frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 16 July 2025
DOI 10.3389/fsufs.2025.1606323

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OPEN ACCESS

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RECEIVED 05 April 2025
ACCEPTED 20 June 2025
PUBLISHED 16 July 2025

CITATION
Ayompe LM, Nkongho RN, Acobta AN, Masso C and Egoh BN (2025) Transforming palm oil production: sustainable techniques and waste management strategies for Cameroon's smallholder farmers. *Front. Sustain. Food Syst.* 9:1606323. doi: 10.3389/fsufs.2025.1606323

Transforming palm oil production: sustainable techniques and waste management strategies for Cameroon's smallholder farmers

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Introduction: The palm oil sector is vital for Cameroon's smallholder farmers but is increasingly scrutinized for its environmental impacts, including deforestation, soil degradation, and waste mismanagement. Bridging productivity and sustainability demands integrated strategies that support farmer livelihoods while meeting global climate and conservation goals.

Methods: We conducted a systematic literature review and analytical synthesis of peer-reviewed studies, industry reports, and technical guidelines on Good Agricultural Practices (GAPs), Good Management Practices (GMPs), diversified cropping systems, fertilizer regimes, and waste valorization in oil palm systems. Drawing on this evidence base, we constructed two decision-support frameworks: one for sustainable palm oil production and another for circular-economy waste management.

Results: Our review confirms that adopting GAPs and GMPs such as soil conservation, optimized fertilizer application, and integrated pest management yields 10–20% gains in yield and income for smallholders, while intercropping enhances land-use efficiency, soil organic matter, and greenhouse-gas mitigation. The sustainable-production framework emphasizes no-deforestation in High Carbon Stock or High Conservation Value areas, prohibits slash-and-burn practices, and integrates incentives (e.g., carbon credits, subsidized inputs) to drive compliance. The waste-management framework demonstrates that palm oil mill residues and effluents can be transformed into organic fertilizers, biogas, bioethanol, and biocomposites, unlocking additional revenue streams and closing nutrient loops.

Discussion: Implementing these frameworks requires strengthening certification schemes, capacity-building, and targeted smallholder support to overcome financial and technical barriers. By synergizing production efficiency, environmental safeguards, and waste valorization, Cameroon's smallholder sector can transition to a resilient, low-carbon model. Scaling these strategies promises to enhance farmer livelihoods, reduce sector-wide emissions by at least 25%, and contribute meaningfully to national climate-mitigation and biodiversity conservation goals.

KEYWORDS

circular economy, intercropping systems, carbon credit incentives, deforestation avoidance, soil fertility enhancement, greenhouse gas mitigation

Highlights

- Sustainable practices enhance productivity and support smallholder livelihoods.
- Good Agricultural Practices improve soil health and reduce chemical inputs.
- Renewable energy from PO biomass reduces GHG emissions and environmental impact.
- Certification schemes and smallholder support foster sustainable palm oil production.
- Integrated waste management transforms PO waste into valuable products.

1 Introduction

The oil palm *(Elaeis guineensis)* is a vital agricultural commodity, accounting for approximately 40% of global vegetable oil production while occupying only 5–7% of the land used for oil crops (Erniwati et al., 2017; Lintemani et al., 2019). Notably, it is highly productive, yielding significantly more oil per hectare than other oilseed crops (Zamri et al., 2022; Sarzynski et al., 2020). Over the past decade, global oil palm (OP) expansion has surged from 19.5 million to 29.1 million hectares, contributing to economic growth and improved living standards in many communities (Masyithoh and Nurjannah, 2024; Said et al., 2022). Additionally, palm oil (PO) plays an essential role as a raw material in various industries, with demand expected to increase due to population growth, rising biofuel consumption, cost-effectiveness, and long shelf life (Hariz et al., 2023; Putri et al., 2021). Indonesia is a leading contributor, accounting for a significant share of global production (Fatmasari et al., 2018).

Despite its economic benefits, rapid expansion in OP cultivation presents environmental and socioeconomic challenges, including habitat destruction, biodiversity loss, and greenhouse gas emissions (Lee et al., 2013; Guillaume et al., 2018). In Cameroon, a major PO producer in Central Africa, production reached ∼450,000 tons in 2020, although a substantial gap remains between local production and demand (Ndam et al., 2024). The country has 270,000 hectares of OP plantations, with industrial plantations producing 180,000 tons and smallholder plantations contributing 90,000 tons (Ayompe et al., 2021). However, processing inefficiencies among smallholder farmers limit extraction rates, emphasizing the need for improved techniques (Khatib and Šišák, 2014).

While industrial mills in Cameroon yield 2-3 tons of crude PO per hectare, smallholder farmers produce only about 1 ton per hectare, largely due to limited resources, unsustainable practices, and market constraints (Kome and Tabi, 2020; Nkongho et al., 2014). Achieving sustainable PO production requires balancing productivity, conservation, and community welfare (Tchindjang et al., 2022). Proposed frameworks emphasize agroecological principles, integrated pest management, and community-based resource utilization (Dislich et al., 2016; Saifullah et al., 2018), offering smallholders viable pathways toward sustainability.

Despite government initiatives, persistent challenges include trust issues and contractual disputes between smallholders and large mills (Nkongho et al., 2015). Recent partnerships with organizations like UNIDO aim to build or refurbish PO mills to support smallholders (Ayompe et al., 2023). However, additional obstacles such as poor-quality planting materials, aging plantations, high input costs, and inadequate financing and technical support remain critical concerns (Nchu and Koona, 2020). Addressing these barriers is essential for ensuring the long-term sustainability and viability of Cameroon's PO sector.

This paper explores frameworks to help smallholder farmers in Cameroon and beyond achieve sustainable PO production. By analyzing the current state and identifying effective practices, we provide practical recommendations for farmers, policymakers, and stakeholders. Specifically, we aim to (1) identify sustainability issues, (2) develop a framework depicting small-scale PO production status, (3) develop frameworks for sustainable PO production and waste management, and (4) provide recommendations to achieve sustainable PO production.

2 Methods

A mixed-methods approach was adopted to investigate smallholder OP farming practices, identify sustainability challenges, and explore pathways for sustainable PO production in Cameroon. The study combined primary field data with secondary literature and integrated preliminary inferential analyses to deepen the empirical basis for the findings.

2.1 Field survey

Between July and September 2021, a structured field survey was conducted among 125 smallholder OP farmers in the Fako Division of Cameroon's South West Region. A stratified random sampling strategy ensured the inclusion of participants from diverse socio-economic backgrounds. Data were collected through face-to-face interviews using a structured questionnaire, which covered aspects such as land use, input utilization, labor allocation, yields, processing methods, market access, and support services. Informed consent was obtained from all participants after they were briefed on the study's objectives and their rights. The collected data were entered into Microsoft Excel and analyzed using descriptive statistics.

The survey population comprised predominantly male oil palm farmers, with 95.2% (119 out of 125) being male and only 4.8% (6) female. No farmers were under the age of 21; 8.0% were aged 21–30 years, 16.8% fell within the 31–40-year range, 26.4% were between 41 and 50, 24.8% were between 51 and 60, and 24.0% were over 60 years of age. In terms of education, 5.6% had no formal education, while the majority, 54.4%, possessed a First School Leaving Certificate; 20.8% had completed the GCE O level/CAP, 12% had attained the GCE A level/BAC, and 7.2% held a Bachelor's degree, with no respondents reporting a Certificate or Higher National Diploma (HND). Regarding household income, 6.4% of the respondents reported an annual income between $182 and $727, 24% earned between $728 and $1,455, 24.8% had incomes ranging from $1,456 to $1,818, and 44.8% earned more than $1,818 per annum. The average household size was seven members.

2.2 Literature review and data triangulation

An extensive literature review was undertaken to supplement the fieldwork and provide a broader context for sustainable PO production and waste management practices. Key electronic databases including Web of Science, Scopus, and Google Scholar were systematically searched with structured queries using Boolean operators and keywords such as "sustainable palm oil," "oil palm smallholder Cameroon," "waste management in palm oil production," "Good Agricultural Practices (GAPs)," "Good Management Practices (GMPs)," and "circular economy." Additional insights were garnered through hand searches of reference lists and gray literature, including government reports and publications by international agencies. The integration of findings from the literature with the survey data allowed for preliminary triangulation, which helped in framing two conceptual models: one for sustainable production practices and another for effective waste management strategies. This triangulation, however, remains primarily conceptual without robust empirical validation and lacks a systematic gender or institutional lens.

3 Results and analysis of smallholder PO production: sustainability issues and production framework

In this section, we present the results from our research on smallholder palm oil production in Cameroon by examining key sustainability challenges and introducing a conceptual framework that maps the current production status. Our analysis reveals that production is influenced by a complex interplay of factors, including environmental challenges such as deforestation and habitat loss, socio-economic difficulties like limited access to quality inputs and technical support, and operational inefficiencies that result in low oil extraction rates. These factors are not isolated; rather, they create an interconnected web of challenges wherein environmental degradation affects soil quality and yields, which in turn are compounded by socio-economic constraints limiting the adoption of improved agricultural techniques. To address these multifaceted issues, we propose a diagnostic framework that visually outlines the entire production process, from land preparation and cultivation to processing and waste management, while highlighting critical gaps and inefficiencies.

