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Sustainability assessment of products of the tropical tree moringa in Ghana with a focus on small-scale producers

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ABSTRACT

With their numerous products and uses, multifunctional crops offer an attractive means for improving smallholder farmer livelihoods. This study applies a Life Cycle Sustainability Assessment (LCSA) to *Moringa oleifera* (moringa), a multifunctional crop with diverse applications in nutrition, cosmetics, and water treatment. The LCSA includes an Environmental Life Cycle Assessment (ELCA), Social Life Cycle Assessment (SLCA), and Life Cycle Costing (LCC). Surveys were conducted with 58 smallholder farmers and five moringa processors in Ghana. The ReCiPe 2016 Midpoint method was used for the ELCA. The 10-year Net Present Value (NPV) and Payback Period (PBP) were calculated for farmers and processors in the LCC. The SLCA focused on the Worker stakeholder category, particularly smallholder farmer impacts, including indicators for Next Generation Farming, Inclusiveness, Access to Services, Food Security, and Livelihood. A composite sustainability score was calculated from the ELCA, SLCA, and LCC results using the Characteristic Objects Method (COMET), a multi-criteria decision analysis method resistant to rank-reversal. The study compared five supply chains: leaf-only, leaf-and-seed, leaf-and-seed with seedcake reuse, seed-only, and seed-only with seedcake reuse. Environmental hotspots were identified in leaf and seed collection. Economically, leaf-only cultivation provided the highest 10-year NPV for farmers, while seed-only with seedcake reuse yielded the highest NPV for processors. The leaf-only supply chain had the best PBP for both farmers and processors. Socially, leaf-only cultivators outperformed reference points across all indicators, making it the most socially sustainable supply chain. Our findings highlight that improving market access, organizing seed cultivators into farmer-based groups, and optimizing farm gate product collection can enhance the sustainability of moringa supply chains, offering a model for other multifunctional crops in rural development. This study is the first to integrate LCSA with COMET, a promising approach that could be adopted in other sustainability assessment case studies.

1. Introduction

Over 90 % of the 608 million farms in the world are family-owned, with smallholder farms accounting for 84 % of global farms (Lowder et al., 2021). Smallholder farms, typically operated by family labor on less than 2 ha (Lowder et al., 2021; FAO, 2015), are vital for food security and rural livelihoods in the Global South (Garzón Delvaux and Riesgo, 2020). However, smallholder farmers remain among the most technologically and economically vulnerable demographics (Nyambo et al., 2022). Moreover, climate change further exacerbates livelihood challenges for smallholder farmers (Agbenyo et al., 2022; Quarshie et al., 2023).

To alleviate these challenges, rural interventions often promote multifunctional crop cultivation to enhance smallholder farmer livelihoods (Snapp, 2020; Kaahwa et al., 2023). Multifunctional crops are crops that have the potential to contribute to multiple societal objectives simultaneously (OECD, 2001). In doing so, they can offer farmers diversified streams of income and livelihood improvements. Multifunctional crops like soybeans (*Glycine* max), corn (*Zea mays*), oil palm (*Elaeis guineensis*), and sugarcane (*Saccharum officinarum*) impact cultivators' livelihoods through their numerous coproducts. While trees such as shea (*Vitellaria paradoxa*), tamarind (*Tamarindus indica*), and baobab (*Adansonia digitata*) also play an integral role in supplementing household income with their products and multiple uses (Kamga, 2023;

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Mahonya et al., 2019).

However, promoting multifunctional crops without holistic sustainability assessments can lead to unmet expectations or unintended consequences (World Vision, 2022; Mashamaite et al., 2020). For example, jatropha (*Jatropha curcas*) was once praised as an environmentally friendly biofuel feedstock that would yield socioeconomic benefits in low- and middle-income countries (FAO, 2010). Jatropha-centered interventions were not only economically unsustainable but also ineffective, leading to adverse effects such as land-grabbing, conflict, and biodiversity loss (Kgathi et al., 2017; Kunda-Wamuwi et al., 2017; Nygaard and Bolwig, 2018). Similarly, oil palm monocultures have had conflicting impacts in Indonesia, contributing positively to smallholder farmer well-being at the detriment of ecosystem health (Chrisendo et al., 2022). In contrast, oil palm production in Ghana relies on mixed cropping and agroforestry. However, the smallholder oil palm farmers in Ghana have lower yields than their counterparts in Indonesia, and the oil palm sector has struggled due to mismanagement and conflict of stakeholder interest (Ruml et al., 2022; Asante, 2023). These examples highlight the complexity of multifunctional agriculture and the critical need for comprehensive assessments that consider environmental, social, and economic conflicts, tradeoffs, and synergies.

Holistic evaluation of multifunctional crop sustainability is crucial to ensure that theoretical prospects (Gebrai et al., 2021) translate into practical positive benefits to smallholder livelihoods (Schurman, 2018; Fischer, 2022). This study helps address this need by applying a life cycle sustainability assessment (LCSA) to *Moringa oleifera* (hereafter referred to as moringa), a multifunctional crop widely promoted for its climate resilience and various uses (Horn et al., 2022). Despite garnering widespread attention, there is a notable lack of comprehensive studies on moringa's sustainability. Given the complex nature of multifunctional crops like moringa, LCSA offers a versatile framework for assessing the impacts of their supply chain.

LCSA, which includes an environmental life cycle assessment (ELCA), social life cycle assessment (SLCA), and life cycle costing (LCC) (Traverso and Valdivia, 2024; UNEP, 2011), is a systematic methodology for evaluating sustainability impacts across different dimensions. Multifunctional crop impacts on smallholder farmers' livelihoods are multidimensional. Consequently, a single evaluation of environmental, social, or economic impacts is not well-suited to capture tradeoffs and synergies across the dimensions of sustainability in a product system. Although a relatively new methodology, LCSA can help improve understanding of the impacts of a multifunctional crop like moringa on smallholder farmers.

However, integrating ELCA, SLCA, and LCC results for decision-making poses challenges (Backes and Traverso, 2021; Zortea et al., 2018; Visentin, 2020). Multi-criteria Decision Analysis (MCDA) is a discipline that offers methodologies to support systematic decision-making in the presence of complexity. MCDA is becoming increasingly adopted in sustainability assessments (Talukder and Hipel, 2021; Thies et al., 2019). In this study, we utilize the Characteristic Object Method (COMET) for the first time in an LCSA. Though many MCDA methods exist, COMET was selected because it is resistant to rank reversal, a property that reduces the reliability of many commonly used MCDA techniques (Kizielewicz et al., 2021; Tsakalerou et al., 2022).

In addition to introducing the use of COMET in an LCSA, we also provide the first sustainability assessment of moringa. Our study objectives are three-fold: (1) Assess the social, environmental, and economic impacts of moringa leaf and seed products from the perspective of smallholder farmers; (2) Identify sustainability hotspots and recommend areas of focus for reducing the environmental footprint and improving the social and economic benefits of moringa leaf powder and seed oil production; (3) Use COMET to integrate the ELCA, LCC, and SLCA results into a composite sustainability score for comparing different product systems.

Beyond providing a new LCSA case study on moringa, this research contributes to the evolving LCSA methodology by considering additional smallholder farmer well-being metrics, selecting economic value as an LCSA functional unit, and including multiple perspectives in our economic assessment. In doing so, we seek to enhance the relevance and applicability of sustainability assessments in agri-food systems. Furthermore, findings from studies such as ours could support agricultural policies and interventions, ultimately supporting sustainability and resilience in multifunctional smallholder farming systems.

2. Literature review

Moringa has two main commercial products: leaf powder and seed oil. Moringa leaf powder is primarily used as a nutraceutical supplement in diets (Kou et al., 2018), attracting customers seeking natural alternatives to supplement their nutrition and health (Liu et al., 2021). Similarly, for moringa seed oil, the public's increasing awareness of potentially harmful ingredients used in cosmetic products has led to a growing interest in natural alternatives (Bilal et al., 2020). As a result, the nutraceutical and cosmetic industries are driving the demand for moringa products. Substituting synthetic ingredients with biobased ones calls for exploring the environmental impacts of biobased or renewable products in these sectors (Fernández-Ríos et al., 2022; Secchi et al., 2016).

ELCAs have been conducted for plantation-style moringa seed cultivation as a biodiesel feedstock in Australia and Algeria (Amouri et al., 2023; Biswas, 2008). In addition to applying different farming practices, the goal and scope of such studies do not translate to smallholder farming systems. Differences in study goal and scope definition lead to different results, even when assessing the same crop (Chéron-Bessou et al., 2024). In Ghana, moringa cultivation is typically done by smallholder farmers growing moringa for household consumption or as a supplemental source of income, not on commercial farms (AgNMR, 2018). Outgrower agribusiness schemes are often leveraged, where smallholder farmers are contracted to produce moringa leaves and seeds for a processor. Once purchased, dried moringa leaves are processed into leaf powder, and oil is extracted from moringa seeds before being packaged and sold as commercial products.

