supplies) from agriculture as a result of poor nutrient use efficiencies (NUE).

Improved access and use of mineral fertilisers has the potential to increase efficiencies in OP cultivation and could significantly improve yields for smallholders in West Africa (closing the gap with other regions), thus reducing the need for expansion and deforestation. However, mineral fertilisers have a large carbon cost associated with them due to the high energy cost of mining minerals or the use of the Haber-Bosch industrial process, which generates nitrogen fertilisers [54,55]. Transportation of minerals over national boundaries (typically shipping) has a high associated carbon footprint, and application of mineral nitrogen fertilisers are the largest global source of the potent greenhouse gas nitrous oxide (N_2O).

It is unavoidable that where harvests are continually extracted, soils will eventually become barren if nutrients are not replaced. Improving access to mineral fertilisers would ultimately be required if productivity was to be maximised in West African agriculture. However, a large-scale increase in subsidised mineral fertiliser availability at the national scale carries with it severe environmental and economic risks. Because of these risks, we do not consider increasing the use of subsidised mineral fertilisers as a favourable climate-smart opportunity to improve OP production in the region, even though it would likely significantly improve agronomic performance. Instead, in this report we offer a summary of approaches that address the nutrient problems in African soils over a more intermediate term, with a focus on sustainable agricultural techniques that would be suitable and achievable for many smallholder OP growers.

3.2.1. Agroforestry and intercropping

There is a common assumption made by oil palm growers within large estates and smallholder farms that the OP crop needs to be cultivated as a monoculture in order to maximise yields (and thus profitability). OP is typically planted as a monocrop, with trees spaced in equilateral triangles to maximise crop density while still receiving sufficient sunlight. Monocropping is popular due to the belief that other crop species growing among the oil palms will compete for light and nutrients. However, there can be many circumstances where intercropping multiple annual and perennial crops together in a system can have beneficial effects for both sustainability and economic outputs (Figure 5). This approach of mimicking a forest system by intercropping multiple tree/crop species is called agroforestry. For farmers, this allows the cultivation of various combinations of high-value crops, such as cacao, rubber, fruit, or timber trees, with minimal negative impacts on oil palm yields. It also allows for a wider choice of crops that can receive adequate light, water and nutrients. This in turn can improve the livelihoods of the farmers (particularly smallholders), as they become less dependent on a single crop, and less prone to the fluctuating price of the commodity (e.g. palm oil).

Intercropping in OP plantations (especially in the juvenile stage of the crop) can provide nitrogen in soils via legumes [56], carbon sequestration [57] and improve smallholder economies [57, 58]. Several nitrogen fixing plant types can be planted within cropping systems in African soils to improve nutrient cycling in nutrient poor soils [59, 60]. Cover crops can prevent weeds, and increased biodiversity can reduce pests via bioregulation [61] (e.g. snakes will reduce numbers of crop eating rats). But there are also risks that must be managed by growers as growing multiple crop types will require more agronomic knowledge and equipment to manage harvests [58], as well as needing access to multiple high-quality seedlings in the desired time scales.

A review of agroforestry in sub-Saharan Africa by Kuyah et al. (2019) [62] suggests that agroforestry can be a means to increase crop yield without compromising provision of ecosystem services. This is important for soils with low soil organic matter that have suffered from nutrient mining where fertiliser or irrigation may not be available. Trade-offs are impacted by competition for water and nutrient resources, but most importantly, success depends on selection of optimal tree-crop combination, and management of tree canopies to minimise shading [62].

Research in South America [63, 64] (e.g. Brazil) has shown that smallholder farmers that utilise agroforestry techniques can increase and stabilise income streams, but that the initial stages of development can prove difficult in terms of costs and labour shortages within the family groups that run smallholder plots. The economic success of agroforestry depends on several factors which are regional specific, such as fertiliser availability, access to market, soil type and prevalence of extreme weather events. Because of this, trials are often required to assess the practicalities of agroforestry schemes at local/regional scales, which due to the long-term nature of perennial crops can take several years to generate the data required for economic and ecological comparisons of costs and benefits.

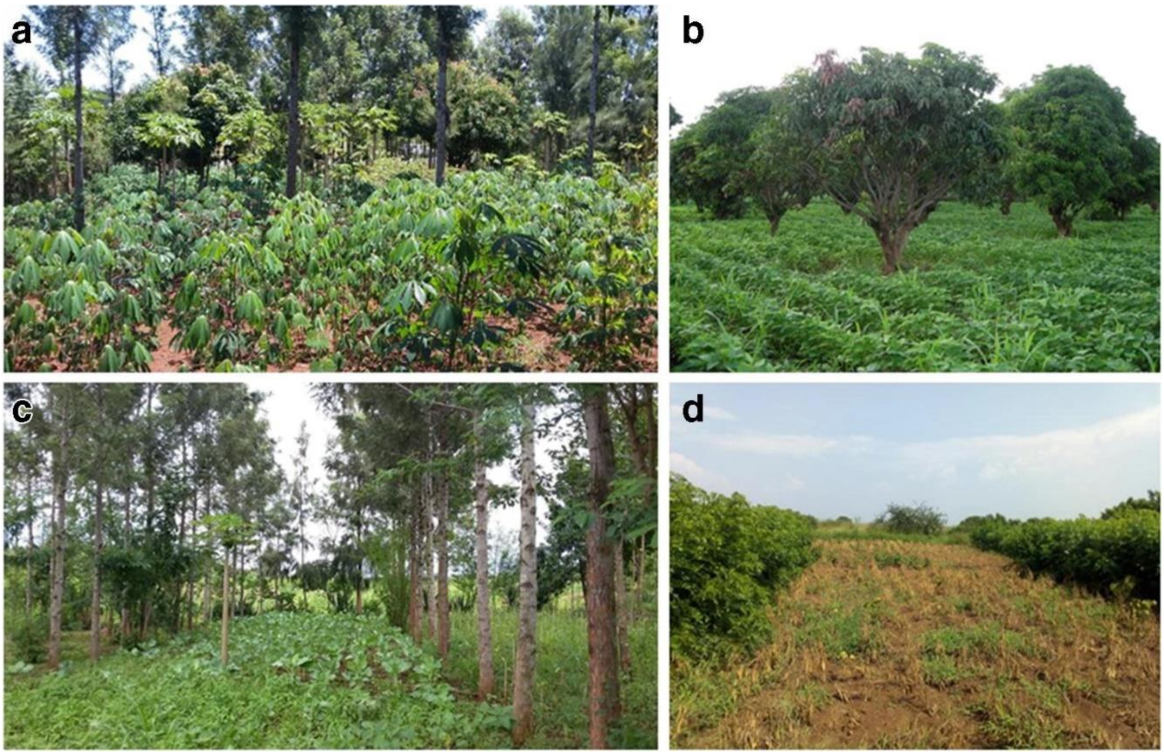

Figure 5 Agroforestry practices common in sub-Saharan Africa. (a) Homegarden (a mosaic landscape with cassava, pawpaw, Mangifera indica L. and Grevillea robusta A.Cunn. ex R.Br. in Uganda). (b) Dispersed intercropping (M. indica in maize-bean intercrop in Malawi). (c) Intercropping with annual crops between widely spaced rows of trees (collard intercropped with G. robusta). (d) Alley cropping (climbing beans planted between hedges of Gliricidia sepium (Jacq.) Kunth ex Walp. in Rwanda). Figure 1 in Kuyah et al. (2019) [62].

Where agroforestry is applied, there is often an increase in biodiversity within plantations, with an increased prevalence of pollinators [65]. The OP tree is a monoecious plant, with separate male and female inflorescences on the same tree. The female inflorescence of OP where fruit bunches develop that are harvested for oil. If the female inflorescence is not pollinated, the fruit will not develop, resulting in reduced yields or even complete crop failure. Beetles (weevils) of the order *coleoptera* are mainly responsible for pollination of OP crops in west Africa [66], though pollination by wind can also occur. Agroforestry can improve pollinator populations, as can protecting parcels of natural forest in heavily farmed areas. By providing a haven for insect life, pollinator numbers can be protected, which then carry out pollination in local OP plantations.

Developing effective agroforestry techniques in West Africa has the potential to increase palm oil yields and reduce poverty in the large smallholder farmer population. However, the technique is not without risk and farmers should be well informed before making decisions that may impact earning potential for several decades. By conducting several medium to long-term agroforestry studies in the region, an evidence base could be established to provide growers with the information they require to make informed decisions regarding their future incomes.

3.2.2. Livestock integration

Livestock ownership in West Africa is common, with a large livestock trade active in the region, dominated by cattle sales (Figure 6) [67,68]. Goats, sheep and chicken are also common in rural areas with smallholders who rear small numbers of animals (typically dwarf varieties) as a source of meat and eggs. While smaller herds can sustain themselves on local plant life for forage, larger herds of livestock need sufficient pasture. Feed scarcity is one of the major constraints to livestock production in the entire West African region and overgrazing has gradually led to deterioration of soil quality and fertility in rangelands (e.g. land classed as savannah during wet seasons). In addition, population growth and increased cultivation of marginal lands and fallows is leading to a significant decline in the available grazing areas and to a consequent growing demand for animal feed.