3.1 Key sustainability issues in smallholder palm oil production

3.1.1 Smallholders and their challenges

Smallholder OP farmers, as defined by the Roundtable on Sustainable Palm Oil (RSPO), cultivate <50 hectares using primarily family labor. They play a crucial role in the global PO industry, contributing approximately 40% of the plantation area and nearly 50% of production (Nagiah and Azmi, 2012). These farmers are categorized into independent smallholders, who manage their plantations autonomously, and scheme smallholders, who are linked to specific mills through contracts with agro-industrial companies. Despite their significant contributions, smallholders face numerous challenges that hinder productivity and sustainability, including poor-quality planting materials, aging plantations, low yields, and high input costs. Furthermore, limited access to technical information regarding good agricultural practices (GAPs), insufficient training, financial constraints, poor market access, land tenure insecurity, and reliance on low-skilled labor, including child labor, exacerbate their situation (Pahri et al., 2023). Multiple intermediaries and inefficient processing methods contribute to low extraction rates, poor quality, and short shelf life of the PO produced by smallholders (Rizal et al., 2021).

3.1.2 Farming systems

Smallholder OP farming systems are integral to enhancing both the productivity and sustainability of PO production. Characterized by their diversity, these systems reflect the socio-economic and environmental contexts of the farmers involved. Typically, smallholders integrate OP cultivation with other agricultural activities, such as food crops like cassava and maize, and livestock rearing. This intercropping practice, particularly during the early growth stages of OP, optimizes land use, contributes to additional income streams, and bolsters household food security (Nchanji et al., 2015). The integration of different crops allows smallholder farmers to create a resilient farming system adapted to household food security needs, market fluctuations, and environmental challenges (Euler et al., 2016).

Labor dynamics within smallholder OP farming systems reveal a reliance on both family and hired labor. From 52 reviewed studies, 63.5% of smallholders use both family and hired labor, while 15.4% rely solely on family labor. Field survey results indicated that 88.0% of smallholders use both hired and family labor, and 9.6% use only family labor (Figure 1a). This labor structure suggests that smallholders not only depend on family members for agricultural tasks but also contribute to local employment by hiring additional workers. Moreover, the choice of the OP cultivar used by smallholders, as reported in 42 studies, shows a preference for Dura (64.3%), followed by Tenera (31.0%) and Pisifera (4.8%). The predominance of Dura, a local breed, highlights the importance of traditional practices in smallholder farming, while Tenera, a commercial hybrid, represents the potential for improved yields through selective breeding (Pahri et al., 2023). Overall, the farming systems employed by smallholders balance economic viability with environmental stewardship (Rizal et al., 2021).

3.1.3 Good agricultural practices

Good agricultural practices (GAP) are crucial for productivity and sustainability in smallholder OP cultivation. These include quality planting materials, maintaining proper planting densities (120-150 palms/hectare), effective pest and disease management, appropriate fertilizer application, and timely harvesting (Woittiez et al., 2018). Fertilizer use is vital, as Tenera yields can drop from 20 to 25 tons/hectare to about 10 tons/hectare without fertilizers (Sigalingging, 2024). Our review found 56.3% of studies reported smallholders have access to quality seeds, and 57.1% use fertilizers (Figure 1c). Field surveys showed 44.8% use both pesticides and improved seeds, while 25.6% use fertilizers, pesticides, and improved seeds. Waste recycling is important for soil fertilization,

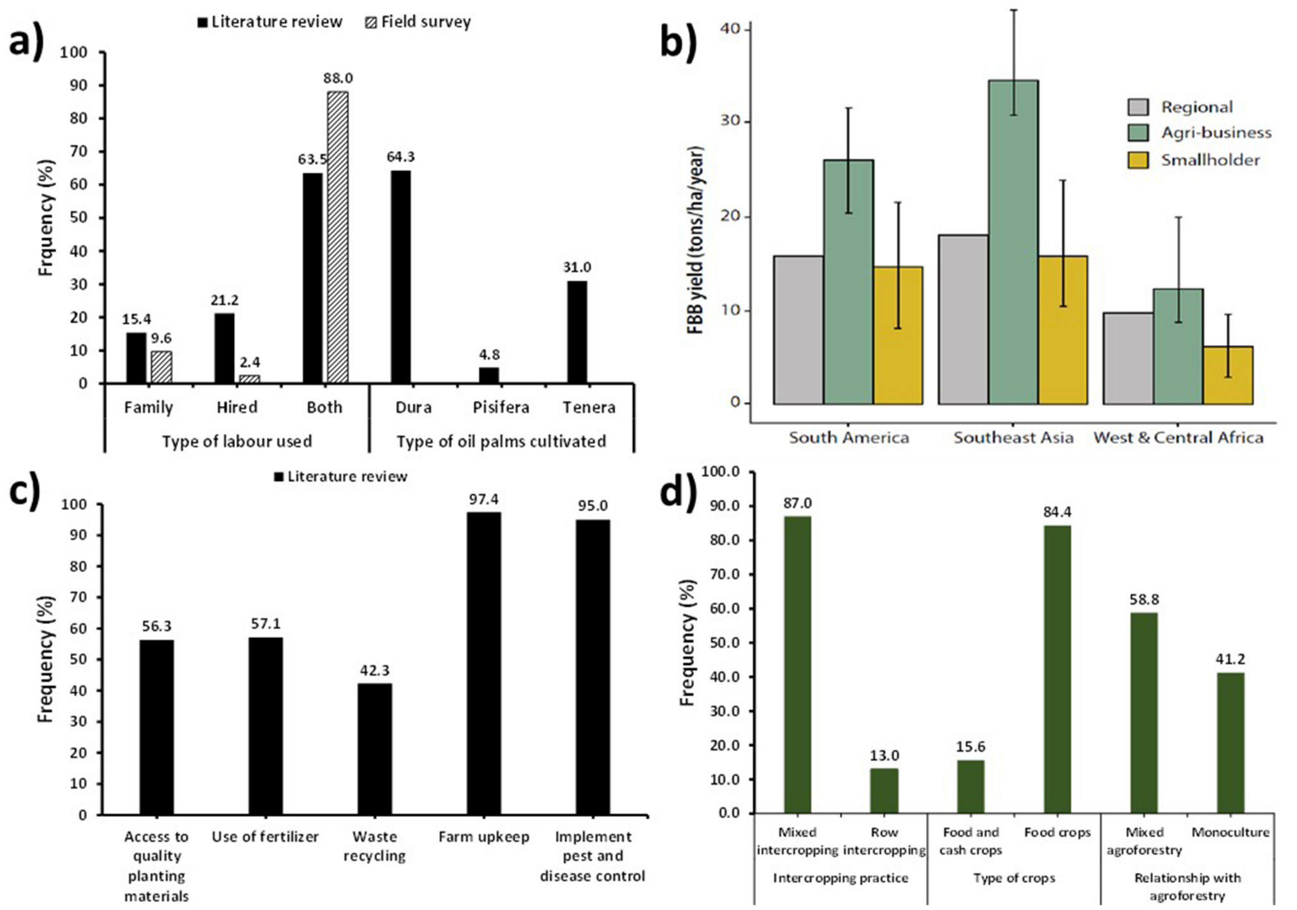

FIGURE 1
(a) Frequency of the type of labor used and OPs cultivated, **(b)** average OP FFB yields in different regions (Hoyle and Levang, 2012), **(c)** frequency distribution of good agricultural practices, **(d)** frequency of the intercropping practices, types of crops intercropped and relationship with agroforestry (source: literature review).

waste reduction, and bioenergy production. Our field survey revealed 1.6% of smallholders use PO waste for biofuel/biogas, 91.2% use palm fibers as biofuel, and 88.8% use empty kernel shells as biofuel.

Despite the 25-year production cycle for OP, African yields are below the yields obtained in Asia and South America (Figure 1b), averaging around 3 tons of PO/hectare annually (Woittiez et al., 2017). Small-scale producers in Cameroon use <30% of the inputs used by large-scale producers, yielding about 5 tons of FFB/hectare compared to 19.3 tons for agro-industries (Folefack et al., 2019). The highest-yielding smallholder farms average only 7.7 tons of FFB/hectare/year, well below the potential 20 tons FFB/hectare/year for Cameroon (Ordway et al., 2017). In Ghana, average smallholder OP yields are 7.0 tons FFB/hectare/year (Rhebergen et al., 2018), while in Malaysia, smallholder yields vary (6.9–37.4 tons FFB/hectare/year) (Al-Khudhairy et al., 2023). These figures show the efficiency of smallholder OP plantations in Africa is below potential, implying that improving yields would spare land for nature and increase economic viability (Soliman et al., 2016). Intercropping is widely practiced, with over 80% of studies reporting its use. Smallholders often intercrop food crops like cassava, plantains, cocoyams, and maize (Sapalina et al., 2022). Agroforestry is also common, with 59.0% of studies indicating mixed agroforestry practices (Figure 1d). In immature OP plantations, 95.2% of respondents practiced intercropping, while 67.2% of mature plantations practiced monocropping.

3.1.4 Land conversion and tenure

Land conversion and tenure are pivotal factors influencing the sustainability of OP cultivation. The conversion of land for OP plantations often results in significant environmental repercussions, including deforestation, biodiversity loss, and increased greenhouse gas emissions. A review of 57 studies indicates that approximately 50% of land converted for OP cultivation originates from forested areas, with 30% from secondary forests and 20% from primary forests (Figure 2a). Additionally, around 25% of conversions are from degraded lands, while 26.3% stem from wild or natural OP groves (Zhao, 2024). Field surveys reveal that a substantial portion of smallholders (59.2%) cultivate OP on forested land, exacerbating ecological degradation (Herdiansyah, 2024). To mitigate these adverse effects, adopting sustainable land management practices is essential, as these can help balance agricultural productivity with environmental conservation (Ariesca et al., 2023).