Moringa seedcake is a coproduct of the seed oil extraction process, and it has applications in water treatment, animal feed, and fertilizer use (Gebrai et al., 2021). Amante et al. (2016) conducted a comparative ELCA on moringa seedcake and aluminum sulfate use as coagulants at a hypothetical wastewater treatment plant in Burkina Faso. However, neither the cultivation of moringa nor the coproduction of seed oil were considered in their analysis. The only ELCA conducted on moringa leaves focused on their polyphenol content. Pappas et al. (2023) used grams of polyphenol as their functional unit to evaluate different extraction technologies. Thus, their results are inapplicable to moringa cultivation by smallholder farmers for supplemental income.

While SLCAs have been performed on multifunctional crops such as sugarcane (Prasara-A and Gheewala, 2021) and oil palm (Haryati et al., 2022), an SLCA has not yet been done on moringa. Previous SLCAs conducted have focused on multifunctional crops grown as cash crops (Luna Ostos et al., 2024; Rahmah et al., 2023; Ngan et al., 2022; Souza et al., 2021). Studies that consider important supplemental sources of income for smallholder farmers, such as moringa cultivation, are not as commonly examined. NGOs and international development agencies widely promote moringa as a crop that can help improve rural livelihoods. Some studies have found that moringa cultivation positively contributes to the livelihood of farmers by applying econometric methods (Meskel et al., 2020; Tafesse et al., 2020). However, there have been cases where moringa cultivation has either underperformed or negatively impacted on farmers (World Vision, 2022; Waterman et al., 2021). In South Africa, there is even a concern that moringa may be an invasive species (Mashamaite et al., 2020). Despite these potential drawbacks, the potential benefits of moringa cultivation indicate a need to assess moringa's social and socioeconomic impacts using a life cycle approach.

Furthermore, prior research has examined the economic feasibility of moringa cultivation (Kudzinawo et al., 2022; Waterman et al., 2021). Nevertheless, both studies examined moringa's economic impacts from the farmer stakeholder perspective only and did not consider processors in their analysis. Kudzinawo et al. (2022) interviewed farmers selling moringa leaves and seeds while Waterman et al. (2021) focused on moringa leaf cultivators. Consequently, no study has compared the economic sustainability of leaf and seed production or considered multiple moringa stakeholder perspectives.

Our study aims to help address these gaps in the literature by adopting economic value as our functional unit to capture functional aspects of smallholder farmer moringa cultivation and address multifunctionality in an LCSA. Additionally, the ELCA conducted in this study focuses on an outgrower agribusiness scheme for moringa leaf and seed production and processing instead of large-scale commercial farming. Furthermore, the social and socioeconomic impacts of moringa leaf and seed cultivation on smallholder farmers are captured with an SLCA. Finally, our study expands on previous economic assessments of moringa production by considering farmer and processor perspectives and distinguishing between leaf and seed harvesters.

3. Methods

Detailed information on the study site and the moringa sector in Ghana can be found in Sections S1.1 and S1.2. The methodology applied in this study follows the ISO guidelines for conducting an LCA and consisted of Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation steps (ISO, 2006a, 2006b). The environmental, economic, and social results were interpreted before MCDA was used to integrate, compare, and rank alternative supply chains.

3.1. Goal and scope definition

This research focuses on moringa leaf powder and seed oil because they are the most popular moringa products. ELCA, SLCA, and LCC were applied to assess their environmental, social, and economic impacts. The intended application of this research is to support decision-making for the stakeholders involved in the moringa supply chain so that positive social and economic impacts are enhanced and negative environmental impacts are reduced. The system boundary for the ELCA and LCC are cradle-to-factory gate, as shown in Fig. 1, while the SLCA focuses on smallholder farmers and has a cradle-to-farm gate system boundary.

Although mass is the most used functional unit in life cycle assessment studies on agri-food products, it has been criticized for not capturing the function of food (Arzoumanidis et al., 2020; O et al., 2024). In our case study, moringa farmers are growing moringa as a supplementary source of income. Therefore, moringa cultivation functions as a means of income generation and economic value was determined to be the most viable functional unit. Economic value captures additional functional aspects of products, such as quality, supplier demand for the product, customer willingness to pay more for a product, and expected benefit on human health (Van der werf and Salou, 2015; Ponsioen and Van der werf, 2017). Our study is also comparative, requiring functional units to be the same for moringa leaves and seeds, and economic value as a functional unit easily accommodates comparison between products. After defining our functional unit as economic value, economic value was converted to equivalent mass reference flows for moringa leaves and seeds.

When this study was conducted, 1 United States Dollar (US$1) was equivalent to 11.02 Ghanaian Cedis (GH¢11.02) (World Bank, 2023). Processors typically purchased moringa leaves and seeds for an average farm gate price of GH¢17 (US$1.54) per kilogram (kg) in dry weight. Approximately 450 kg of dried moringa seeds are needed to produce 100 Liters (L) of moringa seed oil and 450 kg of dried leaves to yield 300 kg of moringa leaf powder. Since the price of moringa seeds and dried leaves are equivalent at the farm gate, the functional unit equates to GH ¢7650 (US$695.5). This functional unit was consistently used throughout the ELCA, SLCA, and LCC, resulting in reference flows of 450 kg of dried seeds and 450 kg of dried leaves. When leaves and seeds were coproduced, the functional unit did not change, but the reference flow became 225 kg of dried seeds and 225 kg of dried leaves. The LCC is performed from the perspective of both farmers and processors, as suggested by Arulnathan et al. (2022) and Padilla-Rivera et al. (2023). The SLCA stakeholder category of interest in this study was Workers, which consists of smallholder moringa farmers. Triangulation was performed to ensure data quality by asking different stakeholders the same questions for verification. Since this study has adopted a socioeconomic approach, economic allocation was used to address coproduction (Pelletier et al., 2015).

3.2. Inventory analysis

Inventory data were collected by working closely with moringa-processing local collaborators such as the Ghana Permaculture Institute (Techiman), Minssap Ventures (Bolgatanga), Agape Moringa Processing Enterprise (Tamale), and GreenGold Ghana (Zongo Macheri). Farmers were identified and interviewed using purposive sampling, and moringa farmers were contacted to participate in this study voluntarily. Data were collected from November 2022 to May 2023 through in-person interviews. Fifty-eight smallholder farmers who grew and sold moringa leaves or seeds were interviewed in this study.

3.2.1. Environmental inventory

None of the farmers interviewed used fertilizers, herbicides, or pesticides for their moringa trees. The moringa growers did not use irrigation, which corroborated Kudzinawo et al.'s (2022) findings when interviewing moringa farmers. The inventory data was collected by interviewing farmers and processors and surveying farms and processing facilities. Data on seedcake coproduction was collected onsite and is presented in Table S1. The ELCA was conducted using the EcoInvent 3.9.1 Cutoff Database. Inventory data details are summarized in Tables S2-S6.

3.2.2. Economic inventory

The economic information collected from farmers was related to the costs of inputs and the selling price of moringa leaves and seeds. Data needed to calculate farmer revenue was collected from interviews. The length of the harvesting season for moringa was divided by the harvest frequency to calculate the annual harvests. The calculated annual harvests were then multiplied by the response farmers gave when asked about the mass of moringa leaves or seeds they collect in each harvest.

Detailed information on the price costs associated with processing moringa leaves and seeds was obtained from interviewing processors and surveying local markets. These estimates are provided in Table S7. One liter of moringa seed oil was sold for GH¢340 (US$30.90), while a kilogram of moringa leaf powder was sold for GH¢80 (US$7.26). Key costs are related to machinery, electricity, employee wages, building rent, leaves and seeds purchasing, and packaging. It was assumed that the moringa processors purchased ten functional units of moringa leaves and seeds for processing. This results in moringa processors being supplied with 4500 kg yearly for ten years.