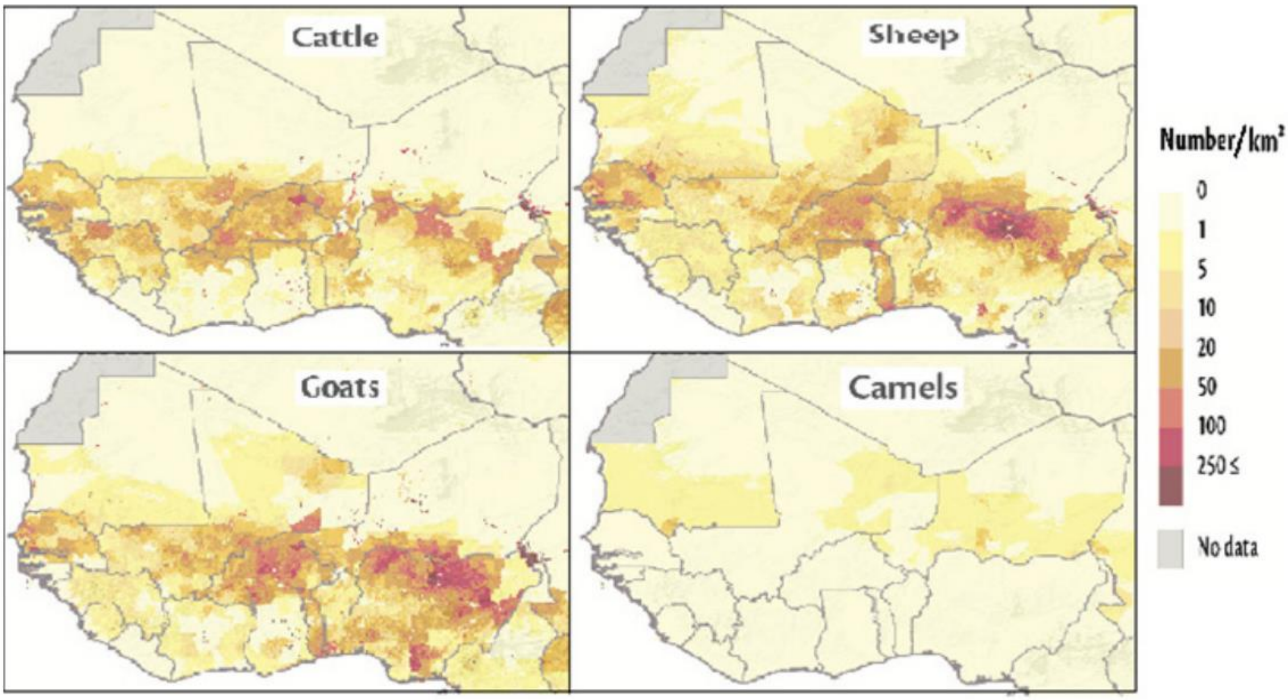

Figure 6 Ruminant livestock distribution in West Africa (Figure 10 in Molina-Flores et al. (2020) [68])

Intercropping OP plantations with fodder crops to allow for livestock grazing is one way in which farmers can attempt to enhance food security and reduce environmental impacts. Agricultural systems that include tree crops with grazing pasture or fodder production are known as silvopastoral or agrosilvopastoral systems (Figure 7). This practice allows for more and diverse food production on the same land, can increase OP yield via better nutrient cycling, and can lower weed control costs with rotational grazing [69,70,71]. The roots of OP trees are shallow and adventitious, forming a dense mat in the top 35 cm of the soil. By incorporating plants with deeper rooting systems (grasses can root as deep as 2 m into the soil), more carbon can be stored in the soil, and much needed nutrients can be restored from deeper soils back to the surface [72,73]. By eating fodder and returning nutrients to the soil (via excreta), nutrient cycling in the whole system can be better managed and recycled. Grazing activities can also reduce the need for herbicide use during OP growth cycles, or burning practices typically used by smallholders to clear OP understorey before or after crop cycles. This improves biodiversity and soil quality. There are many types of agrosilvopastoral systems that farmers can take advantage of with a variety of benefits. Even if landowners do not own the livestock, they can lease their land to livestock owners for the purposes of grazing for a source of income. In this regard, farmers within communities can support each other by maximising nutrient efficiencies between food production systems while improving sustainable credentials.

Figure 7 Cattle grazing in an oil palm plantation (Figure 1 in Bremer et al., 2022 [74]).

Beef and palm oil production are important in both Ghana and Nigeria, and both industries are under threat from climate change and degrading land quality due to poor nutrient cycling. Historically, these activities have been split both in terms of land ownership (farmer wealth) and geographical boundaries. In theory, pairing these activities would make the most of mineral fertilisers applied to soils as well as increasing the sustainability of both production systems without the need for further deforestation or land-use-change. However. while there is a wide array of examples of effective OP agrosilvopastoral systems in practice (particularly in Southeast Asia and South America), there is limited data in the West Africa region by which to determine if these systems would i) benefit smallholders and ii) improve sustainability of OP production.

A cultural shift in livestock management, or village scale cooperation between smallholder and livestock farmers may lead to disputes, especially where benefits of the cooperation favour one system over another (e.g. planting density, fertiliser costs, etc.). Understorey utilisation as feed is a major advantage of cattle–oil palm integration, but declining understorey productivity over time can alter productivity over the plantation's lifecycle, which could lead to a boom/bust cycle of feedstocks [74]. Agrosilvopastoral systems work best at the large scale in commercial estates as fields and livestock are effectively managed across larger scales. It's uncertain whether the economics of livestock/OP integration would benefit smallholders in West Africa enough that farmers would be confident enough to invest in systems that incorporate the most effective fodder crops. Cattle grazing can be difficult in smallholder OP plantations due to land constraints (cattle wandering into neighbour plots due to lack of fences) and potential for theft due to liabilities and lack of insurance.

The application of successful agrosilvopastoral systems could help many farmers in West Africa by improving many aspects of nutrient management in managed fields, but there is currently very limited data on best practice in the region. An understanding of the efficacy of agrosilvopastoral systems in the region can only be improved by carrying out trials, which may take several years to establish credible results. The pairing of agroforestry with livestock grazing addresses some of the key issues in achieving sustainable agriculture in West Africa by maximising the potential of farmable land and improving the efficiencies of available nutrients, both of which are in short supply.

3.2.3. Precision farming and remote sensing

In developed economies with large scale intensive agricultural production systems, nutrient management is a top concern for farmers, and a great deal of technology and novel approaches are applied to determine best practice to maximise crop yields. Precision farming techniques that gather and analyse temporal, spatial and crop data can support management decisions at the field scale for improved resource use efficiency, and sustainability of agricultural production. Nutrient mapping is one method by which farmers can assess optimal fertiliser requirements, balancing the needs of a crop against and what is measured in the soil [75,76]. Mapping and analysing entire farms on a spatial scale for nutrient application efficiencies is only practical if the projected additional income generated by the activity merits the cost of the analysis. In West Africa, this may be possible at the commercial estate scale, but for smallholders (>80% of palm oil production) it would be prohibitively expensive for reasons previously discussed.

In the nutrient poor soils of smallholder OP fields in West Africa, crops often suffer from a variety of problems as a direct result of one or two nutrients being acutely deficient. In these scenarios, a farmer may be able to rectify conditions by applying a commercially available targeted fertiliser solution of trace elements in a small quantity (can be bought at local market) without requiring a full field scale application of nutrients that they cannot access or afford. However, by the time acute nutrient deficiencies are visible, the damage to the crop is already substantial and income is likely to suffer significantly for several years due to a deterioration in crop health (Figure 8). Rather than large-scale, annual spatial mapping of nutrients, smallholder OP farmers in West Africa could benefit from a general knowledge of soil nutrients in their fields every few years, which would allow them to aim to avoid the worst scenarios of nutrient depletion rather than achieve the maximum efficiency in terms of crop production.

Figure 8 Examples of unhealthy trees with nutrient deficiencies and Ganoderma (Figure 3 in Yarak et al. (2021) [77].

Remote sensing is an option that may be preferable to the expense of soil or plant sampling and analysis in West Africa. The application of satellite imagery is developing via artificial intelligence and deep learning to allow for health classification of trees using high-resolution imagery [77]. If models can be developed to identify nutrient deficiencies at early stages of a plantation's lifespan, then appropriate action could be taken. The smallholders themselves would not have direct access to these data or tools, but where information can be disseminated sufficiently to smallholder networks, action could be taken to mitigate the detrimental impacts of acute nutrient deficiencies.

3.2.4. Novel fertilisers

Novel fertilisers use innovative approaches to apply nutrients to crops in ways that are beneficial beyond the application of traditional mineral or organic fertilisers. There is a whole suite of novel fertiliser products being developed for a variety of purposes in agriculture. Primarily, novel fertilisers aim to achieve one or more of the following purposes: i) Reducing cost and increasing availability of fertilisers, ii) reducing waste and pollution in agricultural systems, iii) increasing productivity and crop yields. Research activity investigating new and novel fertiliser methods for OP cultivation has been increasing in Indonesia and Malaysia for several years, with aim to improve both environmental and economic sustainability of OP cultivation at the commercial estate and smallholder level. For the purpose of this review, we highlight what we believe to be feasible options that may have a positive impact in the West African region.

Local production and application of biochar

The application of biochar to soils is considered one way in which farmers can return carbon to soils that also provides agronomic benefits. Biochar is a stable/inert form of charcoal, created by a process called pyrolysis (Figure 9). The pyrolysis process involves cooking biomass in an oxygen depleted environment at temperatures of 400 °C or higher, similar to the production of charcoal. Stable carbon materials in biochar can remain stored for centuries, making biochar a useful material at locking away carbon and storing it in soils.

Figure 9 Palm kernel shells (a) raw (b) after biochar pyrolysis (Figure 3 in Nai Yuh Yek et al. (2020) [78]).

Biochar is not a direct nutrient fertiliser (it will retain some trace elements present in the parent material), but it has been shown to improve soil structure by acting as a porous sponge that retains water and nutrients, thereby enhancing the effectiveness of existing soil amendments. Biochar can be produced from almost any dry organic material, including waste products of which there are many suitable options in the palm oil production process [79,80]. Biochar amendments to soil have reportedly increased the success of oil palm seedlings [81] and improves nutrient uptake rates in OP of phosphorus, magnesium, calcium and boron [82] in comparison to controls. Biochar materials can also significantly increase water content and retention in soils, which would be of great advantage in the dry conditions in which OP is cultivated in West Africa [83,84].

While there may be agronomic potential for the use of biochar in OP cultivation in West Africa, there is skepticism that smallholders would adopt the practice without some kind of financial support. Organic waste from palm oil production is plentiful, but it is mostly utilised as a fuel source for burning by smallholders in rural Africa. Much of the waste that comes from OP is burned locally for cooking and heating purposes (e.g. timber and empty shells). There is no data from West African OP production regarding the costs and benefits of switching from burning organic materials to application of biochar, but local sources suggest that attempting to convince low-income smallholders to make the switch would be very difficult. In theory, after several applications of biochar, the soil structure in OP fields should undergo gradual change, becoming healthier with better nutrient and water retention, boosting crop resilience and yields from OP cultivation, but it could take years for these effects to become noticeable for farmers.