Secure land tenure is crucial for fostering long-term investments in sustainable agricultural practices among smallholder farmers. Survey data show that 46.8% of smallholders

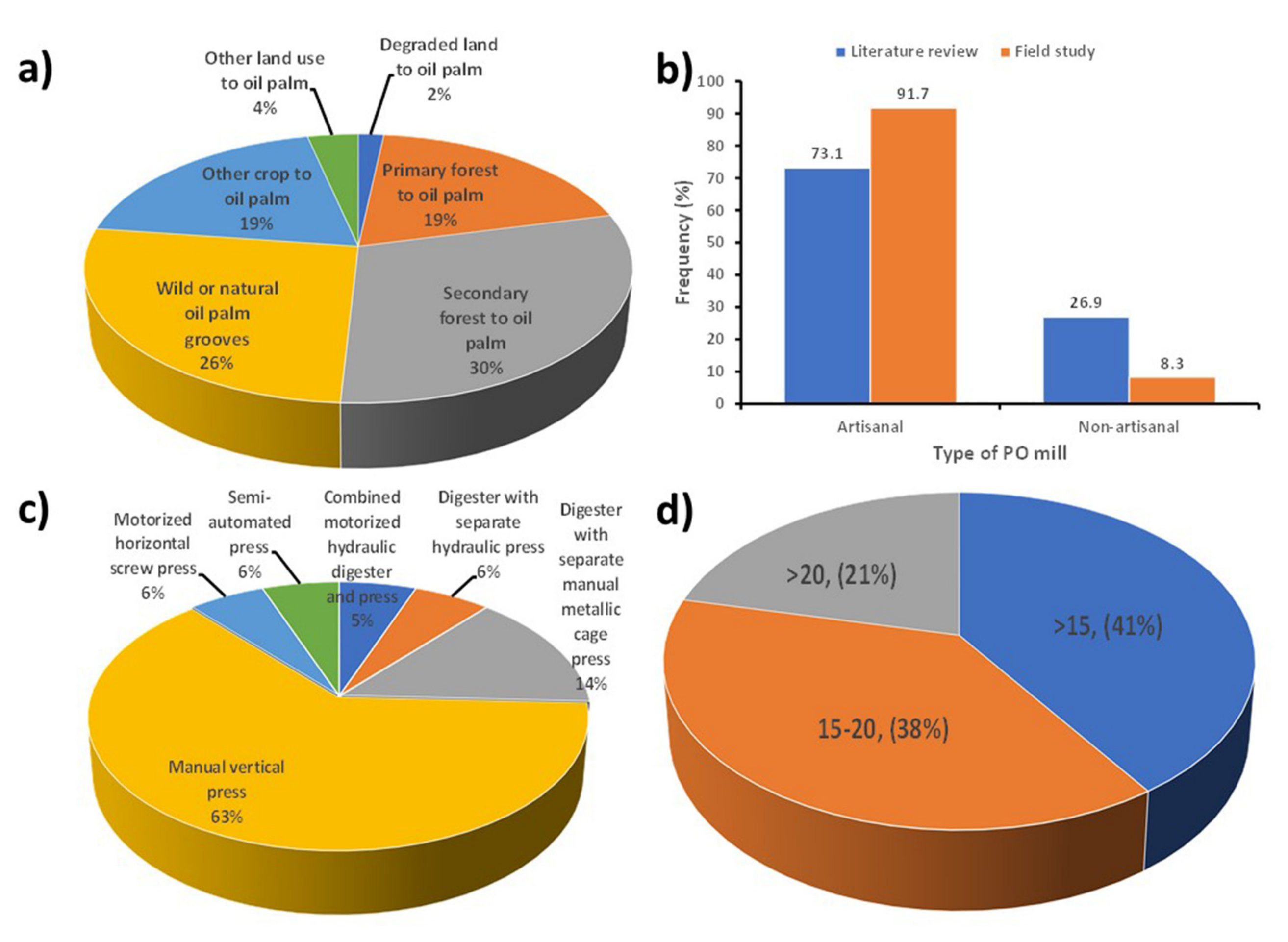

FIGURE 2
(a) Frequency distribution of land conversion to oil palm, **(b)** frequency distribution of milling practices, **(c)** percentage distribution of the type of milling equipment used, **(d)** frequency distribution of PO milling efficiency (source: field survey data).

purchased their land, while 22.6% owned it outright, 21.8% utilized community land, and 5.6% rented. However, land tenure insecurity poses significant challenges as it discourages investments in land improvement and sustainable practices due to fears of land grabbing by more powerful entities (Hamid, 2023). The lack of formal land titles limits smallholders' access to credit and financial services, which are vital for enhancing productivity and sustainability (Apriyanto et al., 2022). Implementing policies that ensure secure land tenure can promote sustainable land management, improve agricultural yields, and enhance the livelihoods of smallholders (Abas et al., 2021). Programs aimed at facilitating land titling can significantly bolster smallholders' land rights, thereby encouraging sustainable farming investments and practices (Suryaningsih, 2023).

3.1.5 PO milling practices

PO milling practices critically influence efficiency, quality, and cost in smallholder PO production. In Africa, traditional manual milling methods are common, yet labor-intensive and often inefficient. Approximately 73% of smallholders use artisanal mills for processing FFB, with field surveys indicating a reliance rate of 91.7% (Figure 2b). While artisanal mills reduce labor demands, they also raise production costs, adversely affecting PO pricing. These mills often produce lower quality outputs due to inefficient extraction processes, with 63% of smallholders using manual vertical presses and 14% relying on hand-operated screw presses (Figure 2c). The cost of manual mills is around $400, while more efficient semi-automated mills can cost up to $35,000 (Anyaoha and Zhang, 2022).

3.1.6 Milling efficiencies and extraction rates

A major challenge for smallholder PO production in Africa is the low milling efficiencies or extraction rates, which are crucial for economic viability. The extraction process includes reception, sterilization, and threshing of FFBs, followed by digestion and pressing to extract PO, which is then purified and dried for storage and commercialization (Suroso et al., 2021). Studies indicate many smallholders experience extraction rates below 20%, with rates in Cameroon ranging from 8% to 12%. A literature review of 41 studies revealed 41% reported extraction rates below 15%, 38% between 15% and 20%, and 21% above 20% (Figure 2d). These low rates affect both the quantity and quality of PO produced, as traditional and artisanal methods used by smallholders are less efficient than mechanized alternatives (Hong, 2024).

3.2 Existing framework for small-scale PO production

Smallholder farmers frequently employ slash-and-burn techniques to establish OP plantations, which drastically diminish ecosystem services such as carbon sequestration, biodiversity conservation, and water regulation (Er et al., 2011). Additionally, they often face significant constraints, including limited access to training, agricultural inputs, and financing, all of which impede the transition to sustainable practices. Many smallholders rely on low-skilled and child labor, raising serious social concerns (Sibhatu, 2019). The lack of access to fertilizers further hampers productivity, as it limits opportunities to enhance yields and income (Naidua et al., 2021). Regarding cultivation methods, intercropping is prevalent in immature plantations (≤5 years), while monocropping dominates in mature plantations (>5 years), illustrating a widespread reliance on traditional farming approaches (Anyaoha et al., 2018b).

Following OP cultivation, FFBs are processed into low-grade PO using inefficient traditional milling systems. Solid biomass is either left to rot or used as fuel, while liquid waste (POME) is discharged into the environment, leading to severe pollution (Stichnothe and Schuchardt, 2010). Alarmingly, land conversion from forests to OP plantations contributes 75–80% of greenhouse gas emissions, while POME accounts for another 18–23%, further intensifying climate change concerns (Acobta et al., 2023). This highlights the urgent need for sustainable land-use strategies and effective waste management solutions (Ewelike et al., 2021). Our proposed framework (Figure 3) maps out the existing PO production processes employed by smallholders in Africa, emphasizing sustainability challenges. Many smallholder farmers lack access to capacity-building programs, agricultural inputs, and financing, exacerbating environmental degradation and inefficient resource use. Furthermore, the widespread land conversion and reliance on chemical fertilizers contribute significantly to greenhouse gas emissions. Although OP cultivation produces useful outputs such as EFBs, old palm trunks, POME, and palm fronds, a large portion of these waste streams remain underutilized, resulting in environmental hazards and missed livelihood opportunities.

4 Discussion on sustainable PO production

In this section, we integrate improved production practices, effective waste management, and practical recommendations to advance sustainable palm oil production. Our approach guides smallholder farmers and stakeholders to move from traditional methods to innovative practices that boost yields while responsibly managing natural resources and reducing deforestation, emissions, and pollution. We stress the importance of repurposing waste, from solid residues to effluent, into valuable resources like biofertilizers, biochar, and renewable energy, thereby fostering a circular economy. Additionally, we propose step-by-step strategies, including Good Agricultural Practices and market incentives such as carbon credits, to ensure these sustainable solutions are accessible to all. Overall, this section provides a clear roadmap for practices that benefit both the environment and local communities.

4.1 Sustainable palm oil production

Promoting sustainable OP cultivation requires a comprehensive approach that integrates land and climate suitability, productivity practices, biodiversity management, sustainability certification, and social responsibility. The High Carbon Stock (HCS) and High Conservation Value (HCV) frameworks are fundamental in mitigating the environmental impact of OP plantations, guiding the preservation of critical ecosystems and biodiversity (Zhao, 2024; Ramlah, 2024). The consequences of unsustainable PO production are severe, including deforestation, biodiversity loss, and ecosystem degradation (Murphy et al., 2021). Despite ongoing debates surrounding its environmental footprint, PO remains the most widely produced and consumed vegetable oil globally, emphasizing the necessity for certified sustainable production to address climate and conservation concerns (Chiriacò et al., 2022).