3.2.3. Social inventory

In-person interviews were conducted with farmers in Bono, Bono East, and Northern regions in Ghana. Local research assistants fluent in English and the Ghanaian languages spoken in communities where this research took place, such as Twi and Dagbani, helped translate interview questions and responses. Each interview lasted between sixty to ninety minutes. OpenDataKit (Hartung et al., 2010) was used to enter interviewee responses as the interview was conducted to mitigate recall bias. The questionnaire consisted primarily of quantitative questions. Although this study did not perform a formal qualitative analysis, key

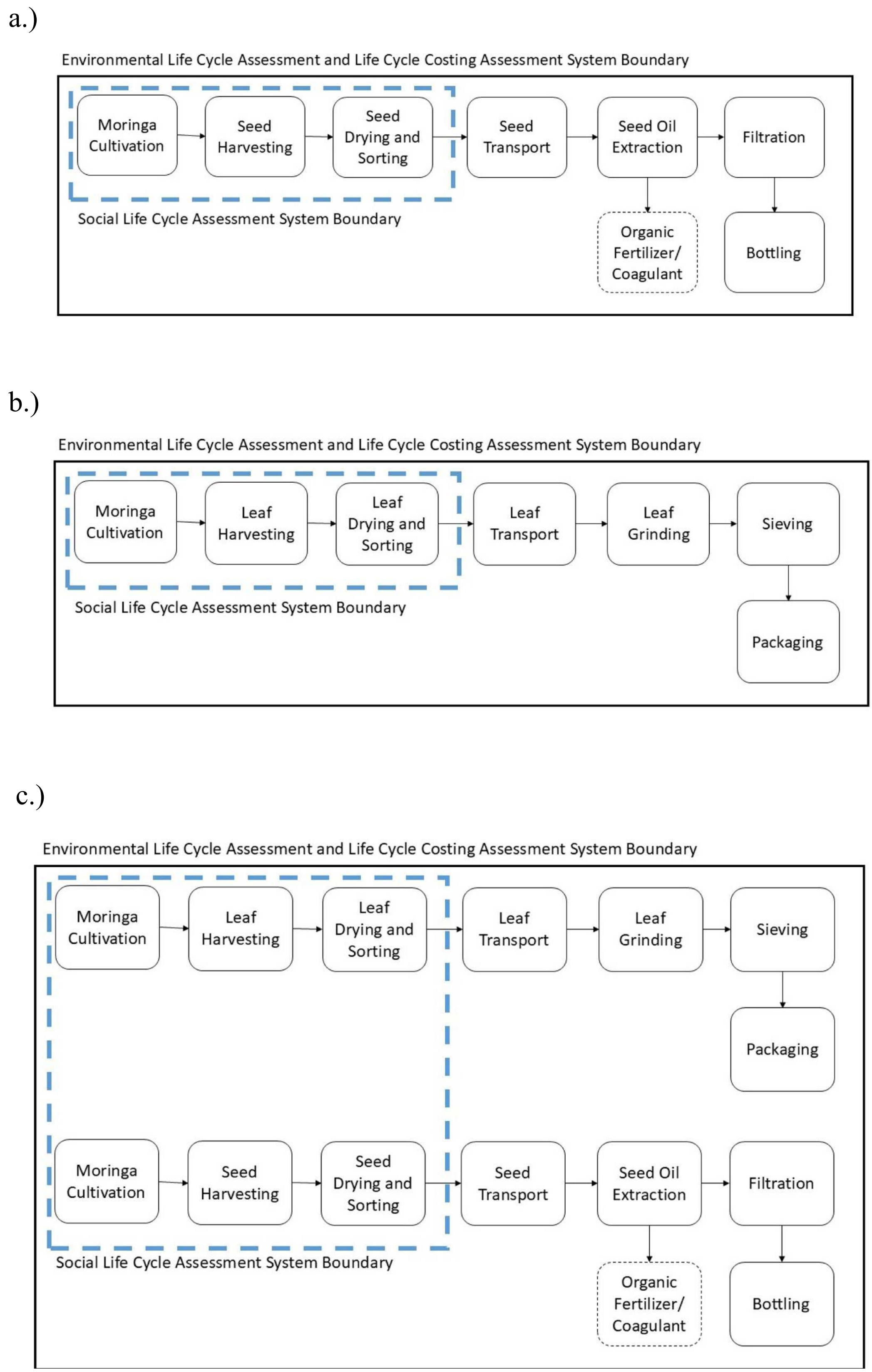

Fig. 1. System boundaries for the environmental life cycle assessment, life cycle costing, and social life cycle assessment (blue dashed line) for moringa (a) leaf powder, (b) seed oil and seedcake coproduction, and (c) leaf-and-seed supply chains.

themes and recurring patterns were identified from interviewee responses to add context to the quantitative findings. The questionnaires used in this analysis are provided in Tables S8 and S9.

For the SLCA, seven social and socioeconomic indicators were used for estimating and comparing social impacts on i) leaf-only cultivators, ii) seed-only cultivators, and iii) leaf-and-seed cultivators. Smallholder farmers are the sole social impact subcategories considered in this study UNEP (2021). Social impacts are focused on moringa farmers since farmers are typically the most vulnerable stakeholders in the supply (Brenes-Peralta et al., 2021; Wei et al., 2022). UNEP (2021) provides inventory indicators for the smallholder subcategory, which are adopted and modified in this study. The mean household farmer age was used to assess the likelihood of moringa cultivation continuity with the next generation of farmers/holders in moringa-growing households. There is also evidence that younger farm managers are more efficient than older ones, which has implications for productivity and food security (Asravor et al., 2023). The fraction of farmers who were members of a group for moringa farming was used as an indicator of inclusiveness. Moringa farmers' access to services was represented by the fraction of farmers who received or continue to receive support concerning access to farming inputs and training programs. Two indicators were used as proxies for food security: mean household food consumption score (FCS) and food expenditure as a fraction of total household expenditure. Finally, the fraction of households with alternative sources of income and the total household expenditure per capita were calculated as social indicators for livelihoods. The surveys were deployed with 32 questions related to the types of food eaten by the household, the number of times eaten over the last seven days, and total household expenditure.

3.3. Impact assessment

3.3.1. Environmental impact assessment

The ReCiPe 2016 Midpoint method in SimaPro 9.4 was used to estimate environmental impacts for various impact categories. The ELCA results considered all eighteen impact categories.

3.3.2. Economic impact assessment

The impact categories considered in this analysis included farmer and processor perspectives in the moringa leaf and seed supply chains. Net Present Value (NPV) and payback period were selected as the indicators for this study. The methodology and assumptions used in Kudzinawo et al. (2022) were applied in this study. This study differs by considering scenarios different from those of Kudzinawo et al. (2022) and extending the analysis to include moringa-processors. A further distinction was made between leaf, leaf-and-seed, and seed farmers. Eqs. 1 and 2 show how the NPV and the Present Value (PV) were calculated, respectively.

$$NPV = \sum PV\ cash\ inflows - \sum PV\ cash\ outflows \tag{1}$$

Eq. (1) is commonly used to consider the time value of money and has utility as an LCC indicator (Arulnathan et al., 2022; Padilla-Rivera et al., 2023). In eq. (2), the PV was calculated by correcting the future value (FV) with a uniform discount rate, R, and accounting for the number of time periods that pass, t (Kudzinawo et al., 2022). The discount rate used in this study was 0.35 (Kudzinawo et al., 2022). This analysis assumes that moringa inputs' and prices increase by 5 % each year and that the processor's production is fixed yearly.

$$PV = \frac{FV}{(1+R)^t} \tag{2}$$

The payback period (PBP) was also calculated as an LCC indicator. PBP determines the amount of time needed for an investment to be balanced. The formula for PBP is provided in Eq. 3, where the investment was divided by the annual inflow.

$$PBP = \frac{Investment}{Annual\ Cash\ Flow} \tag{3}$$

3.3.3. Social impact assessment

The Reference Scale Approach was used for the SLCA impact assessment. This approach uses reference points determined by best practices and established standards for measuring social impacts by assigning threshold values (UNEP, 2020). A positive or negative social impact is then determined by the value of the measured social impact in relation to its reference point. For example, if a social indicator scores higher than its reference point, it can be considered a positive impact. If the social indicator scores worse than its reference point, it is considered to have a negative impact.

These reference points were determined from published studies and applied to the selected indicators to measure positive and negative social impacts. Estimates for the average farmer age in Ghana range from 40 to as high as 55 (Danso-Abbeam et al., 2021a, 2021b; Oduro Akrasi et al., 2021). Accordingly, a reasonable reference point for farmer age was 45. Addai and Temoso (2022) sampled 900 farmers in Ghana and found that 46 % were members of farmer-based organizations. Similarly, Dagunga et al. (2018) sampled 200 farmers in their study on the income diversification of maize farming households in Ghana's Upper East region. They found that 52 % of their sample was a member of a farmer-based organization. Based on these values, 0.5 was selected as the reference point for the inclusiveness subcategory, expressed as the fraction of moringa cultivators in a moringa farmer-based organization.

The reference point for the mean FCS was adopted from Oduro Akrasi et al. (2021), where the household food consumption survey was used to assess shea butter-producing households' food security in northern Ghana. The mean FCS for their study sample of 300 shea butter producers was 35.77. This value was adopted as the reference point in this analysis. For the contribution of food expenses to total household expenditure, another food security proxy, 0.454 (Ghana Statistical Service, 2019), was the average contribution of food and non-alcoholic beverages to total household expenditure and was determined to be an appropriate reference point.