Future efforts to improve African soils via biochar amendments may be to incentivise farmers using a carbon credit system, awarding efforts to lock away carbon in soils. The carbon removal potential of biochar has potential to improve income for both commercial estates and low-income farmers, where an appropriate system of validation and rewards are in place [85]. It is likely that accreditation schemes (RSPO) will incorporate biochar application into its recommendations in the future. Due to the inert nature of biochar and the lack of mechanical agitation in plantation soils in West African OP plantations, once carbon is incorporated, it should remain for a long period of time. A relatively short-term carbon credit program in the region (10 to 20 years) may provide the means by which to improve agricultural soils in smallholder farms with long-term benefits and also generate a significant carbon sink in the region.

Biostimulants

There is a growing understanding that certain microorganisms or enzymes present in nature can help crops access nutrients in soils and improve agronomic performance. Biostimulants are a set of organic materials and/or microorganisms that can enhance water assimilation, nutrient uptake, and resilience to abiotic stresses. Biostimulants are used to manipulate and improve natural biofertilisation process that biological systems carry out in nature. For example, rhizobacteria which colonise rooting structures in soils act symbiotically with plants, providing valuable nutrient processing activities, such as nitrogen fixation. As with biochar, the application of biostimulants is not a fertiliser application, but a method by which to improve nutrient uptake in depleted soils (though can increase nitrogen fixation rates in the rhizosphere).

Bio-stimulants are typically applied to soils at seedling stage by inoculating roots before planting, which can improve the success rate of seedings into adolescent trees. Once inoculated, successful biostimulants will remain in the soil and aid throughout the lifetime of the plant. Extracts from naturally fermenting organic materials like fish waste, seaweed, grass clippings, or fruit, can be used to inoculate seedlings or fertiliser applications with biostimulants with the aim to increase in nutrient use efficiency in soils and boosting OP yields [86, 87]. The use of bio-stimulants is a relatively new field of research, and few studies have been carried out investigating impacts on OP cultivation. Biostimulants have not been rigorously trialed in Africa, but interest is growing, particularly among researchers attempting to boost smallholder agronomic efficiencies.

Inhibitor compounds

Microbial activity can significantly reduce nitrogen (N) content in soils via the naturally occurring processes of nitrification and denitrification. When nitrogen is applied to soils, microbial activity typically increases in response, converting N compounds into inert nitrogen gas (N_2) which is lost to the atmosphere. The powerful GHG N_2O can also be released by these processes, which significantly increases the climate impact of agricultural activities. One promising method which slows microbial cycling of nitrogen in soils is the use of microbial inhibitors which directly target and slow a specific biological pathway [88,89]. These inhibitors work by slowing the availability of N released from a fertiliser, allowing for the crop to better outcompete other loss pathways. Inhibitors are mixed with fertilisers before application, so there is no extra work for farmers. Inclusion of microbial inhibitor compounds in N fertilisers that block nitrification in soils can significantly reduce emissions of N_2O [90], which is associated with fertiliser application in OP cultivation [107]. By blocking urease enzymes with a urease inhibitor, the breakdown of urea-based fertilisers into ammonium can be slowed in soils. This can significantly reduce losses of volatilised ammonia, which can harm both the environment, and human health as a result of air pollution.

While inclusion of nitrogen inhibitors into subsidised mineral fertilisers would be relatively simple and the environmental aspects are reasonably well proven, there is a severe lack of data from West African agriculture regarding the magnitude of nitrogen losses and emissions of N_2O and NH_3 from OP cultivation. There may or may not be an advantage of using these compounds in the region, depending on fertiliser practices and how intense local nitrogen cycling microbial processes are. Nitrogen inhibitors can reduce N losses from agricultural soils and prevent a variety of forms of pollution, but the low nutrient conditions in smallholder soils may not meet the critical threshold at which the added value of inhibitors meets the added cost of their incorporation (increases fertiliser prices by approximately 5%). Research trials investigating nitrogen cycling in soils in African OP plantations would be required to inform on the suitability of the inclusion of inhibitors to subsidised mineral fertilisers.

Foliar treatments

There are several claims in literature that foliar application of fertilisers and novel compounds can have beneficial effects of OP cultivation. The application of fertilisers via foliar application allows for plants to directly absorb required nutrients through leaves and stalks rather than rely on absorption through rooting systems. By applying trace elements directly, losses in soils are reduced via leaching and run-off. Foliar application of fertilisers can improve health of OP crops [91], but care needs to be taken not to provide ideal conditions for mold or other serious pathogens that can harm the crop. Foliar applications of natural compounds such as oil palm wood vinegar can reduce drought stress of some plants [92], though OP specific studies would be required to test the benefits of this treatment. One disruptive technology developed by Crop Intellect (UK) is R-Leaf powder, which captures atmospheric air pollutants (NO_x) and converts them to nitrate (NO_3) via a catalytic conversion with titanium oxide nanoparticles powered by solar ultraviolet light. The technology is prepared into a suspension concentrate solution and it is sprayed on living plant surfaces which remains present for several months. Plants can absorb nitrate directly via stomata, which can result in reduced air pollution and increased crop yield.

Figure 10 Foliar application of fertilisers or pesticides in OP plantations can be achieved using low-cost manual equipment (Figure 3 in Pradana et al. (2022) [93].

3.3. Oil processing and supply chain

The processing of palm oil is an entirely separate process to the cultivation of crops. Farmers typically transport their harvests to mills where the fruit is sold to millers, rather than to the open market. Farmers rarely process their own fruit bunches, with the exception of large commercial OP estates, which typically have their own industrial sized mills. Outside of the estates, the majority of palm oil processing in West Africa is carried out by artisanal millers (>80%) [94].

3.3.1. The artisanal/commercial divide

There is significant disparity in both quality and sustainability of palm oil processed through commercial industrial mills in comparison to small scale artisanal activities. Commercial estates use well refined processes which have been developed by parent companies in Indonesia and Malaysia, which follow RSPO guidelines for accreditation. Commercial estates are aiming to produce high quality oils for refinement or sale on the global market as opposed to artisanal millers who sell their oils for local consumption, with red palm oil being highly sought by West African consumers. Artisanal millers use small scale manual processing equipment that may only take 2 -3 people to operate, but are highly inefficient and prone to quality issues caused by unhealthy crops, aging of fruit bunches (up to 3 weeks between harvest and processing) [95] and contamination from local pollution sources such as polluted water from mining activities or tire burning to cook FFBs [94]. The efficiencies of artisanal milling vary widely depending on a number of factors, but it is believed that FFBs processed via artisanal mills will only generate about two thirds of the amount of oil that industrial processing could generate from the same fruit. However, smallholder farmers still typically make more profits from selling their harvests to artisanal millers than to industrial scale mills, regardless of outputs (especially in the low season when local demand is high) [96].

The local supply chain and harvest pricing is complex at the mill stage and beyond (Table 2). In order to satisfy accreditation standards, industrial mills must verify the source of inputs and carry out quality checks. Smallholders who supply their harvests to company operated mills may have to wait weeks to be paid and can face downgrades in payments due to backlogs in logistics during which period their crop could begin to deteriorate while waiting to be graded. Transportation costs can be excessive where industrial milling is not local, and conflicts between smallholders and companies are commonplace, particularly where loans and financing are involved [96]. Due to a long history of conflicts between independent smallholder farmers and commercial companies in the region, there is a lack of trust and cooperation between the groups in the region, and many farmers highly regard independence from commercial enterprises due to power struggles that may arise. Attempts to reconcile and merge production between these groups would likely prove difficult due to diverging needs and goals (Table 2).

Table 2 A general summary of OP smallholder and commercial estate priorities and general practice for the production of palm oil.

Grower	Smallholder	Commercial Estate
Product	Red Palm Oil (unrefined)	Refined Palm oil
Cultivar	Dura (less fat)	Tenera (higher yields)
Processing	Artisanal	Industrial
Demand	Local markets in West Africa	Local/global demand for food and pharmaceutical products
Advantages	• Higher income • High demand at local level • Independence	• High quality product • High yield and efficiency • Sustainable practices and accreditation
Disadvantages	• Low yields • High waste • Unsustainable practices • Quality issues	• Less independence for growers • Difficult to establish

3.3.2. Waste treatment in palm oil processing

Production of palm oil produces large quantities of organic waste, which can account for up to two thirds of the mass of harvested fruit bunches (Figure 11). The manner in which this waste is handled and disposed of can greatly affect the sustainability and environmental credentials of OP cultivation. The main waste materials that come from palm oil processing are i) empty fruit bunches (EFBs), ii) kernel shells, iii) palm pressed fiber (PPF) and iv) palm oil mill effluent (POME). The locality of commercial mills to owned plantations, the increased income from high quality products and the scale of processing also means that there is significantly more scope to treat and recycle organic wastes back into cultivated soils within estates, providing effective application of nutrients and reducing environmental burden. Thus, commercial OP estates in West Africa are able to utilise almost 100% of waste products, either through biomass burning, biogas capture, or by returning materials back to cultivated soils after treatment. Commercial estates can achieve this success as they have control over the whole OP cultivation process from seedling to refinement, and availability of the finance, land space and labor required to invest in treatment processes at scale. At the artisanal scale, this is not possible. Artisanal millers will often burn a mixture of materials to generate the energy required to process the FFBs via cooking [112], but the majority of waste products will be left to rot or disposed of via drainage channels (e.g. liquid POME) which has serious impacts on the environment.