A truly sustainable PO production system maximizes income generation, resource efficiency, and waste minimization, which can be achieved through innovative strategies such as valorizing by-products, recycling POME, utilizing biogas, and improving wastewater management (Supriatna, 2024). Beyond environmental preservation, sustainability also enhances social equity, ensuring economic gains are distributed within local farming communities (Abas et al., 2021). The overarching objective is to eliminate deforestation, greenhouse gas emissions, land disputes, and exploitative labor practices while positioning PO production as a driver of sustainable development (Sagar et al., 2019). Smallholders play a pivotal role in advancing sustainable agricultural practices, and their participation in certification programs is crucial for improving the global marketability of PO (Sukiyono et al., 2022). As consumer demand for sustainably sourced products continues to rise, the PO industry must adapt by implementing responsible production strategies that address environmental, social, and economic challenges, including recent EU import restrictions (Setiajiati et al., 2024).

4.1.1 Conserving forests and biodiversity

Natural habitats play a vital role in maintaining biodiversity and ecosystem services within tropical agricultural landscapes. Their conservation is essential for protecting threatened species and ensuring long-term ecosystem sustainability. Strategically positioning OP plantations near diverse land-use systems can support biodiversity by creating transitional spaces for various species (Davis, 2024). Additionally, preserving small forest fragments within OP plantations sustains native species diversity while contributing to critical ecosystem services (Hatfield et al., 2019). Research highlights the significance of forest cover in agricultural landscapes, as it enhances biodiversity through a spillover effect, reducing species isolation and strengthening ecosystem resilience (Martinez-Ramos et al., 2016). Furthermore, scattered trees within OP monocultures positively influence

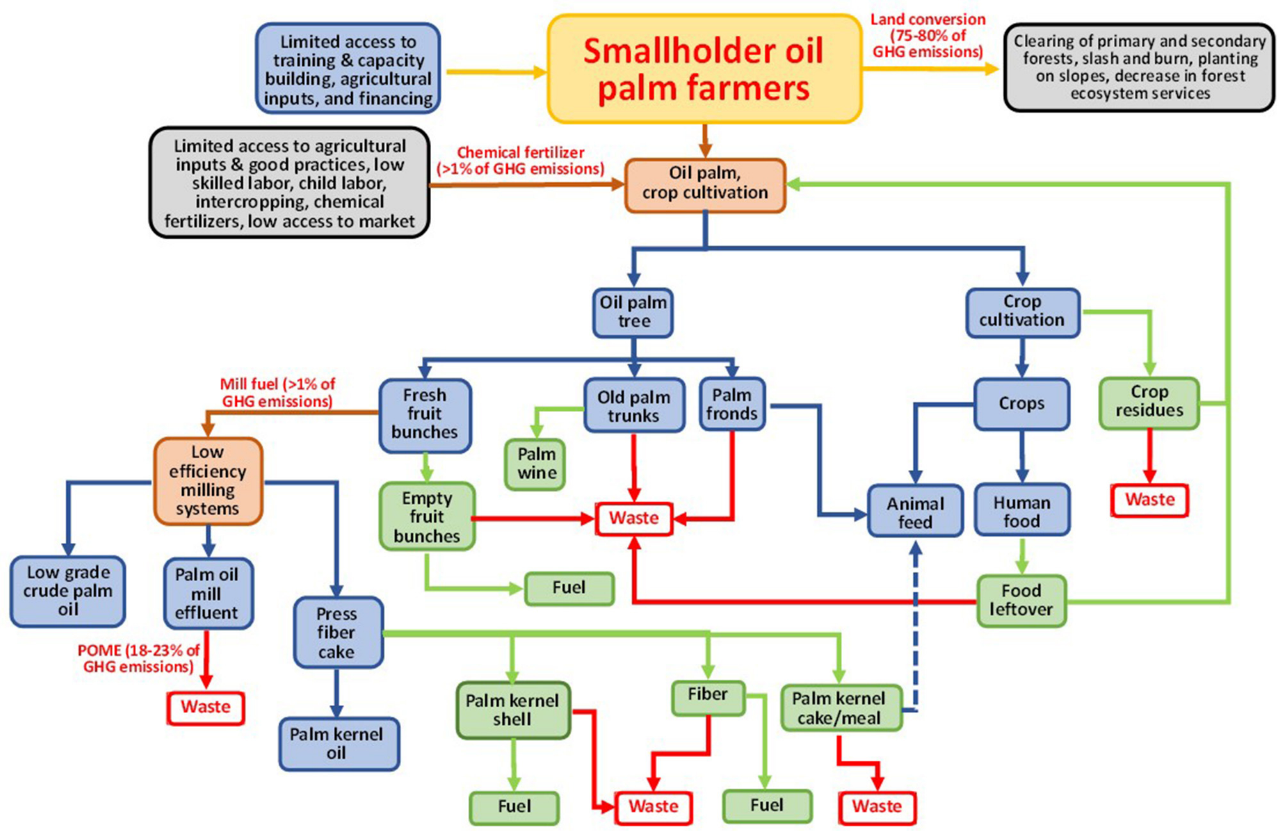

FIGURE 3
Framework diagram for existing smallholder PO production.

biodiversity by regulating essential ecosystem functions (Sreekar et al., 2013).

With increasing consumer demand for deforestation-free PO, sustainable industry practices are becoming more urgent (Decaëns et al., 2018). Effective management of OP expansion is critical to prevent further deforestation and avoid substantial biodiversity losses (Louis, 2024). Studies indicate that prioritizing deforestation reduction is a more effective climate change mitigation strategy than forest conversion for biofuel production, as it supports global biodiversity commitments (Bieng et al., 2022). Consequently, strengthening environmental governance and policies is necessary to minimize forest clearance and encourage responsible land-use practices (Rocha et al., 2015). Protecting natural forests within or near OP plantations and prioritizing oil palm development on low-yielding pastures can harness ecosystem services while optimizing agricultural production (Kadir et al., 2021). Additionally, maintaining forested riparian reserves has proven to support local fish species richness and functional diversity, particularly in vulnerable rainforest streams (Elsen et al., 2018).

4.1.2 Increasing productivity

Smallholder OP plantations often have lower productivity due to limited fertilizer application and resource constraints. To enhance nutrient use efficiency, balanced fertilizer applications, maintaining ground cover vegetation, and utilizing EFBs as organic amendments are essential (Atik et al., 2020). Increasing smallholder awareness of management requirements throughout the plantation life cycle can significantly boost productivity (Soliman et al., 2016). However, barriers such as limited access to credit and agricultural inputs hinder productivity improvement (Krishna et al., 2017). The productivity of OP plantations relies heavily on quality planting materials, water, fertilizers, sunlight, and effective management. Timely processing of harvested FFBs is critical to maintaining PO and PKO quality, as delays can degrade oil quality and increase refining costs (Ayompe et al., 2021).

Artisanal mills, while convenient for smallholders, often produce lower-quality oil compared to mechanized mills. Efficient and timely processing in mechanized facilities can significantly enhance both the quantity and quality of PO (Ayompe et al., 2023). Addressing challenges through improved access to inputs, credit, and training programs is essential for enabling smallholders to enhance productivity and sustainability (Veriasa, 2024). Integrating sustainable practices into smallholder operations is vital for increasing productivity while minimizing environmental impacts. Optimizing fertilizer recommendations based on soil and leaf analysis can improve fertilization strategies, thereby enhancing productivity (Hutabarat et al., 2019). Additionally, adopting innovative technologies and practices like precision agriculture and agroforestry can further enhance productivity and sustainability in smallholder OP plantations (Lee et al., 2013).

4.1.3 Implementing good agricultural practices

Implementing GAP is vital for optimizing yields and ensuring sustainability in OP cultivation. Recommended planting densities of 120–150 palms per hectare, coupled with effective canopy management of 40–60 fronds based on OP age, are key for maximizing productivity (Ntsiapane et al., 2023). Additionally, using irrigation and fertilizers can mitigate unsuitable soil and rainfall effects, but the high costs of fertilizers often deter farmers, especially in regions with limited financial resources (Veriasa, 2024). Addressing financial constraints is crucial for enhancing smallholder plantation productivity.

In Cameroon, poor yields are mainly due to inadequate GAP implementation, suboptimal planting materials, inefficient planting patterns, and limited nutrient application (Soliman et al., 2016). Many smallholders use low-input, low-output systems due to financial limitations and lack of access to quality inputs, exacerbating productivity issues (Cousins, 2012). Improving access to finance and quality planting materials is essential for productivity. While some farmers have improved planting material quality, high fertilizer costs remain a significant barrier (Feliciano, 2019). Government initiatives like FONADER funding (1978-1991) played a crucial role in providing improved OP seeds and subsidized fertilizers, promoting GAP adoption (Chalil and Barus, 2020). To further enhance productivity, priority should be given to training programs, access to technology, integrated pest management, and soil health management (Wang et al., 2020; Miner et al., 2020). Collaboration with agricultural research institutions can facilitate the development and dissemination of improved practices, benefiting smallholders (Mango et al., 2017).