Average household expenditure per capita reference point was estimated by calculating the average total annual household expenditures per capita for the Brong-Ahafo (GH¢ 3429 or US$311.20) and Northern (GH¢ 2353 or US$213.50) regions. This reference point was converted to a monthly average of GH¢ 241 (US$22). Finally, the reference point for non-farm sources of income was determined to be 0.65 based on a sample of farmers participating in non-farm income-generating activities in Ghana's Western and Upper East regions (Danso-Abbeam et al., 2020).

3.4. Multi-criteria decision analysis

This study utilized COMET, a newly developed MCDA method resistant to rank reversal (Kizielewicz et al., 2021). Methodological details on COMET are provided in Section S6. For the composite sustainability score calculation, five of the eighteen impact categories from the ReCiPe 2016 midpoint impact assessment results were included in COMET (climate change, ecotoxicity, human toxicity, fossil fuel consumption, and land use). These impact categories had the largest magnitudes in our ELCA results (Table 2), ensuring that the key environmental burdens of moringa cultivation and processing are reflected in our sustainability assessment. Furthermore, climate change is one of the most widely used impact categories in environmental assessments, and its inclusion in our analysis facilitates comparison with studies of other multifunctional crops (Quevedo-Cascante et al., 2023). By considering ecotoxicity and human toxicity potentials, we capture the environmental impacts of agricultural inputs and their threats to ecosystems and human health where applicable.

Additionally, global warming potential, ecotoxicity, and human toxicity have all emerged as significant impact categories in the life cycle of another multifunctional crop grown in Ghana, cocoa (Ntiamoah and Afrane, 2008; Ntiamoah and Afrane, 2009). Some of the interviewed moringa farmers also grew cocoa, thus similarities among the life cycle results of moringa and cocoa can be anticipated. Fossil fuel consumption is a metric for resource depletion, representing the consumption of non-renewable energy sources, a useful proxy for overall environmental footprints as revealed by Steinmann et al. (2017). Land occupation was included because land ownership is a significant constraint for smallholder farmers, making land use a critical factor in both environmental and socio-economic sustainability. Other impact categories, such as water depletion or particulate matter formation, were excluded as they were less relevant in the context of rain-fed Moringa cultivation or overlapped with the selected categories, which already capture the most significant environmental burdens.

Furthermore, the selected impact categories span the three areas of protection: damage to human health, damage to ecosystems, and damage to resource availability (Huijbregts et al., 2017). In our reduction of ReCiPe 2016 midpoint impact categories included in our MCDA analysis, we are able to reduce redundancy in the sustainability assessment while preserving the comprehensiveness of our ELCA results. Reducing redundancy is particularly crucial when integrating ELCA and MCDA, as too many impact categories can dilute their relative importance and skew the overall results. Additionally, simplifying the COMET rule-base formulation reduces complexity (Sałabun and Karczmarczyk, 2018; Więckowski and Wątróbski, 2021), improving the interpretability of results and facilitating decision-making.

Weights are evenly distributed between the baseline scenario's social, economic, and environmental performance for the baseline comparison. Characteristic values for every environmental and economic indicator ranged from zero to the maximum calculated value. For the SLCA indicators, the characteristic values for the average farmer age ranged from 16 to 65 years, while for Household Food Consumption scores, the range was from 35 to 112 (World Food Programme, 2008). A comparison was then made between the COMET rankings and corresponding composite scores. The "pycdm" Python package was used to implement COMET (Kizielewicz et al., 2023).

3.5. Scenario analysis

Five scenarios were examined, one impacting the ELCA results and two scenarios affecting the LCC results. The focus was on the ELCA and LCC results since they have quantitative parameters that can be altered, unlike the SLCA results, which were obtained using an inductive framework. Mass allocation was used instead of economic allocation for scenario 1. In Scenario 2, the price of moringa seeds and seed oil increased by 20 %, reflecting a decrease in the supply of moringa seeds. Scenario 3 considers a case where the demand for moringa leaves is reduced by 50 %, which is modeled by reducing the quantity of moringa leaves and leaf powder sold by 50 %. The scenario analysis results were then included in the MCDA methods to see the overall effects on the LCSA. The sensitivity of the LCSA results to changes in the weights assigned to the ELCA, LCC, and SLCA were evaluated by assigning one assessment a weight of 0.4 and the remaining two a weight of 0.3, resulting in three additional scenarios. Each scenario examined is described in Table 1.

Table 1
Summary of the scenarios considered in the sensitivity analysis.

Scenario	Description
Scenario 1: Mass allocation	Seedcake coproduction with mass allocation
Scenario 2: Moringa seed price increase by 20 %	Moringa seed farmgate price increased by 20 % from GH¢17/kg to GH¢20.4 /kg due to a supply shortage. (from US$1.54 to US$1.85)*
Scenario 3: Moringa leaf demand decrease by 50 %	Moringa leaf demand decreases by 50 % (half of the Moringa leaves harvested are sold) due to oversupply.
Scenario 4: Emphasis on environmental impacts	0.4 weight assigned to environmental impacts and 0.3 to economic and social impacts results each
Scenario 5: Emphasis on economic impacts	0.4 weight assigned to economic impacts and 0.3 to environmental and social impacts each
Scenario 6: Emphasis on social impacts	0.4 weight assigned to social impacts and 0.3 to environmental and economic impacts each

* GH¢ represents Ghanaian cedis, and US$ stands for the United States Dollar. The exchange rate was approximately GH¢11.02 = US$1 at the time of this study (World Bank, 2023).

4. Results

This section begins with ELCA results by discussing the overall environmental impact results and then focusing on the environmental hotspots for the Global Warming Potential (GWP) impact category to identify the contribution of different processes. GWP is the focus of the contribution analysis because it is the most widely used impact category in environmental assessments, provides a good proxy for the contribution of other impact categories, and allows for comparison with environmental hotspots in other studies. After focusing on GWP, LCC results are presented, highlighting the findings from the perspective of farmers and processors for 10-year Net Present Value (NPV) and payback period (PBP). SLCA findings are then presented before integrating the results to analyze the LCSA with COMET.

4.1. Environmental results

The results for all impact categories are shown in Table 2, where the least environmentally harmful supply chain for each impact category is noted in green and the worst in red. Leaf-only performed the best for eleven out of eighteen total impact categories, making it the most environmentally sustainable supply chain. Seed-only was the worst-performing supply chain for twelve impact categories, making it the worst overall supply chain. Leaf-and-seed cultivation and processing typically performed worse than leaf-only and better than seed-only results since it consumed less electricity than leaf-only and required less collection than seed-only. Reusing seedcake led to marginal variations in impact categories for both leaf-and-seed and seed-only scenarios, where some impact categories increased, others decreased, and others remained unchanged. An essential impact category in our analysis is land use, which calculates the land occupation for each scenario. The least amount of land is needed for leaf-only cultivation, while the land requirements for seed-only cultivation are significantly larger. Land availability is a constraining factor for smallholder moringa cultivation, and there is an opportunity cost associated with using land for moringa cultivation instead of crops perceived to be more profitable.

The GWP values for the leaf-only and seed-only supply chains were 152 kg CO_2eq and 156 kg CO_2eq, respectively. As depicted in Fig. 2, electricity consumption was the most significant contributor to GWP for leaf-only, leaf-and-seed, and leaf-and-seed with seedcake and notably contributed to the seed-only and seed-only with seedcake supply chains. The most noteworthy difference between the GWP profiles of leaf-only and seed-only supply chains was in the contribution of collection from farmers. Seed-only farmers are decentralized and have lower yields than leaf-only and leaf-and-seed cultivators. Consequently, suppliers often travel long distances to collect moringa seeds. Collected seeds are stored and accumulated until suppliers receive an order from a processor. Long travel distances, often on a motorbike, and delivery of the moringa seeds to the processor notably contribute to GWP for the seed-only supply chain.

For the leaf-and-seed supply chain, GWP emissions are reduced to 141 kg CO_2eq. Farmers harvest seeds and leaves from their farms, and the moringa leaves and seeds are collected from a central location. However, the leaves are harvested in the rainy season and the seeds in the dry season, leading to separate trips for transport to the processing

Table 2
ReCiPe 2016 Midpoint impact assessment results for each scenario, scaled by the functional unit. Green indicates the best-performing supply chain, and red indicates the worst.