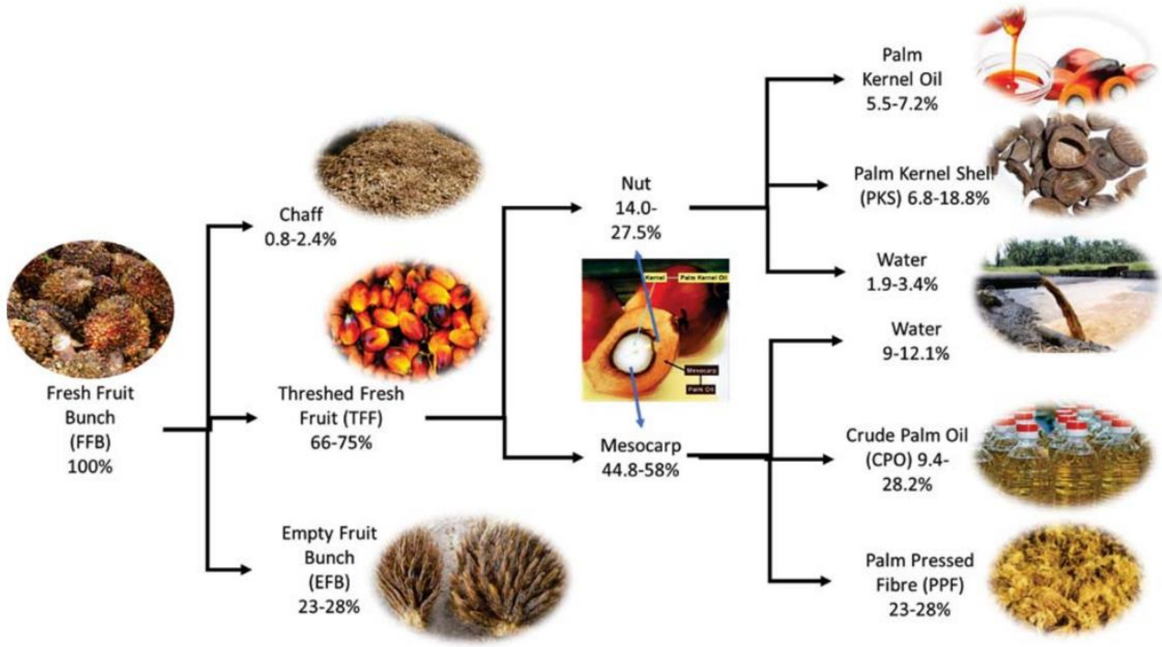

Figure 11 A summary of the fate of organic materials throughout the processing of fresh fruit bunches into palm oil in Cameroon (Figure 1 in Budianta et al. (2022) [97], data from Ohimain et al. (2014) [98].

When considering implementing climate-smart approaches to palm oil production, it makes sense to target smallholder practices as these are an order of magnitude more wasteful than commercial estates and also account for the vast majority of palm oil production in the region. Unlike commercial estates, problems with circular economy approaches at the artisanal scale occur due to limitations in logistics and costs of handling waste. Farmers have to pay significant costs for transport of their harvests and are unlikely to want to pay for waste products to be returned to their farm for the relatively small benefit offered by incorporating waste back into soils. Thus, waste materials tend to accumulate around artisanal mills until the miller decides to move to another location, or it is burned.

POME waste contains high quantities of toxic acids, and it is difficult to handle in large quantities as it is mostly water and cannot be burned. Large POME treatment ponds (bigger than football pitches) utilised by estates allow for the breakdown of harmful compounds over the period of several months [99] and can be used to collect biogas for further use as a fuel [100,101]. After treatment, waste can be applied to fields as fertiliser. Artisanal millers cannot afford the land or labour to carry out waste treatment on this scale, resulting in large quantities of POME being ejected into local drainage channels. One of the reasons that POME is so dangerous to aquatic life is the high nutrient content, which also makes the solution an effective fertiliser, but treatment activities are cost prohibitive at the artisanal scale.

Table 3 A summary of opportunities to work towards climate-smart production of OP in West African nations such as Ghana and Nigeria:

Opportunity	Impact
Climate Adaptation	• **Developing drought resisting OP hybrids and improving irrigation** schemes in the region will improve yields of existing crops and reduce the need to deforest areas with higher rainfall. • **Improving suitability maps for OP** planting in the region will identify the most appropriate zones for future crop expansion without deforestation.
Soil and nutrient management	• **Trials of agroforestry and agrosilvopastoral systems** can increase confidence in mixing additional food production systems with OP cultivation, with the potential to increase overall yields, profits and make the most out of land already converted for agriculture. • **Ability to identify and rectify chronic nutrient deficiencies** before plant health is impacted would prevent waste and improve productivity. • **Incorporating biochar into smallholder soils** made from the waste products of OP cultivation could provide agronomic benefits and reduce climate impacts of farming. • **Application of novel fertilisers** could improve nutrient efficiencies, store carbon in soils and reduce greenhouse gas emissions.
Oil processing and supply chain	• **Improved recycling of waste products** and incorporation back into soils would boost nutrient recycling and soil carbon storage, as well as increasing productivity and wealth in the smallholder community. • **Increasing oil extraction efficiencies**, particularly of artisanal millers, would significantly increase the quantity of usable palm oil generated in Western Africa.

4. Barriers to transformational change

Despite the challenges faced in the West Africa region, commercial scale production of palm oil in large estates in West Africa shows that when managed with agronomic expertise and with adequate investment, that cultivation of OP and production of oil products can be successful, with outputs comparable to the global average. However, smallholders, who dominate production in West Africa, fall far short of their economic and environmental potential, producing 20 to 30% of the yields that commercial estates achieve, while generating significantly more pollution and waste in relative terms. Barriers to transformational change in the region are predominantly the result of practicalities faced by smallholder farmers living in poverty, who suffer from uncertain incomes and are largely powerless in terms of land-ownership and agronomic options (heavily dependent on subsidised seedlings and fertilisers from external organisations). Transformational change in the region faces several key difficulties, which would require significant effort to address.

4.1. Cooperation between stakeholders

Efficiencies in production and sustainability achieved by commercial scale OP estates are achieved by the combination of experience in advanced cultivation techniques and the economic means to invest in long-term facilities. These factors combined with the economy of scales approach that large estates can apply at the local level create a profitable and efficient operation that maximises economic and environmental sustainability. The commercial companies will often invest back into communities with clinics, schools and other commodities to improve the lives of the workers in the estate, an approach which has been popular in Southeast Asia. A question that might be asked is "why is more not done to purchase land from smallholders to expand commercial estates?" to create these high productivity zones of OP cultivation. There are several reasons for resistance to this conversion within rural communities, which primarily comes down to freedoms and individual independence of farmers who do not want to become dependent on powerful international companies, but also the complications in the land-leasing system that smallholders operate by. Village chiefs who own rights to land in rural regions are hesitant to sell land permanently and would rather lease over fixed periods, which can lead to steep price increases and leveraging in the future. Complications in landownership and disputes cause hesitation for commercial investment from external sources, especially when estate land deeds would require agreements with several chiefs over extended periods of time.

There are also many instances where commercial companies have not interacted well with smallholder farmers, particularly when it comes to arguments over the pricing and quality of harvested goods. Commercial companies complain of thievery and dishonesty from smallholder farmers who poach fruit bunches from their land to sell on the artisanal market, while the farmers complain that companies abuse their power and force them into a weak bargaining position at the mills. Where loans have been issued or investments made by companies to support smallholder farmers, there are instances where these have been defaulted, with claims of unfair payment demands which is refuted by company representatives. For many years government initiatives have aimed to support transitions from smallholder to commercial developments, but complications at the local level and the timescale at which negotiations occur usually leads to failure. Generally, there is a lack of trust between all parties involved in negotiations, which prevents incorporation of commercial estates into rural regions in West Africa, which in turn encourages companies to favor deforestation over adoption of smallholder land. The acquisition of forest land from the government bypasses the need for land agreements, which greatly simplifies the process of starting an OP estate at large scale. But as deforestation in the regions is now being curtailed, even this option is not without constraints.

The question of commercial vs smallholder is not something that can be addressed by technological innovation. It is a deeply rooted social issue that has existed since colonial times. The question we may ask instead might be “how do we support smallholders so they can emulate the success of commercial estates?”. There is no technological “silver bullet” which can achieve this, but innovation can be applied to the way that growers operate to improve cooperation and organisation. Smallholders and processing mills go hand-in-hand. One cannot exist without the other and when both systems in the smallholder production chain are inefficient, a cycle of low income and uncontrolled environmental damage is unavoidable. Farmers, delivery drivers, millers and market sellers all need to take a cut of profits for their livelihoods, and disagreements and power struggles between these groups can lead to inefficiencies and breakdown of cooperation, which has been the case for a long-time in the palm oil production chain in West Africa. The advantage that commercial companies have is that all these processes are combined and controlled from the top-down, so activities that may benefit the overall efficiency of the system can come with specific costs in one sector that can be balanced by another (e.g. effective waste treatment could bankrupt a miller but benefit a farmer). The smallholder system does not allow for this flexibility, so any attempt to integrate systems still needs to improve the outcome for each individual, or the system will break down. Essentially, a cooperative grouping of innovative approaches is required to improve the overall outcome for all involved.

Smallholder farmers already operate in small cooperative groupings to an extent, but efficiencies in systems can be drastically improved with the appropriate leadership and direction. The main approaches we have identified to improve climate-smart cultivation of OP requires some level of agronomic cooperation, evidenced by studies that have outlined the benefits of such approaches. This can be local level recycling of waste products back into soils (e.g. POME waste or biochar incorporation), or communication between researchers and farmers that may help with climate adaptation (e.g. availability of drought resistant hybrids). Where medium sized palm oil mills are established at local levels, these can be run in more integrated fashion with smallholders than the larger commercial mills. These mills can significantly increase the efficiency of oil extraction while still offering a more malleable attitude towards quality of crops as products are still sold for local consumption and not for further refinement into vegetable oil products. Locality of mills with smallholder farmers can offer the possibility to significantly increase waste recycling into local fields and improves logistics between farmer and miller, but construction of such infrastructure still requires investment and an expectation of financial returns. Thus, local villagers are often priced out of such schemes which require some element of commercial ownership.

The idea of a highly efficient and integrated farming and processing system at the village scale is perhaps the aim of future efforts to achieve climate smart OP production in West Africa. Aiming for a more holistic approach that benefits stakeholders at each stage in the palm oil production system may be more effective than a direct emulation of commercial estates. Intercropping using agroforestry and agrosilvopastoral systems, paired with the re-incorporation of organic wastes into soils (e.g. biochar and processing waste) can theoretically boost sustainability, yields and profits for farmers. If villages could operate with the same principles as the commercial estates, there is significant room for improvement of both economic and sustainability outcomes. But the important factor and the barrier preventing this is cooperation between stakeholders.