4.1.4 Fertilizer use and micro nutrients

Oil palms require substantial macronutrients and micronutrients to achieve optimal growth and yield, making agrochemical-based fertilizers a key component of plantation management (Viégas et al., 2021). As OP plantations continue to expand, fertilizer demand is expected to increase proportionally (Viégas et al., 2018). While chemical fertilizers are effective in boosting yields, they also come with drawbacks, such as higher production costs and environmental concerns, including soil degradation and microbial imbalance (Salamat et al., 2019). Therefore, adopting effective fertilizer management strategies is crucial to improving nutrient use efficiency while minimizing ecological harm (Ashraf et al., 2017). In smallholder OP plantations, nutrient deficiencies, particularly in potassium and phosphorus, frequently hinder productivity (Yap et al., 2022). To counter this challenge, integrating biofertilizers alongside reduced chemical fertilizers offers a more sustainable approach, ensuring plant growth while preserving soil microbial diversity (Rosenani et al., 2016).

Although organic fertilizers tend to be more expensive, they provide significant long-term benefits when applied correctly. For example, compost derived from OP biomass, such as EFBs and POME, serves as a cost-effective nutrient source that enhances soil fertility (Goh et al., 2020). Moreover, research suggests that compost application improves soil structure, enhances microbial activity, and strengthens long-term soil health (Siang et al., 2022). By optimizing fertilizer practices, smallholder farmers can increase yields while reducing the environmental impact associated with excessive chemical fertilizer use (Yi et al., 2019). Ultimately, a balanced fertilization strategy ensures sustainable PO production while maintaining healthy ecosystems for future cultivation.

4.1.5 Intercropping and mixed cropping

Traditionally, both industrial and smallholder OP plantations have followed a monocrop model. However, emerging practices increasingly incorporate various crops alongside OP to create diversified, mixed intercropping systems. These systems enhance land use efficiency, reduce monoculture-associated risks, and decrease greenhouse gas emissions (Rocha et al., 2020). Smallholders adopt intercropping strategies, planting food crops alongside immature OP, which aids in poverty reduction, improves household food security, and stabilizes yields (Abas et al., 2021). Diversification provides additional income during the initial years of OP cultivation and mitigates economic risks associated with relying solely on palm oil production (Dissanayake and Palihakkara, 2023).

Intercropping is recognized as a nature-based solution that optimizes land use and improves soil health. For instance, intercropping soybeans during the initial years of OP establishment provides additional income while enhancing soil organic carbon and biological activity (Oluwatobi et al., 2020). In India, intercropping OP with maize, turmeric, and pineapple increased yields and improved carbon stocks in degraded lands (Putra et al., 2012). Additionally, crops like black pepper and pineapple enhance microbial diversity, benefiting overall soil health (Oluwatobi et al., 2020). In Nigeria, smallholders maximize land use by intercropping OP with cocoyams, soybeans, and maize (Dissanayake and Palihakkara, 2023). Similarly, in Cameroon, intercropping during the juvenile phase of OP supports nutrient cycling and soil conservation (Obi et al., 2022). Planting shade-tolerant forage in OP plantations supports cattle productivity and increases FFB yields (Hutasoit et al., 2020). As OP matures, nutrient competition can affect growth, necessitating careful fertilizer management (Giam et al., 2015). Mulching enhances soil organic carbon content, particularly in intercropped OP plantations (Khasanah and Noordwijk, 2018). Overall, intercropping provides food and revenue during the maturation phase of OP and contributes to economic stability and environmental sustainability (Hutabarat et al., 2019).

4.1.6 Weed management

Weeds present a significant challenge in OP plantations, and while herbicides are commonly used, they can adversely affect soil microbial populations and essential biochemical processes (Sarathambal et al., 2015). Overuse of herbicides can destroy understory vegetation, diminishing vital ecosystem services such as nutrient cycling, water regulation, natural pest control, and pollination (MacLaren et al., 2018). Proper herbicide use is crucial for effective weed management while ensuring environmental safety (Zhao et al., 2023). Sustainable weed management practices, such as cover cropping, have emerged as viable alternatives to herbicides, effectively controlling weeds and reducing reliance on chemical inputs (Järvan et al., 2014). However, many cover crop species are heliophytic and may allow other plants to establish after canopy coverage, leading to ecological succession (Wicke et al., 2019).

Integrating livestock into OP plantations is an innovative approach to weed management, enhancing sustainability within the PO supply chain (Dubey, 2023). This integration allows for controlling understory vegetation while providing food security, ecosystem services, and habitat heterogeneity (Mathew et al., 2023). Sustainable weed management practices, such as cover cropping and ecological grazing, help smallholder farmers maintain biodiversity, reduce environmental impacts, and improve the overall sustainability of OP plantations. Studies have shown that integrating livestock can effectively manage weeds while enhancing soil health and productivity (Pattanayak et al., 2022). Additionally, using cover crops can improve soil structure and organic matter content, further contributing to the sustainability of the agricultural system (Damin et al., 2021). Despite the benefits of these practices, challenges remain, particularly regarding nutrient competition between OP and intercropped species during mature OP growth stages (Bundt et al., 2015). Careful management and monitoring are necessary to ensure that the advantages of intercropping and cover cropping do not compromise OP productivity.

4.1.7 Cattle grazing in OP plantations

Integrating cattle production within OP plantations addresses the rising beef demand due to population growth and improving living standards. The understory of over 19 million hectares of OP plantations provides valuable cattle feed, mitigating the need for additional land conversion (Azhar et al., 2021). Smallholders have increasingly adopted cattle production using OP understory as feed, with OP fronds serving as feed and cattle manure as organic fertilizer, creating a symbiotic relationship that enhances agricultural outputs and sustainability (Nobilly et al., 2022). Rotational grazing systems minimize management costs, reduce production inputs, and increase resource use efficiency. This practice helps mitigate deforestation, sequester carbon, restore topsoil, improve biodiversity, and reduce chemical fertilizer use (Aldinas et al., 2023). Intensive cattle integration can lead to an average daily weight gain of 0.8 kg per head, and semi-intensive systems can increase FFB production by over 10% while reducing inorganic fertilizer use (Tohiran et al., 2017). Additionally, cattle grazing enhances biodiversity by creating habitats and food sources for invertebrates like dung beetles, which rely on cattle dung for nourishment and reproduction (Murphy et al., 2021).

4.1.8 Reducing GHG emissions

Reducing GHG emissions in agriculture, particularly methane (CH4) and nitrous oxide (N_2O), is essential for meeting the Paris Agreement's targets of limiting global warming to 1.5°C or below 2°C. If agricultural emissions remain unaddressed, the pressure to reduce carbon dioxide (CO_2) emissions will intensify, complicating global climate mitigation efforts (Fawzy et al., 2020). The palm oil (PO) industry plays a significant role in GHG emissions due to biomass residues and palm oil mill effluent (POME), which contribute to long-term environmental challenges (Aziz and Hanafiah, 2017). Oil palm cultivation alone generates 64–225 kg CO_2 equivalent (CO_2eq) per ton of fresh fruit bunches (FFB) while consuming 550–1,749 m^3 of water per ton (Nasrin et al., 2019). Additionally, the application of nitrogen fertilizers in OP plantations is a major source of N_2O emissions, estimated at 1,052–1,209 kg CO_2eq per hectare (Kusin et al., 2015). These combined emissions highlight the urgent need for more sustainable agricultural practices to reduce environmental harm.

To transition toward a low-emission PO production system, adopting modern technologies is essential. Biomass and biogas recovery systems derived from POME offer a promising solution for generating steam and electricity while minimizing emissions (Lim and Biswas, 2019). Additionally, repurposing solid biomass residues into biofertilizers, biochar, and biofuels can enhance waste valorization, while ensuring that liquid discharges adhere to environmental regulations (Tan, 2024). Integrating renewable energy technologies, such as battery-powered electric vehicles charged by solar photovoltaic systems, can further enhance sustainability in the PO sector (Fahrudin, 2024). Moreover, research shows that biogas recovery technologies can cut GHG emissions by up to 373 kg CO_2eq per ton of PO (Mondamina et al., 2020). Effective strategies, including wastewater-dispersed cooling systems and transitioning from stabilization ponds to aerated lagoons, can further improve emission reductions (Wongfaed et al., 2021). Ultimately, by embracing advanced technologies, refining waste management systems, and integrating renewable energy solutions, the PO industry can significantly curb its environmental impact while contributing to global climate mitigation goals.

4.1.9 Certification schemes

Certification schemes, such as the RSPO, have played a crucial role in promoting sustainable PO production since 2004, with approximately 20% of global PO certified as sustainable by 2015 (Morgans et al., 2018). However, despite growing recognition of the importance of sustainability, uptake among smallholders remains low due to socio-economic barriers, including limited access to information and support necessary for certification (Rizal and Nordin, 2022). Addressing these challenges is essential, as certification offers significant social, environmental, and economic benefits, including mitigating deforestation, improving rural livelihoods, and integrating smallholders into ethical supply chains (Chiriacò et al., 2022). Nonetheless, the financial burden of certification is a considerable obstacle for independent farmers, with RSPO certification costs exceeding USD 9,630 in some cases (Abdullah et al., 2022). Additionally, concerns regarding certification integrity, such as the potential allowance of forest clearance, have raised questions about its effectiveness in achieving sustainability goals (Noor et al., 2017). Research suggests that certification can significantly reduce deforestation, reinforcing its value in conservation efforts (Rizal et al., 2021). To enhance accessibility and effectiveness, targeted interventions, including capacity building, financial assistance, and improved information dissemination, are crucial for overcoming smallholder barriers and maximizing sustainability outcomes (Abidin et al., 2024).