Impact category	Unit	Leaf-and-Seed	Leaf-and-Seed w/ Seedcake	Leaf-only	Seed-only	Seed-only w/ Seedcake
Global warming	kg CO_2 eq	1.41×10^{2}	1.42×10^{2}	1.52×10^{2}	1.56×10^{2}	1.58×10^{2}
Stratospheric ozone depletion	kg CFC_{11} eq	9.98×10^{-5}	9.96×10^{-5}	6.76×10^{-5}	1.37×10^{-4}	1.36×10^{-4}
Ionizing radiation	kBq Co-60 eq	2.06	2.05	1.60	3.10	3.07
Ozone formation, Human health	kg NOx eq	3.13×10^{-1}	3.14×10^{-1}	3.08×10^{-1}	5.64×10^{-1}	5.61×10^{-1}
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.15×10^{-1}	1.15×10^{-1}	1.12×10^{-1}	1.51×10^{-1}	1.51×10^{-1}
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.47×10^{-1}	3.47×10^{-1}	3.26×10^{-1}	7.05×10^{-1}	7.00×10^{-1}
Terrestrial acidification	kg SO_2 eq	2.31×10^{-1}	2.31×10^{-1}	2.14×10^{-1}	3.18×10^{-1}	3.18×10^{-1}
Freshwater eutrophication	kg P eq	2.70×10^{-2}	2.70×10^{-2}	2.72×10^{-2}	3.17×10^{-2}	3.16×10^{-2}
Marine eutrophication	kg N eq	1.94×10^{-3}	1.95×10^{-3}	2.23×10^{-3}	1.96×10^{-3}	1.96×10^{-3}
Terrestrial ecotoxicity	kg 1,4-DCB	5.03×10^{2}	5.01×10^{2}	5.28×10^{2}	5.65×10^{2}	5.62×10^{2}
Freshwater ecotoxicity	kg 1,4-DCB	3.73	3.73	2.77	4.53	4.53
Marine ecotoxicity	kg 1,4-DCB	5.03	5.02	3.84	6.17	6.16
Human carcinogenic toxicity	kg 1,4-DCB	1.68×10^{1}	1.71×10^{1}	2.15×10^{1}	1.22×10^{1}	1.28×10^{1}
Human non-carcinogenic toxicity	kg 1,4-DCB	6.04×10^{1}	6.03×10^{1}	4.66×10^{1}	9.57×10^{1}	9.50×10^{1}
Land use	m^2a crop eq	4.16×10^{4}	4.12×10^{4}	3.30×10^{4}	5.03×10^{4}	4.95×10^{4}
Mineral resource scarcity	kg Cu eq	9.22×10^{-1}	9.31×10^{-1}	1.14	7.00×10^{-1}	7.18×10^{-1}
Fossil resource scarcity	kg oil eq	5.27×10^{1}	5.32×10^{1}	5.82×10^{1}	5.47×10^{1}	5.54×10^{1}
Water consumption	m^3	4.69×10^{-1}	4.72×10^{-1}	4.61×10^{-1}	5.21×10^{-1}	5.26×10^{-1}

facility for leaves and seeds. Coproduction of leaves and seeds with seedcake led to a marginal increase in GWP to 142 kg CO_2eq. Similarly, for seedcake coproduction with seeds-only, the GWP increased marginally to 158 kg CO_2eq compared to seed-only due to additional electricity and machinery for pelletizing the seedcake for fertilizer production.

Moringa seed oil was bottled in plastic bottles, while moringa leaf powder was packaged in paper pouches. Leaf-only paper packaging and seed-only plastic bottles are assumed to be sourced from Accra and shipped to the processing facility site in this study. The environmental impact of the packaging stage was found to be dependent on the number of bottles or pouches that are ordered and shipped. Since paper pouches have a smaller mass and volume than 1 L plastic bottles, they are seen here to have a lower environmental impact than plastic bottling.

4.2. Economic results

4.2.1. Smallholder farmers

The PBP results for smallholder farmers are shown in Table 3. For seed-only cultivators, the PBP was estimated to be 4.00 years, while for leaf-only, the PBP was estimated to be 1.53 years (1 year and 6.4 months). Leaf-and-seed farmers had an estimated PBP of 1.83 years (1 year and 10 months). The NPV for leaf-only farmers was estimated to be seven times larger (GH¢8050 or US$731) than the NPV for seed farmers (GH¢1160 or US$105) and 29 % larger than the NPV for leaf-and-seed farmers (GH¢6260 or US$568) for the baseline. For scenario 2 (20 % increase in seed prices), there was a 5 % increase in NPV for leaf-and-seed farmers (GH¢6580 or US$597) and an increase in NPV by a factor of 2.4 to GH¢2800 (US$254) for seed farmers. If the demand for moringa leaves is reduced by 50 % (scenario 3), the leaf farmer NPV is reduced by 76 % (GH¢1900 or US$172), and the leaf-and-seed farmer NPV is reduced by 90 % (GH¢640 or US$58).

4.2.2. Processors

Seed-only processors have a PBP of approximately 1.38 years (1 year and 4.5 months), while leaf-only processors have a payback period of 0.14 years (approximately 1 month and 3 weeks). Moringa seed processors must wait one year for farmers' trees to bear seeds before they can begin processing and selling seed oil. Three months of the moringa leaf growing season are needed for the trees to mature enough for their first harvest. Processing leaves and seeds have the highest startup costs due to the need to acquire machinery for both processes. The payback

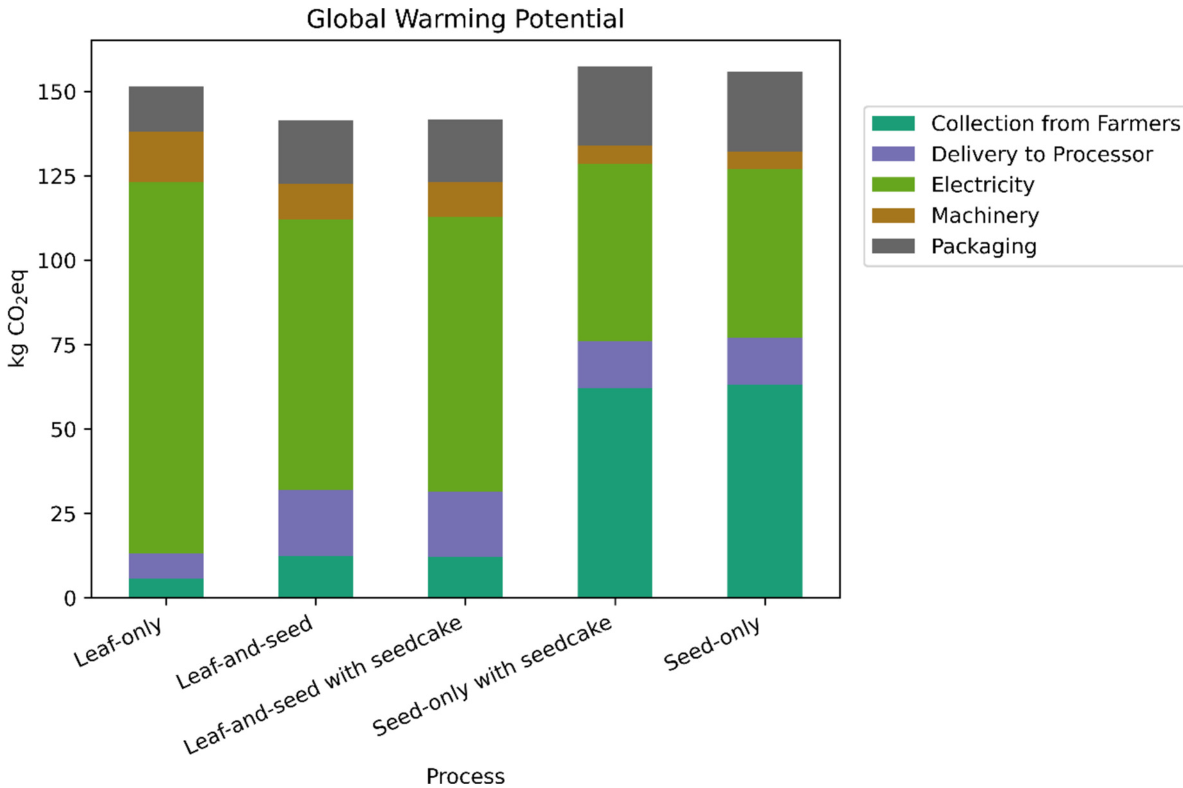

Fig. 2. Global Warming Potential for leaf-only, leaf-and-seed, leaf-and-seed with seedcake, seed-only with seedcake, and seed-only supply chains.