4.2. Informed decision making

One major barrier faced in the development of climate-smart OP cultivation in West Africa is the lack of experimental data from the region. Research institutes local to the region have some expertise in yield, germination success and food quality, evidenced by multiple studies, but local access to the physical sciences is lacking without international engagement and collaborations. Studies investigating carbon balances or emissions of greenhouse gases from agronomic practices are severely limited, thus predicting the potential success of future mitigation strategies is highly uncertain. As the vast majority of palm oil production in the region is produced by low-income smallholder farmers, the appetite for innovative risk-taking to pursue environmental credentials is small. This report has highlighted several routes of action which could improve both the economic and environmental credentials of OP cultivation in the West Africa region; however, many of these are based on evidence collected from other continents and uncertainties remain regarding their suitability in the African climate. It is likely that the agronomic and environmental benefits of these still apply to some extent in the African environment, but it would not be ethically responsible to encourage low-income farmers to adopt these practices at scale without appropriate trials to evidence success.

Small trials are of some value when assessing the possibilities of climate-smart options, but the reality of OP cultivation means that long-term trials (10+ years) are substantially more meaningful. Without evidence of success, it is significantly more difficult to approach and convince farmers to take action at the smallholder level. But, because of the long lifetime of OP crops, this evidence is difficult to collect. Achieving innovative improvements in OP cultivation in West Africa requires the setup of medium to large scale trials in the region that may last up to a decade. The development of “model villages” or controlled trials which incorporate several of the methods we have discussed would add significantly to our understanding of what approaches are effective in the region. Where local research teams can be involved and controls are also cultivated with trials, the impact and added value of novel methods can be quantified, providing confidence for growers that practices work and can improve their livelihoods. There is large scope in this remit for international research collaborations between the local OP research institutes with external partners who are able to train teams and support research in the West African region.

4.3. The availability of nutrients

The availability of nutrients (e.g. fertilisers) is one of the greatest challenges faced by all agricultural systems in Western Africa. For decades, the nutrients extracted from agriculture in the region (smallholder farms in particular) has exceeded those returned by fertiliser inputs for a large proportion of farmed land. Nutrient mining and land degradation are accelerating in the region, significantly reducing yield potential and the fertility of farmland. As the impacts of climate change become more apparent over the next century, changing rainfall patterns will further decrease productivity in the region and pressure farmers to increase deforestation in search of more fertile land. Innovative approaches can improve nutrient use efficiency and utilise ecosystem services (e.g. biological nitrogen fixation) to better sustain crops in low nutrient systems, but ultimately if fertiliser (all critical elements beyond nitrogen) is not available in the region for farmers, production will fall with time.

The issue of nutrient availability goes beyond OP cultivation. The nutrient cycling in the whole food chain is highly inefficient in Africa. Some fertiliser compounds are mined in the region, but deposits are limited, and treatment and recycling of sewage into agriculture is not carried out as the infrastructure to do so is not there. The majority of organic wastes are burned, and composting potential in agriculture is limited. Innovative approaches to nutrient generation can be applied in the region (e.g. the Haber-Bosch process produces nitrogen fertiliser via solar energy and hydrogen generation), but to be sustainable (without dependence on external aid), the cost of these approaches must be met my local farmers which is the limiting factor. The cost of palm oil generated by smallholders and sold to local markets is so minimal, that any attempt to apply innovative technologies is almost entirely reliant on government or international support. The issue of nutrient flows in West Africa is a significant barrier to productive farming systems but cannot be addressed fully in the near future by smallholders without the need for external investment. For this reason, smallholders should focus on increasing efficiencies that they can control at the agronomic scale and aim to increase profitability to the point at which they are more able to afford commercial fertilisers to boost yields in future.

5. Key stakeholders, their roles, and opportunities for collaboration

A range of stakeholders are critical to advancing climate-smart palm oil production in Ghana and Nigeria. These include local growers (e.g. smallholder and estate run farms) research institutions, industry groups, government bodies, and non-governmental organizations (NGOs), each playing distinct roles in transferring, developing, commercialising, adopting, and scaling sustainable technologies and practices. Although all of these stakeholders can interact to some degree, there are major routes by which collaborations would have maximum impact over the short to medium-term. The primary route of interaction ultimately ends with the smallholder farmers, who need the support of all mentioned groups. However, interaction between international collaborators and smallholders requires mediation to be effective, either through collaboration with local research institutions or charitable groups who support local farmers (Figure 12).

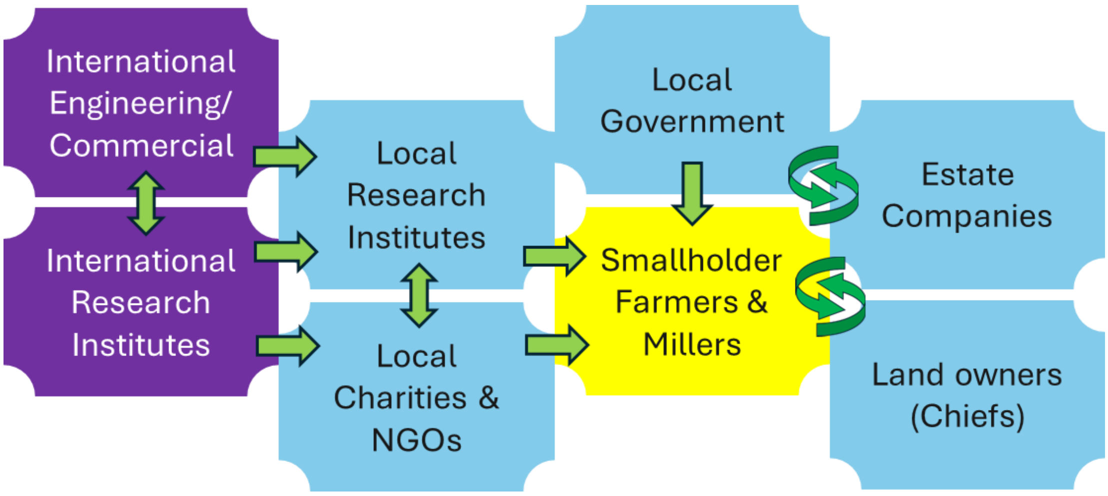

Figure 12 A flow chart of potential collaborations between key stakeholders that could support development of climate-smart palm oil production in West Africa.

There is dynamic interaction between the local stakeholders in the region, but future progress in terms of climate-smart activities is likely to rely more in international engagement and support. We summarise the roles and opportunities that each group may provide for future collaboration, with particular focus on collaborative projects that could advance the potential for climate-smart production of palm oil in the region. By leveraging these partnerships and collaborative opportunities, Ghana and Nigeria can drive the adoption of climate-smart palm oil production practices, ensuring long-term sustainability and economic benefits for all stakeholders.

1. West African Research Institutions

Council for Scientific and Industrial Research - Oil Palm Research Institute (CSIR-OPRI) (Ghana)

Conducts scientific research on oil palm and coconut, including breeding, soil management, and environmental impact assessments.

Nigerian Institute for Oil Palm Research (NIFOR) (Nigeria)

Focuses on breeding high-yielding varieties, soil fertility, fertiliser trials, and oil palm processing technologies.

Opportunities:

- Joint research on greenhouse gas (GHG) emissions, climate models, and biochar applications.
- Training programs for West African researchers at UKCEH in GHG measurement techniques.
- Collaboration on soil carbon stock measurements, nutrient use efficiency studies, and biochar application trials.

2. Government and Policy Organizations

Tree Crop Development Authority (TCDA) (Ghana)

Regulates the oil palm and coconut industries, overseeing policy implementation and market development.

Federal Ministry of Agriculture and Rural Development (Nigeria)

Oversees agricultural policies and provides subsidies and technical support to smallholder farmers.

Opportunities:

- Policy alignment to support climate-smart agriculture, leveraging government extension services for knowledge dissemination.
- Joint development of sustainability policies, carbon trading mechanisms, and incentives for climate-smart practices.

3. Industry Groups and Private Sector
Oil Palm Development Association of Ghana (OPDAG) Represents small, medium, and large-scale oil palm stakeholders, promoting best practices and sustainability in the sector. *Large Oil Palm Estates (e.g., Benso Oil Palm Plantation – BOPP)* Operate on a commercial scale and implement sustainable certification programs (e.g., RSPO certification). *Smallholder Farmers and Cooperatives* Account for a significant proportion of palm oil production but often lack access to technical knowledge and modern inputs.
Opportunities: • Facilitating smallholder training, providing industry data for research collaborations, and supporting GHG measurement initiatives. • Collaboration on emissions monitoring, best-practice adoption, and integration of climate models into plantation management. • Training programs on sustainable intensification, resource management, and technology adoption.

4. NGOs and Development Organizations
Solidaridad West Africa Works on sustainable palm oil initiatives, including smallholder training and methane capture technology for artisanal mills. *Centre for Development and Communication (CEDECOM) (Ghana)* Supports agricultural initiatives and capacity-building programs in rural communities.
Opportunities: • Joint projects on reducing GHG emissions, sustainable milling, and soil conservation. • Hosting farmer workshops, piloting digital farm management tools, and supporting greenhouse gas measurement studies.

Opportunities for Collaboration and Scaling Climate-Smart Technologies	
Data Sharing and Joint Research Initiatives	• Collaboration between research institutions (CSIR-OPRI, NIFOR, UKCEH) to develop standardised methodologies for soil carbon sequestration and nutrient cycling studies. • OPDAG and private estates to provide field data on soil health, emissions, and processing efficiency.
Technology Adoption and Commercialisation	• Introduction of biochar production and application to improve soil health and carbon sequestration. • Testing and scaling of digital tools for farm management, fertiliser optimisation, and emissions tracking.
Infrastructure Development	• Exploring funding opportunities for centralised storage facilities to reduce post-harvest losses. • Investment in medium-scale processing facilities for smallholders to enhance efficiency and reduce waste.
Training and Capacity Building	• Organising regional workshops involving Ghana, Nigeria, and Liberia to train farmers and industry stakeholders on climate-smart practices. • University partnerships to involve students in field research and GHG measurement.
Policy and Governance Enhancement	• Collaborating with TCDA and government agencies to develop policies supporting sustainable intensification over land expansion. • Engaging policymakers to create financial incentives for carbon sequestration projects and deforestation-free palm oil certification.
Sustainable Land Use and Climate Resilience	• Modelling future climate scenarios for oil palm suitability in Ghana and Nigeria. • Research on intercropping systems and agroforestry models to enhance resilience and biodiversity conservation.