4.1.10 Framework for sustainable PO production

The framework for sustainable PO production (Figure 4) addresses land degradation caused by forest conversion to agriculture, resulting in significant losses of environmental services and adversely impacting tropical landscapes and ecosystems. The

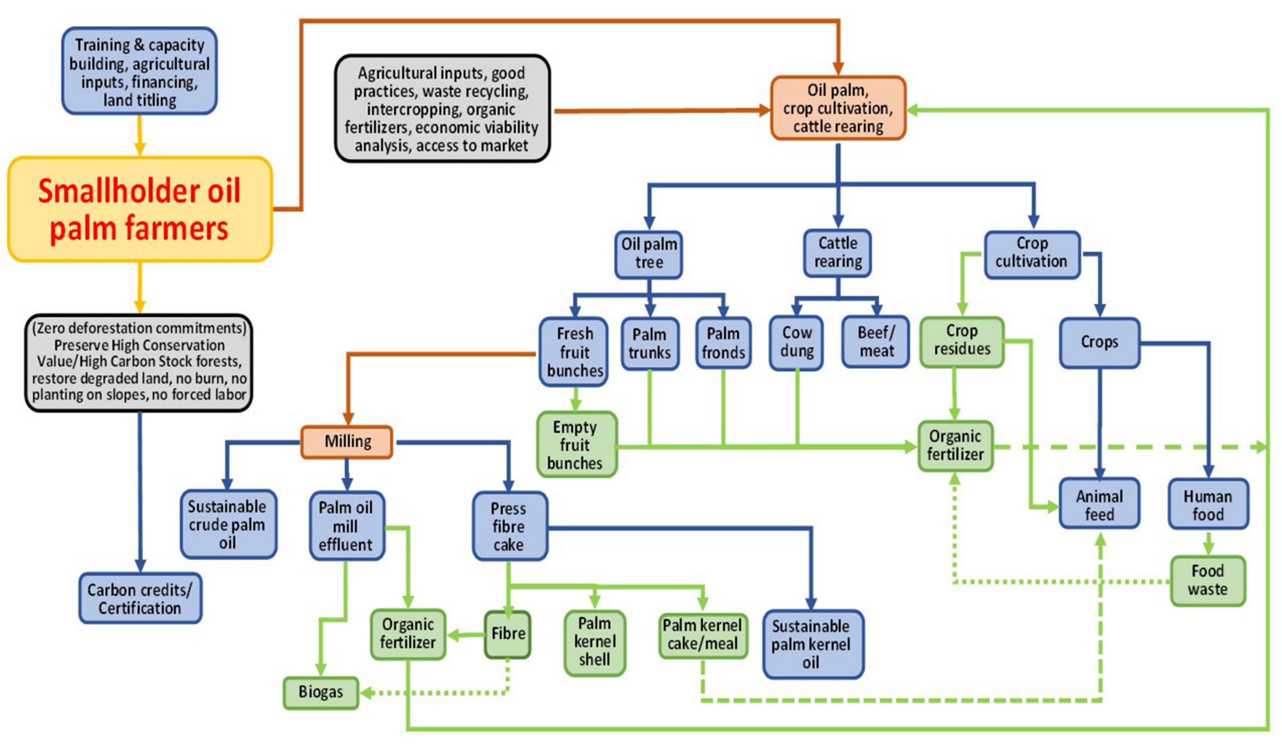

FIGURE 4
Framework for sustainable PO production for smallholders.

expansion of OP plantations can compromise food and livelihood security for rural and indigenous communities, especially when land is taken without adequate consultation or compensation. To foster sustainability, upholding ecological integrity, rationalizing land allocation, and adopting effective management practices is crucial. This includes using high-yield, disease-resistant cultivars, implementing zero-waste milling technologies, and establishing plantations on suitable land without further deforestation.

The proposed framework provides pathways for smallholders to produce PO while minimizing negative impacts on people and the environment. Smallholders are encouraged to avoid deforestation of HCS and HCV lands, abstain from slash-and-burn practices, and avoid employing forced labor. In return, they may receive benefits such as carbon credits, training, agricultural inputs, and financing. Diversified, mixed OP systems can improve land use efficiency, mitigate risks for farmers, and reduce GHG emissions per unit of product. Additionally, cultivation residues can be repurposed as animal feed or processed into organic fertilizers, contributing to soil reconditioning. Integrating cattle into plantation management can control undergrowth, enhance biodiversity, optimize land use efficiency, diversify income, and reduce weeding costs.

4.2 Managing waste from PO production

Managing waste from PO production is a critical aspect of enhancing the sustainability of the industry. PO production generates substantial amounts of biomass residues and POME, which, if not properly managed, can have significant environmental impacts. Efficient waste management practices are essential to mitigate these effects, reduce GHG emissions, and convert waste into valuable resources such as biofertilizers, bioenergy, and biomaterials. By adopting innovative and sustainable waste management strategies, the PO industry can minimize its ecological footprint, promote circular economy principles, and contribute to broader environmental and socio-economic goals. This section explores various waste management techniques, their potential benefits for sustainable PO production, and presents a framework for managing waste from PO production.

4.2.1 Palm oil mill effluent (POME)

POME, a by-product of palm oil production, is generated at approximately 2.5 to 3 times the volume of extracted oil and contains high concentrations of organic pollutants, including 2% oil, 2–4% suspended solids, and 94–96% water, along with notable levels of nitrogen, phosphorus, calcium, and magnesium. Due to its chemical oxygen demand (COD) of up to 51,000 mg/L and biochemical oxygen demand (BOD) reaching 25,000 mg/L, POME poses serious environmental challenges, particularly for aquatic ecosystems, where it can lead to pollution and eutrophication (Nwaneri et al., 2022). Given its potential to degrade water quality, effective POME management strategies are essential for mitigating environmental harm, reducing GHG emissions, and preventing the acidification of terrestrial and aquatic systems (Finalis et al., 2023). To address these concerns, several innovative treatment methods have been explored, with anaerobic digestion emerging as a promising approach to convert POME's high organic content into renewable energy sources such as biogas, thereby reducing waste accumulation while supporting energy production (Prasetyani, 2024). Additionally, biological treatments using microorganisms, including bacteria and fungi, have demonstrated effectiveness in lowering POME's organic load (Bala et al., 2014). Beyond waste reduction, treated POME can serve as a nutrient-rich liquid fertilizer, promoting agricultural productivity while increasing FFB yields by approximately 13% (Heriyanti et al., 2024). By integrating advanced treatment technologies and repurposing POME as a valuable resource, the PO industry can significantly reduce its environmental footprint and contribute to a more sustainable circular economy (Hidayatullah, 2024).

4.2.2 Empty fruit bunches (EFBs)

EFBs, a major by-product of palm oil (PO) production, are often discarded as waste, yet improper management can lead to GHG emissions. Therefore, adopting effective EFB management strategies is crucial for improving sustainability in the PO sector. Since EFBs are rich in essential nutrients such as nitrogen, phosphorus, potassium, and magnesium, they serve as valuable organic fertilizers that enhance soil properties, improve moisture retention, and suppress weed growth, ultimately leading to higher crop yields and better soil health (Supriatna et al., 2022). Furthermore, integrating EFBs into composting processes with POME produces high-quality compost, which strengthens soil structure and nutrient availability while reducing reliance on chemical fertilizers (Tang et al., 2023). Beyond their role in fertilization, EFBs possess a high calorific value, making them suitable for bioenergy production through combustion, gasification, and pyrolysis, methods that simultaneously generate renewable energy and curb GHG emissions (Wibowo et al., 2024). Additionally, EFBs can be converted into biochar, further enhancing soil fertility while facilitating carbon sequestration, a process that supports climate change mitigation efforts (Anyaoha et al., 2018a). To advance sustainable waste management, innovative recycling technologies such as gasification and composting offer environmentally friendly solutions, with integrated biological treatment and advanced filtration systems proving more efficient than conventional disposal methods (Hwang et al., 2022). By adopting these circular economy approaches, the PO industry can minimize its ecological footprint, improve agricultural productivity, and expand renewable energy solutions, thereby contributing to broader sustainability goals (Januari and Agustina, 2022).

4.2.3 Oil palm fronds (OPFs)

OPFs, an underutilized by-product of oil palm cultivation, yield approximately 11 tons per hectare and offer significant opportunities for sustainable management and resource recovery. One promising approach is gasification, which converts OPFs into high-value gaseous fuels or syngas, contributing to renewable energy production (Sulaiman et al., 2014). Additionally, recycling pruned OPFs can enhance soil fertility and nutrient cycling in mature plantations, improving soil health and overall productivity (Dislich et al., 2016). Given their composition approximately 70% fiber and 22% soluble carbohydrates, OPFs are also well-suited for ruminant feed, with an optimal inclusion rate of 30-40% in diets for lactating dairy cows (Hanum, 2023). Beyond their role in animal nutrition, OPFs can be processed into lignin for corrosion inhibition in mild steel, used in printing paper production (Rasat et al., 2013), fermented into bioethanol (Fitria et al., 2021), converted into charcoal, composted into organic fertilizers, or applied as mulch to support soil microbial biomass and nutrient recycling (Khomphet, 2024). By adopting effective OPF management strategies, the PO industry can enhance soil health, minimize waste, and lower GHG emissions, ultimately reinforcing environmental stewardship and advancing circular economy principles for long-term sustainability (Vijay et al., 2016).