Table 3
Ten-year Net Present Value and Payback Period results for smallholder farmers across scenarios. Green indicates the best-performing supply chain, and red represents the worst.*

Scenario	Leaf-only	Leaf-and-seed	Seed-only
Baseline 10-year Net Present Value in GH¢ (US$ equivalent)	8050 (731)	6260 (568)	1160 (105)
Baseline Payback Period in Years	1.53	1.83	4.00
Scenario 2 10-year Net Present Value in GH¢ (US$ equivalent)	8050 (731)	6580 (597)	2800 (254)
Scenario 2 Payback Period in Years	1.53	1.82	3.19
Scenario 3 10-year Net Present Value in GH¢ (US$ equivalent)	1900 (172)	640 (58)	1160 (105)
Scenario 3 Payback Period in Years	3.75	4.43	4.00

* GH¢ represents Ghanaian cedis, and US$ stands for the United States Dollar. The exchange rate was approximately GH¢11.02 = US$1 at the time of this study (World Bank, 2023).

period was calculated to be 1.06 years, less than the payback period for seed-only and more than the payback period for leaf-only.

The 10-year NPV for seed-only processing (GH¢450,000 or US $40,800) was found to be 10 % higher than leaf-only processing (GH¢ 411,000 or US$37,300) and 11 % higher than leaf-and-seed processing (GH¢407,000 or US$36,900) for the baseline scenario. Coproduction of seedcake with moringa seed oil led to a 4 % increase in NPV for seed-only processing (GH¢452,000 or US$41,020) and a 1 % decrease in leaf-and-seed processing (GH¢401,000 or US$36,400). For scenario 2, the NPV for seed-only processing increased by 20 %, and the NPV for leaf-and-seed processing increased by 11 %. A 50 % reduction in leaf demand (scenario 3) resulted in a proportional reduction in the leaf-only processing NPV and a 25 % reduction in the leaf-and-seed NPV. Detailed results of the NPV and PBP for different scenarios are provided in Table 4.

4.3. Social results

Indicators of the social indicators are shown in Table 5. For Next Generation Farmers, a lower age indicates a stronger positive social impact, while an older age indicates a negative one. In leaf-only households, it was determined that the mean household farming age was 51. The average household farming age was 46 for leaf-and-seed harvesters, while for seed harvesters, the mean household farming age was 44 years. Seed harvesters have a slightly younger household average farmer age than leaf-and-seed harvesters. This difference could be due to the concentration of moringa seed farmers in northern Ghana, where the proportion of households owning or operating a farm is among the highest in the country. As a result, youth are more likely to be involved in farming (Ghana Statistical Service, 2019). The fraction of moringa farmers participating in an organization was highest for leaf producers at 73 %, followed by those cultivating leaves and seeds at 36 %. Seed cultivators had the slightest participation in an organization at 17 %.

Table 4
Ten-year Net Present Value and Payback Period results for leaf-only, leaf-and-seed, seed-only, leaf-and-seed with seedcake, and seed-only with seedcake processors. Green indicates the best-performing supply chain, and red represents the worst.*, **

Scenario	Leaf-only	Leaf - and-seed	Seed-only	Leaf-and-seed w/ seedcake	Seed-only w/ seedcake
Baseline Net Present Value in GH¢ (US$ equivalent)	411,000 (37,300)	407,000 (36,900)	450,000 (40,800)	401,000 (36,400)	452,000 (41,020)
Baseline Payback Period in Years	0.14	1.06	1.38	1.11	1.34
Scenario 2 Net Present Value in GH¢ (US$ equivalent)	411,000 (37,300)	451,000 (40,900)	538,000 (48,800)	445,000 (40,400)	541,000 (49,100)
Scenario 2 Payback Period in Years	0.14	1.10	1.70	1.33	1.83
Scenario 3 Net Present Value in GH¢ (US$ equivalent)	207,000 (18,800)	307,000 (27,900)	450,000 (40,800)	317,000 (28,800)	452,000 (41,020)
Scenario 3 Payback Period in Years	0.30	1.30	1.38	1.36	1.34

* GH¢ represents Ghanaian cedis, and US$ stands for the United States Dollar. The exchange rate was approximately GH¢11.02 = US$1 at the time of this study (World Bank, 2023).
** Based on processing a total of 4500 kg of moringa seeds and/or leaves per year.

Table 5
Social life cycle assessment results for leaf, leaf-and-seed, and seed smallholder farmer indicators. Green signifies indicators that outperform the reference point, red indicates those that underperform, and yellow represents the reference point threshold values.*

<table>
<tr><th>Impact Subcategory</th><th>Area of Interest</th><th>Inventory Indicators</th><th>Leaf-only (n=30)</th><th>Leaf-and-seed (n=22)</th><th>Seed-only (n=6)</th><th>Reference Point</th><th>Units</th></tr>
<tr><td rowspan="7">Smallholder Farmers</td><td>Next Generation Farmers</td><td>Mean Household Farmer Age</td><td>51</td><td>46</td><td>44</td><td>45</td><td>Years</td></tr>
<tr><td>Inclusiveness</td><td>Membership in Moringa Organizations</td><td>0.73</td><td>0.36</td><td>0.17</td><td>0.50</td><td>Unitless</td></tr>
<tr><td>Access to Services</td><td>Received inputs or training</td><td>0.80</td><td>0.64</td><td>0.17</td><td>0.50</td><td>Unitless</td></tr>
<tr><td rowspan="2">Food Security</td><td>Mean Household Food Consumption Score</td><td>64</td><td>59</td><td>63</td><td>35.8</td><td>Unitless</td></tr>
<tr><td>Avg Food Expense/Total Expenditure</td><td>0.22</td><td>0.16</td><td>0.17</td><td>0.45</td><td>Unitless</td></tr>
<tr><td rowspan="2">Livelihood</td><td>Avg Household Expenditure Per Capita</td><td>302 (27)</td><td>322 (29)</td><td>257 (23)</td><td>241 (22)</td><td>GH¢* (US$)</td></tr>
<tr><td>Alternate Sources of Income</td><td>0.73</td><td>0.59</td><td>0.5</td><td>0.65</td><td>Unitless</td></tr>
</table>

* GH¢ represents Ghanaian cedis, and US$ stands for the United States Dollar. The exchange rate was approximately GH¢11.02 = US$1 at the time of this study (World Bank, 2023).

Similarly, 80 % of leaf cultivators received support, while 64 % of those who harvested leaves and seeds had access to services. Again, the seed cultivators had a lower access to services at only 17 %.

All three groups performed well above the reference point of 35.77 for the Mean Household Food Consumption Score. The FCS was 64 for leaf production and 59 for leaf-and-seed production, while seed producers had an FCS of 63. Similarly, the average food expenses of the three groups, expressed as a fraction of total monthly expenditures, were notably less than the reference point of 0.454. Food expenses of leaf-and-seed and seed producers accounted for 0.16 and 0.17 of their total household expenditures, respectively. Leaf producers' food expenses accounted for 0.22 of their total household expenses. Average monthly household expenditure per capita, a proxy for household welfare, was higher than the reference point of GH¢241 (US$22) for leaf, leaf-and-seed, and seed producers. Seed producers had the lowest household expenditure per capita at GH¢257 (US$23), followed by leaf producers at GH¢302 (US$27), and finally, leaf-and-seed producers at GH¢322 (US $29).

The fraction of farmers with non-farm sources of income was greatest for leaf producers at 0.73, followed by leaf-and-seed producers at 0.59, and finally seed producers at 0.5. Such diversification is particularly important for overall farm productivity since farmers can reinvest in their farm. Non-farm income can support farmer investments in inputs and overall farmer income (Danso-Abbeam et al., 2020).

4.4. Multi-criteria decision analysis results

The MCDA rankings are shown in Table 6, where the rankings of the alternatives and corresponding COMET scores are provided. The sustainability of the leaf-only case was ranked first for each scenario. Leaf-and-seed was ranked second for all scenarios apart from Scenario 1. Scenario 1 used mass allocation for seedcake coproduction. Since a larger mass of seedcake is produced than seed oil, the environmental impact of seed oil production is reduced significantly with mass allocation. Mass allocation leads to leaf-and-seed with seedcake ranked second, and seed-only with seedcake ranked third in scenario 1. Seed-only was consistently ranked as the worst alternative for each scenario considered, apart from scenario 2. In scenario 2, the price of moringa seeds and seed oil was increased by 20 %, and their PBP decreased. However, since seedcake coproduction has a higher upfront cost, seed-only received a higher COMET score in scenario 2.

Nevertheless, for the other scenarios, seed-only with seedcake coproduction consistently ranked marginally above the seed-only case due to slightly better environmental and economic indicators. Changes in weighting did not alter the rankings, as observed in Scenarios 4, 5, and 6. It has been well-documented that different MCDA methods can yield different results (Cinelli et al., 2014). As a result, rankings from alternative MCDA methods were implemented and compared to COMET results for the ELCA, LCC, SLCA, and LCSA indicators (Tables S14-S19).