6. Conclusions

Palm oil production in Ghana and Nigeria has the potential to support economic development, rural livelihoods, and food security. However, the sector faces significant challenges that hinder its sustainability. This report has examined the barriers and opportunities associated with climate-smart palm oil production, highlighting key areas for intervention.

Land suitability is a major constraint, as the most favourable regions for OP cultivation are densely populated, already in use for agriculture, or protected as forests. Climate change further complicates expansion by altering rainfall patterns and increasing water deficits. Weak enforcement of environmental regulations has also led to deforestation and land-use conflicts, worsening sustainability concerns.

Smallholder farmers account for over 80% of production but struggle with low yields due to limited access to quality seedlings, fertilisers, and financing. No fruit to harvest in the first three years of OP cropping requires other income during that period. Reliance on inefficient artisanal mills leads to high waste and low-quality oil. Without stronger cooperatives, better extension services, and decentralised processing facilities, smallholders will struggle to adopt climate-smart practices.

Sustainability certification schemes like the Roundtable on Sustainable Palm Oil (RSPO) could improve environmental and social standards, but high costs and administrative burdens make them inaccessible for most smallholders. Strengthening cooperative structures and investing in shared processing infrastructure could help smallholders meet sustainability requirements and access premium markets.

Governance and policy frameworks are crucial to the sector's future. Past initiatives have failed due to inconsistent political support and weak land governance. Addressing these challenges is essential for a more sustainable and inclusive industry.

Despite these barriers, climate-smart practices such as agroforestry, intercropping, and drought-resistant oil palm varieties present viable solutions. International collaboration and private sector investment can drive change by supporting infrastructure, technical assistance, and fair market access for smallholders.

In conclusion, while challenges remain, climate-smart palm oil production offers a pathway to sustainability. Addressing land-use issues, supporting smallholder farmers, and strengthening governance are critical to realising this potential. With coordinated efforts, Ghana and Nigeria can build a resilient palm oil sector that balances economic growth with environmental and social responsibility.

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8. References:

1. Ayompe, L.M., Schaafsma, M., Egoh, B.N., 2021. Towards sustainable palm oil production: The positive and negative impacts on ecosystem services and human wellbeing. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2020.123914
2. Sheil, D., Casson, A., Meijaard, E., van Nordwijk, M. Gaskell, J., Sunderland-Groves, J., Wertz, K. and Kanninen, M. 2009. The impacts and opportunities of oil palm in Southeast Asia: What do we know and what do we need to know? Occasional paper no. 51. CIFOR, Bogor, Indonesia. https://www.cifor-icraf.org/publications/downloads/Publications/PDFS/OP16401.pdf
3. US Department of Agriculture (USDA). (2024). Palm oil: production. Available at: https://fas.usda.gov/data/production/commodity/4243000
4. Ahmad, M.J., Ismail, R., Ghani, F.A., 2023. Review on socioeconomic and sustainability of oil palm plantations among rural communities in Malaysia. IOP Conf. Ser.: Earth Environ. Sci. https://doi.org/10.1088/1755-1315/1208/1/012054
5. Turner, E.C., Snaddon, J.L., 2023. Deforestation in Southeast Asia. Biological and Environmental Hazards, Risks, and Disasters. https://doi.org/10.1016/b978-0-12-820509-9.00004-6
6. Ocampo-Peñuela, N., Garcia-Ulloa, J., Kornecki, I., Philipson, C.D., Ghazoul, J., 2020. Impacts of Four Decades of Forest Loss on Vertebrate Functional Habitat on Borneo. Front. For. Glob. Change. https://doi.org/10.3389/ffgc.2020.00053
7. Gaveau, D.L.A., Locatelli, B., Salim, M.A., Yaen, H., Pacheco, P., Sheil, D., 2018. Rise and fall of forest loss and industrial plantations in Borneo (2000–2017). CONSERVATION LETTERS. https://doi.org/10.1111/conl.12622
8. Sasmito, S.D., Taillardat, P., Adinugroho, W.C., Krisnawati, H., Novita, N., Fatoyinbo, L., Friess, D.A., Page, S.E., Lovelock, C.E., Murdiyarso, D., Taylor, D., Lupascu, M., 2025. Half of land use carbon emissions in Southeast Asia can be mitigated through peat swamp forest and mangrove conservation and restoration. Nat Commun. https://doi.org/10.1038/s41467-025-55892-0
9. Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H., Jauhiainen, J., 2010. Current and future CO2 emissions from drained peatlands in Southeast Asia. Biogeosciences. https://doi.org/10.5194/bg-7-1505-2010
10. WEF, 2022 https://www.weforum.org/stories/2022/11/how-african-palm-oil-can-boost-livelihoods-and-protects-forests/
11. Paradis, E., 2021. Forest gains and losses in Southeast Asia over 27 years: The slow convergence towards reforestation. Forest Policy and Economics. https://doi.org/10.1016/j.forpol.2020.102332
12. Meijaard, E., Brooks, T.M., Carlson, K.M., Slade, E.M., Garcia-Ulloa, J., Gaveau, D.L.A., Lee, J.S.H., Santika, T., Juffe-Bignoli, D., Struebig, M.J., Wich, S.A., Ancrenaz, M., Koh, L.P., Zamira, N., Abrams, J.F., Prins, H.H.T., Sendashonga, C.N., Murdiyarso, D., Furumo, P.R., Macfarlane, N., Hoffmann, R., Persio, M., Descals, A., Szantoi, Z., Sheil, D., 2020. The environmental impacts of palm oil in context. Nat. Plants. https://doi.org/10.1038/s41477-020-00813-w

13. Murphy, D.J., Goggin, K., Paterson, R.R.M., 2021. Oil palm in the 2020s and beyond: challenges and solutions. CABI Agric Biosci. https://doi.org/10.1186/s43170-021-00058-3
14. Mei, L., Newing, H., Almås Smith, O., Colchester, M., and McInnes, A., 2021. Identifying the Human Rights Impacts of Palm Oil: Guidance for Financial Institutions and Downstream Companies. https://globalcanopy.org/wp-content/uploads/2022/08/FPP-Palm-Oil-Report-FINAL52.pdf
15. Sibhatu, K.T., 2023. Oil palm boom: its socioeconomic use and abuse. Front. Sustain. Food Syst. https://doi.org/10.3389/fsufs.2023.1083022
16. USDA, 2022, Foreign Agricultural Service Commodity Intelligence Report. Record Palm Oil Production Forecast for Côte d'Ivoire and Ghana. https://ipad.fas.usda.gov/highlights/2022/09/Ghana/index.pdf
17. Ofosu-BUDU, K., and Sarpong, D.B.. 2013. Oil Palm Industry Growth in Africa: A value chain and smallholders' study for Ghana. study for Ghana, In book: Rebuilding West Africa's Food Potential, FAO, Chapter: 11, pp.349-389
18. Guillaume, T., Kotowska, M.M., Hertel, D., Knohl, A., Krashevska, V., Murtilaksono, K., Scheu, S., Kuzyakov, Y., 2018. Carbon costs and benefits of Indonesian rainforest conversion to plantations. Nat Commun. https://doi.org/10.1038/s41467-018-04755-y
19. Djalante, R., Jupesta, J., Aldrian, E., 2021. Correction to: Climate Change Research, Policy and Actions in Indonesia. Springer Climate. https://doi.org/10.1007/978-3-030-55536-8_16
20. Reiss-Woolever, V.J., Luke, S.H., Stone, J., Shackelford, G.E., Turner, E.C., 2021. Systematic mapping shows the need for increased socio-ecological research on oil palm. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abfc77
21. Rhebergen, T., Fairhurst, T., Zingore, S., Fisher, M., Oberthür, T., Whitbread, A., 2016. Climate, soil and land-use based land suitability evaluation for oil palm production in Ghana. European Journal of Agronomy. https://doi.org/10.1016/j.eja.2016.08.004
22. Paterson, R.R.M., Chidi, N.I., 2023. Climate Refuges in Nigeria for Oil Palm in Response to Future Climate and Fusarium Wilt Stresses. Plants. https://doi.org/10.3390/plants12040764
23. Kalischek, N., Lang, N., Renier, C., Daudt, R.C., Addoah, T., Thompson, W., Blaser-Hart, W.J., Garrett, R., Schindler, K., Wegner, J.D., 2023. Cocoa plantations are associated with deforestation in Côte d'Ivoire and Ghana. Nat Food. https://doi.org/10.1038/s43016-023-00751-8
24. Ahmed, Y.A., Olaitan, R.A., 2024. The Challenges of Deforestation and Management in Nigeria: Suggestions for Improvement. Ghana J. Geography. https://doi.org/10.4314/gjg.v16i1.7
25. Asante, K.T., 2023. The politics of policy failure in Ghana: The case of oil palm. World Development Perspectives. https://doi.org/10.1016/j.wdp.2023.100509
26. Essono, D.M., Batamack Nkoué, B., Voundi, E., Kono, L., Verrecchia, E., Ghazoul, J., Mala, A.W., Buttler, A., Guillaume, T., 2023. Nutrient availability challenges the sustainability of low-input oil palm farming systems. Farming System. https://doi.org/10.1016/j.farsys.2023.100006
27. Ayompe, L.M., Nkongho, R.N., Wandum, L.M., Orang, B.O., Fiaboe, K.K.M., Tambasi, E.E., Kettunen, M., Egoh, B.N., 2023. Complexities of sustainable palm oil production by smallholders in sub-SaharanAfrica. Sustainable Development. https://doi.org/10.1002/sd.2674