4.2.4 Oil palm trunks (OPTs)

Oil palm trunks (OPTs), harvested every 25–30 years for replanting, pose both challenges and opportunities for sustainable waste management in the PO industry. Composed primarily of cellulose, hemicellulose, and lignin, OPTs offer various applications that enhance sustainability. One key use is in bioenergy production, where OPTs are converted into biomass pellets, syngas, bio-oil, and biochar, effectively reducing fossil fuel dependency and mitigating greenhouse gas emissions (Yeo et al., 2020). Additionally, they can be processed into biocomposites and construction materials like particleboard and fiberboard, which help alleviate timber demand and promote sustainable forestry practices (Dungani et al., 2018). Their high cellulose content also makes them well-suited for bioethanol production through saccharification and fermentation, offering a renewable fuel alternative (Srinophakun et al., 2020). Furthermore, composting OPTs enhances soil fertility and structure, benefiting agriculture and crop productivity, while repurposing them for oil palm weevil larvae cultivation converts waste into valuable animal feed or protein sources. Ultimately, integrating effective OPT management strategies into PO waste frameworks can strengthen sustainability, minimize waste, and advance environmental stewardship (Shahirah et al., 2015).

4.2.5 Renewable energy generation

The growing urgency of climate change has intensified interest in renewable energy generation from oil palm biomass (OPB), a promising coal alternative that helps mitigate GHG emissions. PO production yields valuable bioproducts, biofuels, and biopower, contributing to sustainable energy solutions. Notably, small-scale biomass gasification power plants (5 to 200 kW) utilize palm kernel shells (PKS) to supply electricity to remote areas near OP plantations, increasing energy accessibility (Yacob et al., 2021). Additionally, a PO mill processing 45 tons of FFB per hour can generate 0.95–1.52 MW of electricity, with POME-based biogas digesters producing an additional 0.93 MW (Zamri et al., 2022). Methane capture systems from POME further enhance energy output by yielding approximately 28 m^3 of biogas, which translates to 25.4 to 40.7 kWh per ton of FFB processed (Nuryadi et al., 2019).

By replacing fossil fuels, OPB contributes to climate change mitigation and promotes sustainability through effective PO waste management (Wu et al., 2017). Malaysia's PO industry produces approximately 168 million tons of biomass annually, consisting of solid waste such as EFB and PKS, along with liquid waste like POME, which accounts for a significant portion of processed FFB (Rahman et al., 2023; Mondamina et al., 2020). Leveraging biogas capture technologies improves PO mills' sustainability, offering renewable energy solutions (Ahmed et al., 2015). Furthermore, integrating biomass into existing coal-fired power systems lowers GHG emissions and enhances combustion efficiency, enabling a gradual transition toward more sustainable energy practices (Siregar et al., 2020).

4.2.6 Framework for managing waste from PO production

OP cultivation for FFB and PO production generates substantial solid and liquid waste throughout its lifecycle. The solid residues, collectively termed oil palm biomass (OPB), consist of trunks (OPT), fronds (OPF), empty fruit bunches (EFB), mesocarp fiber (OPMF), and palm kernel shells (PKS) (Zamri et al., 2022). Meanwhile, liquid waste primarily comprises POME, which presents environmental challenges due to its high organic load (Gay-Des-Combes et al., 2017). Notably, processing one ton of FFB yields EFB (23%), OPMF (12%), PKS (5%), and POME (60%), underscoring the volume of waste generated (Thomas and Andres, 2021). On an annual scale, each hectare of OP plantations produces approximately 21.6 tons of biomass, including EFB (20.4%), OPT (11.7%), OPF (50.3%), and additional residues (Said et al., 2022). However, improper waste disposal can lead to environmental degradation, including water pollution and nutrient leaching, emphasizing the need for sustainable waste management practices (Tang and Yap, 2020).

To reduce environmental impacts, OPB and POME are increasingly repurposed into value-added products (Yeo et al., 2020). For instance, composting OPB residues such as EFB and decanter cake (DC) facilitates nutrient recycling into organic fertilizers, thereby enhancing soil health (Zhao, 2024). Similarly, POME treatment, when integrated with bioenergy production, generates renewable energy, compost, and liquid fertilizers, aligning with zero-emission goals (Schleifer and Sun, 2018). These circular solutions not only minimize waste but also contribute to increased FFB yields, particularly through co-composting POME with EFB, which has been shown to boost plantation productivity (Zhao, 2024).

Technological innovations further expand the potential for waste valorization in the PO sector. Thermochemical processes such as gasification, pyrolysis, and torrefaction transform OPB into biochar, solid fuels, and syngas, offering scalable clean energy solutions (Khoon et al., 2019). Meanwhile, biological methods such as anaerobic digestion and fermentation generate biogas and biofuels, providing renewable energy alternatives (Carvalho et al., 2021). The development of commercially viable OPB-derived products, including biocomposites, bioplastics, and palm wine, highlights emerging opportunities for waste repurposing (Achten et al., 2010). Furthermore, biomass co-gasification and methane capture from POME anaerobic digestion exemplify strategies that enhance energy recovery and emissions reduction (Singh et al., 2010; Hamdani et al., 2023). Ultimately, integrating these innovations into a circular economy framework strengthens renewable energy systems, reduces emissions, and promotes sustainable resource utilization in the PO industry (Gyamfi, 2017), as illustrated in Figure 5.

4.3 Recommendations for achieving sustainable PO production

Promoting sustainable PO production requires a multifaceted approach that addresses practical recommendations for smallholder farmers, policy suggestions for governments and stakeholders, and strategies for implementing and adopting sustainable practices. These recommendations aim to enhance productivity, improve environmental sustainability, and support the livelihoods of smallholder farmers. By tackling the challenges and seizing opportunities within the PO sector, these guidelines seek to create a balanced, sustainable framework that benefits both producers and the environment. The following sections outline specific actions that can be taken to achieve these goals.

4.3.1 Practical recommendations for smallholder farmers

Smallholder farmers should integrate sustainable agricultural practices by adopting Good Agricultural Practices (GAP) and Good Management Practices (GMP), as these approaches have been shown to enhance crop yields and environmental health, while promoting a positive image of palm oil production (Abas et al., 2021). One effective strategy is intercropping and mixed cropping systems, where food crops are integrated within oil palm (OP) plantations, improving income diversification, soil health, and biodiversity (Edvanido, 2023). Additionally, optimizing fertilizer use efficiency through biofertilizers, balanced chemical fertilizers, and organic amendments like compost and treated POME plays a crucial role in enhancing nutrient uptake, increasing yields, and minimizing environmental impact (Obi et al., 2022; Palihakkara et al., 2022). To further support sustainable farming, implementing weed and pest management strategies, such as biological control agents and cover cropping systems, reduces reliance on chemical inputs, ensuring healthier plantation ecosystems (Famaye et al., 2020). Beyond agricultural improvements, OP biomass can be converted into renewable energy through gasification and pyrolysis, offering alternative energy sources while supporting effective waste management (Khasanah and Noordwijk, 2018). Furthermore, circular waste management systems that transform agricultural waste into organic fertilizers, biogas, bioethanol, and biocomposites contribute to long-term sustainability (Rocha et al., 2020). Lastly, modernizing PO milling systems through capacity enhancements, improved oil extraction rates, and advanced waste reduction techniques can significantly boost production efficiency and reduce environmental impacts, highlighting the value of updated milling equipment and targeted training programs for smallholders (Palihakkara et al., 2022).

4.3.2 Policy recommendations for government and stakeholders

Government bodies and stakeholders should prioritize financial support mechanisms, including grants, low-interest loans, and subsidies, to help smallholders access quality inputs, fertilizers,

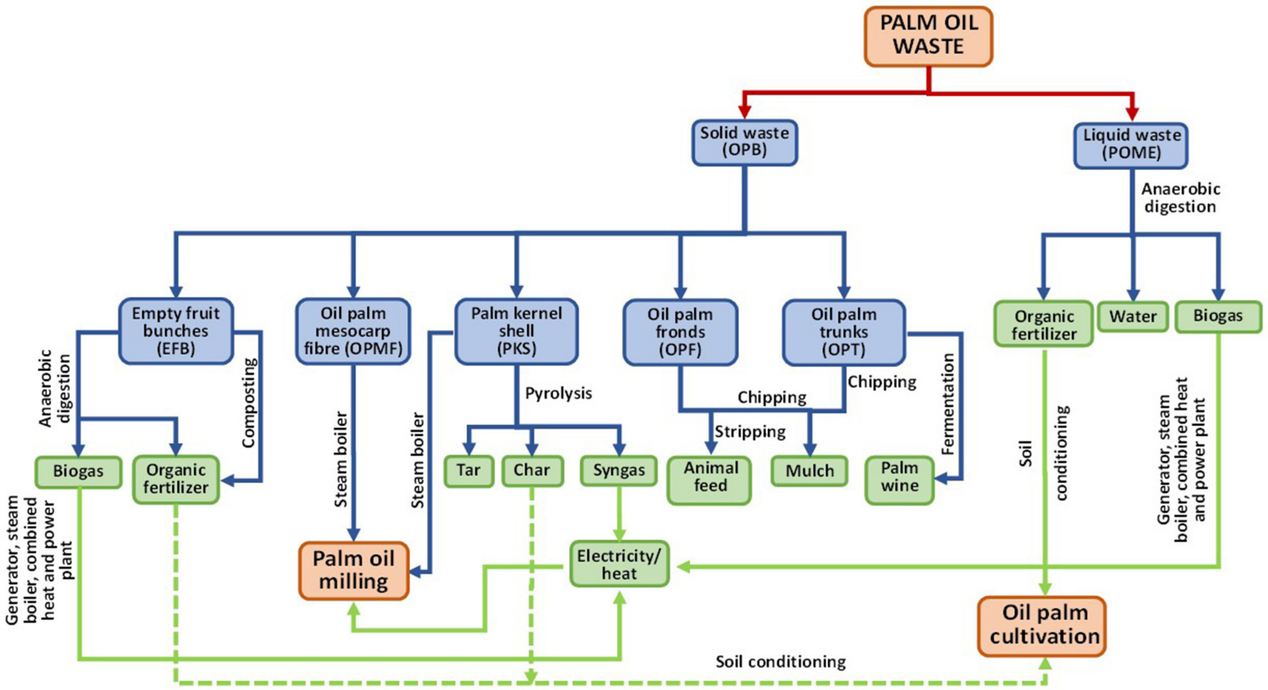

FIGURE 5
Framework diagram for circular palm oil waste management by smallholders.