5. Discussion

5.1. Discussion

5.1.1. Environmental impacts

In many ELCA studies on multifunctional crops, the cultivation or production stage is typically reported as an environmental hotspot due to the land-use change and farming inputs such as synthetic fertilizers, pesticides, and herbicides (Romeiko et al., 2020; Brito et al., 2023; Farizal et al., 2024). Identification of cultivation as an environmental hotspot was also reported in ELCAs conducted on moringa seed oil-derived biodiesel (Biswas, 2008; Amouri et al., 2023). However, in this case study, moringa cultivation had no environmental footprint beyond land occupation since the farmers interviewed did not use any farming inputs on moringa. While the absence of synthetic inputs in moringa cultivation allows for the marketing of an organic product, it also raises challenges related to yield and nutritional quality (Sokombela et al., 2022; Ishfaq et al., 2023). The use of organic fertilizers could bridge this gap for moringa farmers, but their adoption depends on overcoming barriers such as cost, accessibility, and farmer training (Christophe et al., 2019; Panday et al., 2024).

Transportation emerged as a hotspot in this study, primarily for the seed-only supply chains. Frequent trips are needed to collect moringa seeds in quantities sufficient for regular seed oil production, leading to more environmental emissions and reductions in the overall sustainability of moringa seed supply chains. Our findings align with studies on other multifunctional crops where transportation is identified as an environmental hotspot (Prasara-A et al., 2019; Farizal et al., 2024). However, unlike Biswas (2008) and Amouri et al. (2023), where plantation-style cultivation minimized transportation impacts, our study highlights the unique challenges faced by smallholder moringa farmers in outgrower schemes. These differences reveal the need for improved seed collection coordination and context-specific strategies to reduce the environmental footprint of moringa supply chains.

Land occupation is another important factor to consider when comparing leaf-only, leaf-and-seed, and seed-only supply chains. Compared to commercial moringa production, leaf cultivation requires significantly less land and has a lower land occupation than seed cultivation. Using agricultural inputs could reduce the amount of land needed for leaf and seed cultivation. Danso-Abbeam et al. (2021a, 2021b) found that fertilizer, labor, and sowing more seeds were associated with greater productivity. They also revealed that moringa farm size negatively affected moringa output and associated that with inadequate access to resources.

It is important to note that most of the farmers surveyed in our analysis intercropped moringa with other crops, which could lead to discrepancy when compared to commercial cultivation of moringa (Mabapa et al., 2017; Sutarno and Rosyida, 2020). While low-input moringa cultivation offers environmental benefits through reduced farming inputs, challenges such as transportation emissions and land occupation remain. Using economic value as a functional unit in ELCA achieves a more balanced assessment, accounting for the higher costs and the market value of organic products. This approach offers a more comprehensive understanding of the sustainability of moringa supply chains, particularly in low-input agricultural systems.

5.1.2. Economic impacts

A key difference between the moringa leaf and seed supply chains is the harvest frequency. Leaf-only farmers reported having six monthly harvests, leaf-and-seed farmers reported five leaf harvests and one seed

Table 6
Multi-criteria decision analysis results for all supply chains. Rankings are provided, with Characteristic Object Method calculated scores in parentheses. Green indicates the best-performing supply chain for each scenario, and red represents the worst.

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Leaf-only	1 (0.63)	1 (0.63)	1 (0.57)	1 (0.39)	1 (0.51)	1 (0.71)	1 (0.67)
Leaf-and-Seed	2 (0.46)	4 (0.45)	2 (0.47)	2 (0.31)	2 (0.34)	2 (0.52)	2 (0.46)
Seed-only	5 (0.16)	5 (0.16)	4 (0.18)	5 (0.22)	5 (0.07)	5 (0.19)	5 (0.13)
Leaf-and-seed w/ seedcake	3 (0.45)	2 (0.60)	3 (0.45)	3 (0.31)	3 (0.33)	3 (0.51)	3 (0.45)
Seed w/ seedcake	4 (0.16)	3 (0.50)	5 (0.17)	4 (0.23)	4 (0.07)	4 (0.19)	4 (0.13)

harvest, and seed-only farmers reported biannual harvesting. With both products being sold for the same price at the farm gate, this leads to leaf-only farmers having the highest 10-year NPV, followed by leaf-and-seed farmers, with their seed-only counterparts earning the least income. Additionally, the payback period is significantly shorter for leaf-only and leaf-and-seed than for seed-only production. Other studies have evaluated the economic impact of moringa cultivation on farmers (Kudzinawo et al., 2022; Waterman et al., 2021), however none compare leaf, leaf-and-seed, and seed-only growers.

Kudzinawo et al. (2022) did an economic analysis from the smallholder farmer perspective in Ghana. Their demographic harvested and sold leaves and seeds and had a 10-year NPV of GH¢ 4857, equivalent to US$833 at the time of their study, and a payback period of 1 year and 10 months. These results correspond with our leaf-and-seed scenario, where the 10-year NPV for farmers was GH¢6260 (US$568), and the payback period was also 1 year and 10 months. The higher 10-year NPV in our study compared to Kudzinawo et al. (2022) was likely due to the higher market price of moringa leaves during our study period (GH¢17 instead of GH¢15 or US$1.55 instead of US$2.55) and local currency depreciation. The depreciation of the Ghana cedi relative to the United States Dollar has been substantial, losing nearly 50 % of its value since Kudzinawo et al. (2022). Our study offers additional insights since leaf-only farmers had a shorter PBP at 1 year and 6 months and higher 10-year NPV GH¢8050 (US$731), while seed-only had a longer PBP and lower 10-year NPV.

Waterman et al. (2021) conducted a comparative analysis of moringa cultivation in Kenya revealing significant economic disparities between a cooperative selling non-organic moringa leaf powder in local markets and a European-owned company that sold organic certified leaf powder and operated a network of contract farmers. Their study found that a cooperative farmer had a 12-year NPV of US$8049 compared to a contract farmer, who was calculated to have a negative 12-year NPV of US $697. Waterman et al. (2021) reported a wide range, with each of our analyses falling between the values they found in their study. However, all the surveyed farmers in our study were estimated to have positive 10-year NPV values. Still, our findings contribute to this discussion by highlighting similar economic challenges and opportunities between moringa leaf and seed growers.

No study was found that evaluated the economic impacts of moringa processing. Our study found that moringa processors stand to benefit from the short payback period for leaf cultivation and processing if the market for moringa leaf products is strong. Processors can reduce their PBP by processing and selling leaf powder while benefiting from the higher profit margins from seed oil sales. However, that would require a higher initial investment to purchase the machinery needed for processing moringa leaves and seeds. If a moringa processor is seeking the more profitable of the two products and has access to a sufficient number of seed growers, then moringa seed oil production has the highest 10-year NPV of the processes considered. Selling the seedcake byproduct as a fertilizer can also generate a higher 10-year NPV. However, the disconnect between the least economically impactful seed farmer income and seed processor profits represents a bottleneck in the seed supply chains, which could lead to an increase in moringa seed prices and, subsequently, seed-only farmers' income.

5.1.3. Social impacts

The leaf-only supply chain showed the strongest social performance, with the highest rates of moringa organization membership, service access, and income diversification among growers. Farmer-based organizations offer benefits such as increased income, improved food security, reduced environmental impacts, better product quality, and access to training (Bizikova et al., 2020; Methamontri et al., 2022). These organizations also enhance yield, diversify income sources, and improve bargaining power (Ma et al., 2023). For example, Abdul-Rahaman and Abdulai (2018) found that group participation increased rice yields and farming efficiency. Waterman et al. (2021) showed that cooperative moringa farmers were more economically sustainable than contract farmers. Therefore, it is recommended that moringa farmers, especially leaf-and-seed and seed-only farmers, form farmer-based groups to maximize these benefits.

Service access, often facilitated by organization membership, promotes technology adoption and market participation (Anang and Zakariah, 2022; Meskel et al., 2020). Income diversification, which leads to higher household incomes and resilience to economic shocks, is vital for climate resilience, though barriers like lack of capital or market access can hinder it (Bojnec and Knific, 2021). Notably, seed-only moringa farmers, with the lowest 10-year NPV and PBP, may face greater challenges in diversifying income (W/kidan and Tafesse, 2023).

Moringa farmers demonstrated better food security than reference points from Oduro Akrasi et al. (2021) and Ghana Statistical Service (2019), with higher Food Consumption Scores (FCS) and lower food expenditure ratios. Our results align with findings by Tafesse et al. (2020), who reported greater food security among moringa farmers. Meskel et al. (2020) also highlighted the positive impact of moringa market participation and organizational membership on welfare. However, food security results may vary seasonally (Tay et al., 2023).

Although these social indicators are likely interconnected, the reference point social impact assessment method cannot fully explore these interactions. Nevertheless, the outgrower scheme analyzed shows potential for positive social impacts, particularly for leaf-only farmers. Establishing trust through expanded market access and timely payments is crucial, and farmer-based organizations can help sustain this trust (Khalili et al., 2024).