28. Asante, E. A. (2012). The case of Ghana's president's special initiative on oil palm (PSI-oil palm). Danish Institute for International Studies. DIIS Working Paper Vol. 2012 No. 11
29. Brandão, F., Schoneveld, G., Pacheco, P., Vieira, I., Piraux, M., Mota, D., 2021. The challenge of reconciling conservation and development in the tropics: Lessons from Brazil's oil palm governance model. World Development. https://doi.org/10.1016/j.worlddev.2020.105268
30. Corley, R.H.V., Lee, C.H., 1992. The physiological basis for genetic improvement of oil palm in Malaysia. Euphytica. https://doi.org/10.1007/bf00039396
31. John Martin, J.J., Yarra, R., Wei, L., Cao, H., 2022. Oil Palm Breeding in the Modern Era: Challenges and Opportunities. Plants. https://doi.org/10.3390/plants11111395
32. Ávila-Méndez, K., Avila-Diazgranados, R., Pardo, A., Herrera, M., Sarria, G., Romero, H.M., 2019. Response of in vitro obtained oil palm and interspecific OxG hybrids to inoculation with Phytophthora palmivora. Forest Pathology. https://doi.org/10.1111/efp.12486
33. Astorkia, M., Hernández, M., Bocs, S., Ponce, K., León, O., Morales, S., Quezada, N., Orellana, F., Wendra, F., Sembiring, Z., Asmono, D., Ritter, E., 2019. Analysis of the allelic variation in the Shell gene homolog of E. oleifera and design of species specific Shell primers. Euphytica. https://doi.org/10.1007/s10681-019-2538-7
34. Abubakar, A., Gambo, J., Ishak, M.Y., 2023. Navigating climate challenges: Unraveling the effects of climate change on oil palm cultivation and adaptation strategies. Advances in Food Security and Sustainability. https://doi.org/10.1016/bs.af2s.2023.07.002
35. Bayona-Rodríguez, C., Romero, H.M., 2024. Drought Resilience in Oil Palm Cultivars: A Multidimensional Analysis of Diagnostic Variables. Plants. https://doi.org/10.3390/plants13121598
36. Osei Darkwah, D., Blay, E., Amoatey, H., Sapey, E., Bakoume, C., Agyei-Dwarko, D., 2020. Genetic diversity and selection within natural dura oil palm accessions collected in Ghana for oil palm productivity improvement. Biodiversitas. https://doi.org/10.13057/biodiv/d210815
37. Ubara, U.E., Agho, C.A.,Aye, A.I.,Yakubu, M., Eke, C.R., and Asemota. O Identification of drought tolerant progenies in oil palm (Elaeis guineensis Jacq.), 2017. Int. J. Adv. Res. Biol. Sci. https://doi.org/10.22192/ijarbs.2017.04.06.018
38. Woittiez, L.S., van Wijk, M.T., Slingerland, M., van Noordwijk, M., Giller, K.E., 2017. Yield gaps in oil palm: A quantitative review of contributing factors. European Journal of Agronomy. https://doi.org/10.1016/j.eja.2016.11.002
39. Fan, Y., Roupsard, O., Bernoux, M., Le Maire, G., Panferov, O., Kotowska, M.M., Knohl, A., 2015. A sub-canopy structure for simulating oil palm in the Community Land Model (CLM-Palm): phenology, allocation and yield. Geosci. Model Dev. https://doi.org/10.5194/gmd-8-3785-2015
40. Carcedo, A.J.P., Vieira Junior, N., Marziotte, L., Correndo, A.A., Araya, A., Prasad, P.V.V., Min, D., Stewart, Z.P., Faye, A., Ciampitti, I.A., 2023. The urgency for investment on local data for advancing food assessments in Africa: A review case study for APSIM crop modeling. Environmental Modelling & Software. https://doi.org/10.1016/j.envsoft.2023.105633
41. Tapia, J.F.D., Doliente, S.S., Samsatli, S., 2021. How much land is available for sustainable palm oil? Land Use Policy. https://doi.org/10.1016/j.landusepol.2020.105187
42. Abraham, A., Bamweyana, I., 2022. Geospatial assessment of land suitability for oil palm (Elaeis guineensis Jacq.) growing in Northern Uganda. SA J of Geomatics. https://doi.org/10.4314/sajg.v11i2.10

43. Rhebergen, T and Fairhurst, T and Zingore, S and Fisher, M and Oberthür, T and Whitbread, A M (2016) Adapting oil palm best management practices to Ghana: opportunities for production intensification. Better Crops with Plant Food, 100 (04). pp. 12-15. ISSN 0006-0089
44. You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., Nelson, G., Guo, Z., Sun, Y., 2011. What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. Food Policy. https://doi.org/10.1016/j.foodpol.2011.09.001
45. Svendsen, M., Ewing, M., Msangi, S., 2009. Measuring Irrigation Performance in Africa (IFPRI Discussion Paper No. 00894). International Food Policy Research Institute (IFPRI).
46. Namara, R. E.; Sally, H. (Eds.). Water Management Institute (IWMI), I., 2014. Women's vulnerability to climatic and non-climatic change in the Eastern Gangetic Plains. In Nepali. International Water Management Institute (IWMI). https://doi.org/10.5337/2014.218
47. Brum, M., Oliveira, R.S., López, J.G., Licata, J., Pypker, T., Chia, G.S., Tinôco, R.S., Asbjornsen, H., 2021. Effects of irrigation on oil palm transpiration during ENSO-induced drought in the Brazilian Eastern Amazon. Agricultural Water Management. https://doi.org/10.1016/j.agwat.2020.106569
48. Geleta, Y., Simane, B., Assefa, E., Haileslassie, A., 2023. Impacts of small-scale irrigation water use on environmental flow of ungauged rivers in Africa. Environ Syst Res. https://doi.org/10.1186/s40068-023-00283-x
49. Redicker, S., Dimova, R., Foster, T., 2022. Synthesising evidence on irrigation scheme performance in West Africa. Journal of Hydrology. https://doi.org/10.1016/j.jhydrol.2022.127919
50. Rhebergen, T., Fairhurst, T., Giller, K.E., Zingore, S., 2019. The influence of water and nutrient management on oil palm yield trends on a large-scale plantation in Ghana. Agricultural Water Management. https://doi.org/10.1016/j.agwat.2019.05.003
51. Druilhe, Z., and Barreiro-Hurlé, J., 2012. Fertilizer subsidies in sub-Saharan Africa. https://www.fao.org/4/ap077e/ap077e.pdf
52. Wijerathna-Yapa, A., Henry, R.J., Dunn, M., Beveridge, C.A., 2023. Science and opinion in decision making: A case study of the food security collapse in Sri Lanka. Modern Agriculture. https://doi.org/10.1002/moda.18
53. Holland, J., Behrendt, K., Ghosh, B., 2025. Remove subsidies to solve India's fertilizer-overuse problem. Nature. https://doi.org/10.1038/d41586-025-00114-2
54. Gao, Y., Cabrera Serrenho, A., 2023. Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions. Nat Food. https://doi.org/10.1038/s43016-023-00698-w
55. Hasler, K., Bröring, S., Omta, S.W.F., Olfs, H.-W., 2015. Life cycle assessment (LCA) of different fertilizer product types. European Journal of Agronomy. https://doi.org/10.1016/j.eja.2015.06.001
56. Agamuthu, P., Broughton, W.J., 1985. Nutrient cycling within the developing oil palm-legume ecosystem. Agriculture, Ecosystems & Environment. https://doi.org/10.1016/0167-8809(85)90054-4
57. Ahirwal, J., Sahoo, U.K., Thangjam, U., Thong, P., 2022. Oil palm agroforestry enhances crop yield and ecosystem carbon stock in northeast India: Implications for the United Nations sustainable development goals. Sustainable Production and Consumption. https://doi.org/10.1016/j.spc.2021.12.022

58. Hendrawan, D., Musshoff, O., 2024. Risky for the income, useful for the environment: Predicting farmers' intention to adopt oil palm agroforestry using an extended theory of planned behaviour. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2024.143692
59. Glover, J.D., Reganold, J.P., Cox, C.M., 2012. Plant perennials to save Africa's soils. Nature. https://doi.org/10.1038/489359a
60. Snapp, S.S., Cox, C.M., Peter, B.G., 2019. Multipurpose legumes for smallholders in sub-Saharan Africa: Identification of promising 'scale out' options. Global Food Security. https://doi.org/10.1016/j.gfs.2019.03.002
61. Masure, A., Martin, P., Lacan, X., Rafflegeau, S., 2023. Promoting oil palm-based agroforestry systems: an asset for the sustainability of the sector. Cah. Agric. https://doi.org/10.1051/cagri/2023008
62. Kuyah, S., Whitney, C.W., Jonsson, M., Sileshi, G.W., Öborn, I., Muthuri, C.W., Luedeling, E., 2019. Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. Agron. Sustain. Dev. https://doi.org/10.1007/s13593-019-0589-8
63. Villanueva-González, C.E., Pérez-Olmos, K.N., Mollinedo, M.S., Lojka, B., 2024. Exploring agroforestry and food security in Latin America: a systematic review. Environ Dev Sustain. https://doi.org/10.1007/s10668-024-05352-4
64. Somarriba, E., Beer, J., Alegre-Orihuela, J., Andrade, H.J., Cerda, R., DeClerck, F., Detlefsen, G., Escalante, M., Giraldo, L.A., Ibrahim, M., Krishnamurthy, L., Mena-Mosquera, V.E., Mora-Degado, J.R., Orozco, L., Scheelje, M., Campos, J.J., 2012. Mainstreaming Agroforestry in Latin America. Advances in Agroforestry. https://doi.org/10.1007/978-94-007-4676-3_21
65. Centeno-Alvarado, D., Lopes, A.V., Arnan, X., 2023. Fostering pollination through agroforestry: A global review. Agriculture, Ecosystems & Environment. https://doi.org/10.1016/j.agee.2023.108478
66. Riley, S.O., Dery, S.K., Afreh-Nuamah, K., Agyei-Dwarko, D., Ayizannon, R.G., 2022. Pollinators of oil palm and relationship to fruitset and yield in two fruit forms in Ghana. OCL. https://doi.org/10.1051/ocl/2022009
67. Valerio, V.C., Walther, O.J., Eilittä, M., Cissé, B., Muneepeerakul, R., Kiker, G.A., 2020. Network analysis of regional livestock trade in West Africa. PLoS ONE. https://doi.org/10.1371/journal.pone.0232681
68. Molina-Flores, B., Manzano-Baena, P., and Coulibaly, M. D., 2020. The role of livestock in food security, poverty reduction and wealth creation in West Africa. https://openknowledge.fao.org/server/api/core/bitstreams/58bb0896-5cf1-4231-b987-d731b451af64/content
69. Grinnell, N.A., van der Linden, A., Azhar, B., Nobilly, F., Slingerland, M., 2022. Cattle-oil palm integration – a viable strategy to increase Malaysian beef self-sufficiency and palm oil sustainability. Livestock Science. https://doi.org/10.1016/j.livsci.2022.104902
70. Umar, Y., Syakir, M.I., Yusuff, S., Azhar, B., Tohiran, K.A., 2023. The integration of cattle grazing activities as potential best sustainable practices for weeding operations in oil palm plantations. IOP Conf. Ser.: Earth Environ. Sci. https://doi.org/10.1088/1755-1315/1167/1/012014
71. Álvarez, E.R., Castiblanco, J.S., Montoya, M.M., 2024. Sustainable intensification of palm oil production through cattle integration: a review. Agroecology and Sustainable Food Systems. https://doi.org/10.1080/21683565.2023.2299012