and sustainable technologies, thereby enhancing productivity and environmental sustainability (Lodhi and Shah, 2024). Additionally, expanding training and capacity-building programs focused on Good Agricultural Practices (GAP) and other sustainable farming methods is essential for facilitating smallholder adaptation to environmentally responsible approaches (Senyolo et al., 2021). Strengthening certification schemes and support programs, such as RSPO certification, can further improve market access, ensuring that smallholder farmers meet sustainability standards while overcoming socio-economic challenges (Yanita and Ningsih, 2021). Moreover, targeted investment in rural infrastructure, including roads, transportation networks, and storage facilities, plays a critical role in enhancing market connectivity and reducing post-harvest losses, ultimately bolstering the economic viability of smallholder farming (Lodhi and Shah, 2024).

4.3.3 Strategies for implementation and adoption of sustainable practices

Facilitating collaborations among smallholders, agricultural research institutions, NGOs, and private sector stakeholders is essential for effectively disseminating sustainable farming practices, ensuring mutual benefits across sectors (Velten et al., 2021). Equally important, providing incentives such as carbon credits, tax breaks, and premium prices for sustainably produced goods encourages smallholders to adopt environmentally responsible practices while fostering a more supportive agricultural landscape (Amuda and Parveen, 2024). Additionally, establishing robust monitoring and evaluation frameworks plays a critical role in tracking the progress and impact of sustainable initiatives, enabling continuous improvement and adaptability (Horan, 2019). To further support adoption, public awareness campaigns should focus on educating smallholders and consumers about the economic and environmental advantages of sustainable palm oil production, ultimately driving market demand for sustainable practices and products (Dragomir and Foriş, 2022).

Figure 6 presents a flowchart that illustrates the key recommendations for promoting sustainable PO production. It highlights practical actions for smallholder farmers, policy suggestions for governments and stakeholders, and strategies for implementing and adopting sustainable practices. This visual representation aims to provide a comprehensive overview of the proposed recommendations.

4.3.4 Recommendations for further research

The limitations identified in the current study open several avenues for further investigation, which can significantly enhance the robustness and applicability of future research on sustainable palm oil production. Future research should expand on the preliminary inferential analyses by employing more advanced statistical techniques, such as multivariate regression, ANOVA, or structural equation modeling, to rigorously test specific hypotheses and uncover causal linkages between farming practices, socio-economic variables, and sustainability outcomes. This approach would generate more generalizable findings across different smallholder contexts.

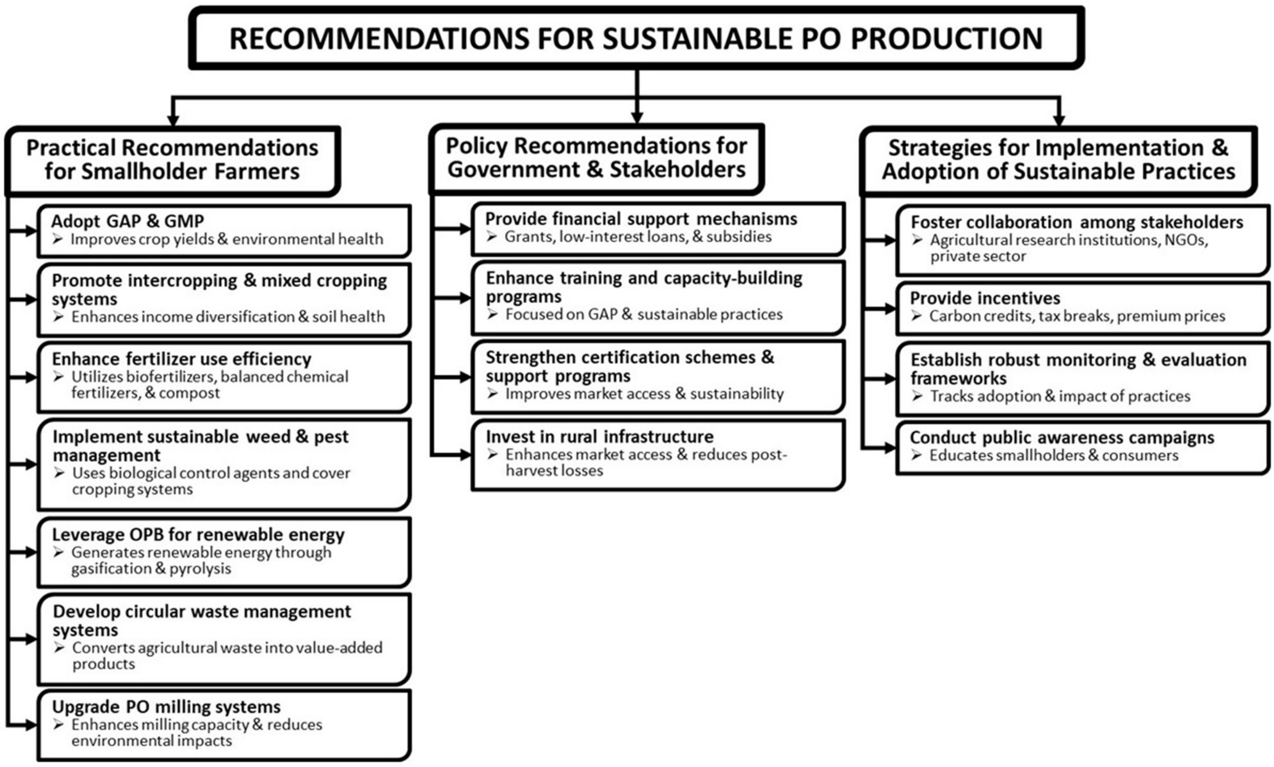

FIGURE 6
Flowchart of recommendations for sustainable PO production.

In addition, further studies should adopt a more robust mixed-methods design to strengthen the empirical foundation. Integrating surveys with in-depth interviews, focus groups, and participatory observation can serve to verify and enrich the quantitative data. A multi-source triangulation strategy would enhance the credibility and depth of insights by effectively integrating qualitative narratives with quantitative trends.

Moreover, addressing the study's limited gender representation and lack of institutional analysis is crucial. Future investigations should design survey instruments and qualitative protocols specifically to capture gendered differences in access to resources, decision-making, and labor distribution. Examining the role of local institutions, policy environments, and extension services will provide a more nuanced understanding of how these factors influence the adoption of sustainable practices.

Finally, the conceptual frameworks developed in this study require empirical validation to confirm their practical utility. Pilot projects, case studies, or longitudinal studies that track the implementation of proposed sustainable practices and waste management strategies among smallholder farmers would not only validate these models but also allow for their iterative refinement and adaptation to local conditions and challenges. By addressing these recommendations, future research can contribute to a more comprehensive understanding of sustainable palm oil production, ultimately supporting evidence-based interventions and policies that benefit smallholder farmers and promote environmental sustainability.

5 Conclusion

The palm oil industry faces both challenges and opportunities in achieving sustainability. With global demand continuing to rise, it is essential to implement environmentally responsible practices that also enhance the livelihoods of smallholder farmers. Applying Good Agricultural Practices (GAP) and Good Management Practices (GMP) can significantly improve productivity and farmer wellbeing. Furthermore, diversified cropping systems, such as intercropping, enhance land use efficiency, soil health, and income diversification. In addition, optimizing fertilizer use and pest management strategies is crucial for maintaining soil fertility while reducing reliance on chemical inputs. Another key strategy involves repurposing oil palm biomass (OPB) for renewable energy production, which lowers greenhouse gas emissions and promotes energy independence, thus contributing to global climate change mitigation efforts.

Equally important, developing a circular waste management framework can enhance sustainability by transforming solid and liquid waste into value-added products, reducing environmental impact while maximizing resource efficiency. Strengthening certification schemes and providing targeted support for smallholder farmers is essential for encouraging widespread adoption of sustainable practices. Addressing socio-economic challenges, such as limited access to quality planting materials, financing, and training, can further enhance smallholder productivity and resilience. Ultimately, by integrating these approaches, the palm oil industry can improve its environmental performance, elevate smallholder wellbeing, and achieve long-term sustainability gains.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LA: Data curation, Writing – review & editing, Methodology, Writing – original draft, Visualization, Conceptualization, Formal analysis. RN: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. AA: Writing – review & editing, Writing – original draft. CM: Writing – original draft, Methodology, Conceptualization, Writing – review & editing. BE: Writing – review & editing, Supervision, Writing – original draft, Funding acquisition.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This article was supported by SLOAN Foundation (https://sloan.org), HELLMAN Foundation (https://hellmanfoundation.org) and Schwab Charitables (www.schwab.com).

Acknowledgments

BE was supported by SLOAN Foundation (https://sloan.org) and HELLMAN Foundation (https://hellmanfoundation.org) as a Fellow. We acknowledge funding from Schwab Charitables (www.schwab.com).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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