72. Callesen, I., Harrison, R., Stupak, I., Hatten, J., Raulund-Rasmussen, K., Boyle, J., Clarke, N., Zabowski, D., 2016. Carbon storage and nutrient mobilization from soil minerals by deep roots and rhizospheres. Forest Ecology and Management. https://doi.org/10.1016/j.foreco.2015.08.019
73. Germon, A., Laclau, J.-P., Robin, A., Jourdan, C., 2020. Tamm Review: Deep fine roots in forest ecosystems: Why dig deeper? Forest Ecology and Management. https://doi.org/10.1016/j.foreco.2020.118135
74. Bremer, J.A., Lobry de Bruyn, L.A., Smith, R.G.B., Cowley, F.C., 2022. Knowns and unknowns of cattle grazing in oil palm plantations. A review. Agron. Sustain. Dev. https://doi.org/10.1007/s13593-021-00723-x
75. Singh, H., Halder, N., Singh, B., Singh, J., Sharma, S., Shacham-Diamand, Y., 2023. Smart Farming Revolution: Portable and Real-Time Soil Nitrogen and Phosphorus Monitoring for Sustainable Agriculture. Sensors. https://doi.org/10.3390/s23135914
76. Silva, F.M., Queirós, C., Pereira, M., Pinho, T., Barroso, T., Magalhães, S., Boaventura, J., Santos, F., Cunha, M., Martins, R.C., 2024. Precision Fertilization: A critical review analysis on sensing technologies for nitrogen, phosphorous and potassium quantification. Computers and Electronics in Agriculture. https://doi.org/10.1016/j.compag.2024.109220
77. Yarak, K., Witayangkurn, A., Kritiyutanont, K., Arunplod, C., Shibasaki, R., 2021. Oil Palm Tree Detection and Health Classification on High-Resolution Imagery Using Deep Learning. Agriculture. https://doi.org/10.3390/agriculture11020183
78. Yek, P.N.Y., Osman, M.S., Wong, C.C., Wong, C.S., Kong, S.H., Sie, T.S., Foong, S.Y., Lam, S.S., Liew, R.K., 2020. Microwave wet torrefaction: A catalytic process to convert waste palm shell into porous biochar. Materials Science for Energy Technologies. https://doi.org/10.1016/j.mset.2020.08.004
79. Mohamed, M., Yusup, S., 2021. A review on sustainability and quality of biochar production from oil palm biomass in Malaysia using thermal conversion technology. E3S Web Conf. https://doi.org/10.1051/e3sconf/202128704011
80. Promraksa, A., Rakmak, N., 2020. Biochar production from palm oil mill residues and application of the biochar to adsorb carbon dioxide. Heliyon. https://doi.org/10.1016/j.heliyon.2020.e04019
81. Utami, S.N.H., Indrawati, U.S.Y.V., 2023. Oil palm empty fruit bunch biochar fertilizer as a solution to increasing the fertility of peat soil for sustainable agriculture. OICC Press (United Kingdom). https://doi.org/10.57647/J.IJROWA.2024.1301.03
82. Hwong, C.N., Sim, S.F., Kho, L.K., Teh, Y.A., Harrold, L.D., Chua, K.H., Zainal, N.H., 2022. Effects Of Biochar From Oil Palm Biomass On Soil Properties And Growth Performance Of Oil Palm Seedlings. Jssm. Https://Doi.Org/10.46754/Jssm.2022.4.014
83. Razzaghi, F., Obour, P.B., Arthur, E., 2020. Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma. https://doi.org/10.1016/j.geoderma.2019.114055
84. Aziz, M.A., Arisandy, P., Wahyuni, S., Fadila, H., Siregar, V.M.R., Priyono, Luktyansyah, I.M., Sulastri, Siswanto, 2024. Biostimulant activity of Eucheuma cottonii extract on early growth of Elaeis guineensis Jacq. IOP Conf. Ser.: Earth Environ. Sci. https://doi.org/10.1088/1755-1315/1308/1/012045
85. Salma, A., Fryda, L., Djelal, H., 2024. Biochar: A Key Player in Carbon Credits and Climate Mitigation. Resources. https://doi.org/10.3390/resources13020031

86. Aziz, M.A., Arisandy, P., Wahyuni, S., Fadila, H., Siregar, V.M.R., Priyono, Luktyansyah, I.M., Sulastri, Siswanto, 2024. Biostimulant activity of Eucheuma cottonii extract on early growth of Elaeis guineensis Jacq. IOP Conf. Ser.: Earth Environ. Sci. https://doi.org/10.1088/1755-1315/1308/1/012045
87. Santoso, D., Gunawan, A., Budiani, A., Sari, D.A., Priyono, 2018. Plant biostimulant to improve crops productivity and planters profit. IOP Conf. Ser.: Earth Environ. Sci. https://doi.org/10.1088/1755-1315/183/1/012017
88. Abalos, D., Jeffery, S., Sanz-Cobena, A., Guardia, G., Vallejo, A., 2014. Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency. Agriculture, Ecosystems & Environment. https://doi.org/10.1016/j.agee.2014.03.036
89. Mosier, A., Kroeze, C., 2000. Potential impact on the global atmospheric N2O budget of the increased nitrogen input required to meet future global food demands. Chemosphere - Global Change Science. https://doi.org/10.1016/s1465-9972(00)00039-8
90. Cowan, N., Carnell, E., Skiba, U., Dragosits, U., Drewer, J., Levy, P., 2020. Nitrous oxide emission factors of mineral fertilisers in the UK and Ireland: A Bayesian analysis of 20 years of experimental data. Environment International. https://doi.org/10.1016/j.envint.2019.105366
91. Sukmawan, Y., Riniarti, D., 2022. Effectiveness of Various Foliar Fertilizer on the Growth and Performance of Oil Palm (Elaeis guineensis Jacq.) Seedlings in Main Nurseries. JTCS. https://doi.org/10.29244/jtcs.9.01.1-7
92. Mohd Amnan, M.A., Teo, W.F.A., Aizat, W.M., Khaidizar, F.D., Tan, B.C., 2023. Foliar Application of Oil Palm Wood Vinegar Enhances Pandanus amaryllifolius Tolerance under Drought Stress. Plants. https://doi.org/10.3390/plants12040785
93. Pradana, M.G., Priwiratama, H., Rozziansha, T.A.P., Prasetyo, A.E., Susanto, A., 2022. Field evaluation of Bacillus thuringiensis product to control Metisa plana bagworm in oil palm plantation. IOP Conf. Ser.: Earth Environ. Sci. https://doi.org/10.1088/1755-1315/974/1/012025
94. Sarpong, F., Dery, E.K., Danso, I., Oduro-Yeboah, C., 2022. The socio-economic impact of mitigating the challenges at the artisanal palm oil mills in Ghana. World Food Policy. https://doi.org/10.1002/wfp2.12047
95. Osei-Amponsah, C., Stomph, T.-J., Visser, L., Sakyi-Dawson, O., Adjei-Nsiah, S., Struik, P.C., 2014. Institutional change and the quality of palm oil: an analysis of the artisanal processing sector in Ghana. International Journal of Agricultural Sustainability. https://doi.org/10.1080/14735903.2014.909638
96. Raymond, N.N., Yvonne, N., Ofundem, T., Patrice, L., 2014. Less oil but more money! Artisanal palm oil milling in Cameroon. Afr. J. Agric. Res. https://doi.org/10.5897/ajar2013.7533
97. Budianta, I.A., Gozan, M., 2022. What Should We Do with the Oil Palm Solid Waste? IOP Conf. Ser.: Earth Environ. Sci. https://doi.org/10.1088/1755-1315/1111/1/012015 Awoh, E.T., Kiplagat, J., Kimutai, S.K., Mecha, A.C., 2023. Current trends in palm oil waste management: A comparative review of Cameroon and Malaysia. Heliyon. https://doi.org/10.1016/j.heliyon.2023.e21410
98.] Ohimain, E.I., Izah, S.C., 2014. Energy self-sufficiency of smallholder oil palm processing in Nigeria. Renewable Energy. https://doi.org/10.1016/j.renene.2013.10.007
99. Mohammad, S., Baidurah, S., Kobayashi, T., Ismail, N., Leh, C.P., 2021. Palm Oil Mill Effluent Treatment Processes—A Review. Processes. https://doi.org/10.3390/pr9050739

100. Kan, K.W., Chan, Y.J., Tiong, T.J., Lim, J.W., 2024. Maximizing biogas yield from palm oil mill effluent (POME) through advanced simulation and optimisation techniques on an industrial scale. Chemical Engineering Science. https://doi.org/10.1016/j.ces.2023.119644

101. Sodri, A., Septriana, F.E., 2022. Biogas Power Generation from Palm Oil Mill Effluent (POME): Techno-Economic and Environmental Impact Evaluation. Energies. https://doi.org/10.3390/en15197265