5.1.4. Seedcake coproduction

Coproducing moringa seedcake led to a marginal economic incentive over the 10-year time horizon for life cycle costing for the seed-only with seedcake supply chain. For leaf-and-seed with seedcake coproduction, the PBP slightly increased due to an increase in initial investment from purchasing additional equipment. The environmental impacts of pelletizing the seedcake were also marginal. Other uses of moringa seedcake could also be explored, such as substituting alum in wastewater treatment (Amante et al., 2016). However, more case studies on using raw seedcake in water treatment are needed (Yamaguchi et al., 2021). Byproducts can strongly impact a process's sustainability, as witnessed by the evolution of the market for palm kernel expeller as an animal feed (Gellert and D'Onofrio, 2024). Future research could evaluate the impacts of moringa seedcake reuse as an organic fertilizer, animal feed, or coagulant on society with a consequential life cycle assessment (Ekvall, 2019; Ekvall and Weidema, 2004). If the multiple uses of moringa seedcake can be demonstrated and awareness of its uses spread, then there is potential for accessing a larger market and having a more pronounced impact on the moringa seed supply chain.

5.1.5. Overall impacts

Overall, the leaf-only supply chain was the most sustainable of the five scenarios considered. Even with reductions in the environmental impact of seed-only and seed-only with seedcake in scenario 1, the COMET rankings still favor leaf-only over the alternatives. This high sustainability score is due to the leaf-only supply chain's performance with respect to farmer and processor PBP, farmer 10-year NPV, nearly all SLCA indicators, and overall lower environmental impact.

A significant SLCA indicator contributing to the leaf-only supply chain's high sustainability score was the strong membership in moringa farmer-based organizations. As discussed in the *Social Impacts Section 4.1.3*, these organizations can provide numerous benefits. In this context, membership in a moringa farmer organization helped facilitate the collection of moringa leaves from farmers living in a single community on a single trip using a passenger car. Improving membership in such associations can also lead to access to training and farming inputs, both of which can improve the productivity of moringa cultivation.

In contrast moringa seed collection, which often occurs on motorbikes, requires frequent trips for collection of smaller quantities because seed growers are more decentralized. Organizing moringa seed farmers into groups similar to leaf-only farmers can significantly reduce the environmental impact of seed-only supply chains by requiring less trips needed for seed collection, and subsequently less emission for seed collection. It may also lead to farmers reducing their moringa land footprint due to access to training and farming inputs increasing their yield.

Market forces also play a crucial role in determining sustainability outcomes. In scenario 2, where seed prices increased by 20 %, led to higher NPVs for all scenarios that included seed oil production. Though, it did not result in a noticeable shift in the rankings outside the seed-only processes, which rose to fourth in the rankings. Similarly, scenario 3 considers a decrease in the demand for moringa leaves by 50 %, did not change baseline rankings despite decreases in the COMET score for supply chains that included leaf cultivation and processing. These scenarios highlight the importance of market forces in such an analysis, showing that while the baseline sustainability rankings remained stable, shifts in supply and demand dynamics can significantly influence outcomes.

Scenarios 4, 5, and 6 explored different weights for social, environmental, and economic indicators and further reinforced the baseline rankings, which remained unchanged. The rank reversal resistant nature of COMET was a strong benefit to this MCDA approach. The rankings were consistent, with minor changes in the rankings from the scenario analysis. This is especially useful and demonstrates the reliability of this MCDA approach in LCSA.

A critical challenge for moringa-farmers, and leaf growers specifically, was the lack of a market for moringa leaves, which has led to a decline in their cultivation. Some farmers reported that despite initial encouragement from non-profits and agricultural extension agents, they were unable to find buyers for their moringa leaves. Consequently, they abandoned moringa cultivation in favor of more profitable cash crops like cocoa and cashew. This emphasizes the need for better market access and support structures to sustain the cultivation of moringa and other multifunctional crops that may be promoted to smallholder farmers.

5.2. Limitations

The selection of economic value as a functional unit was appropriate in this study because it reflects the primary purpose of Moringa cultivation for supplemental income. It also provides a consistent basis for comparing the different supply chains and coproducts. However, it's important to acknowledge that with economic value as the functional unit, price fluctuations directly affect the reference flow. Specifically, as product prices rise (e.g., moringa seeds or leaves), the reference flow decreases, leading to lower calculated environmental impacts, assuming the functional unit remains unchanged. When the price of Moringa increases, fewer resources are needed to produce a set economic value, resulting in lower environmental impacts in the ELCA. Conversely, when prices decrease, the reference flow increases, potentially raising the associated environmental impacts. This dynamic highlights the price sensitivity of environmental results when using economic value as the functional unit, which should be considered during interpretation. While this functional unit provides useful insights into low-input farming systems, it also helps mitigate ELCA bias that favors more efficient or highly productive systems (Van der Werf et al., 2020). Still, the effect of product cost on social impacts could not be explored using a reference point approach. Interactions between changes in the functional unit could not be evaluated for all dimensions of sustainability. Therefore, the scenario analysis focused on how changes in moringa leaf and seed prices alter the economic impacts. Exploring the impact of price fluctuations on social, economic, and environmental impacts with economic value as a functional unit should be explored further, but may require adopting a consequential approach.

Purposive sampling was employed to ensure collaboration with in-country partners and project stakeholders. Although such a sampling approach may limit the generalizability of the findings, it allowed for a detailed examination of the local context. The small sample of moringa seed farmers did not allow for uncertainty analysis. Future research could explore alternative sampling procedures and consider exploring the uncertainty in reference point approaches.

This study adopts FCS, the fraction of total household expenditure on food expenses, and total monthly expenditure per capita as well-being indicators, which have not previously been applied in SLCA studies of smallholder farmers to the authors' knowledge. While FCS effectively captures the availability and utilization aspects of food security, it does not fully address access and stability or the seasonality of food security. Future SLCA studies could enhance these metrics by incorporating additional indicators or using panel data.

The SLCA methodology, while offering valuable insights into the social impacts of moringa cultivation, is still evolving. This study contributes to its development but recognizes the need for further research to explore additional social indicators and capture interactions among variables. This is particularly true for smallholder farmers, where the authors found the reference point approach to be limiting. Future research should consider using a causal pathways approach, which can help better understand cause-effect relationships (UNEP, 2020). This approach could be especially useful for studying smallholder farming systems and allocating social impacts accordingly.

The use of COMET in this study demonstrates a valuable approach to overcoming rank reversal in MCDA. The drawback is the complexity of the method in the presence of numerous alternatives and characteristic values; however, frameworks exist for bypassing this issue (Więckowski and Wątróbski, 2021). While other MCDA methods can yield different results, the robustness of COMET offers a helpful tool in sustainability assessments, especially when scenario analysis is explored, and alternative supply chains are compared. However, although the objective treatment that MCDA methods such as COMET offer for LCSA can assist decision-makers, each dimension of LCSA should be evaluated individually, and tradeoffs among results need to be communicated to avoid compensating poor performance with a single score (Valdivia et al., 2021).

6. Conclusions

This study presented the first life cycle sustainability assessment on moringa, focusing on its environmental, economic, and social impacts on smallholder farming systems. Environmental life cycle assessment (ELCA) results revealed minimum impacts during cultivation due to the absence of farming inputs. For all supply chains, electricity consumption was an environmental hotspot, highlighting the need for efforts to reduce energy consumption during processing. Additionally, transportation emerged as a critical hotspot for seed-only supply chains, revealing the need for optimizing seed collection and better coordination with farmers to reduce emissions. Selecting economic value as a functional unit for such a low-input system can capture key functional aspects, such as moringa cultivation as a source of supplemental income and product quality.

The life cycle costing (LCC) demonstrated that the leaf-only supply chain offers the highest economic viability for farmers with the highest 10-year NPV and the shortest payback period (PBP). In contrast, seed-only supply chains were more profitable for processors and posed economic challenges for farmers due to lower returns and longer PBPs. Socially, the leaf-only supply chain outperformed leaf-and-seed and seed-only supply chains, particularly in terms of membership in moringa farmer organizations, access to services, and alternative sources of income. These social benefits are critical for enhancing smallholder resilience and offer a promising model for other supply chains to replicate, as they contribute to increased revenue, better food security, and increased access to resources. Our analysis highlights the need for smallholder farmers to organize and form groups to replicate these social benefits across other supply chains.

Our findings demonstrate the additional insights provided from the integration of environmental, economic, and social dimensions in sustainability assessments on multifunctional crops. We recommend improving farm-gate collection efficiency, enhancing market access, and strengthening farmer organizations as targeted measures for advancing the sustainability of moringa. Our results apply to other multifunctional crops since many of the sustainability hotspots identified are present in other agri-food supply chains reliant on smallholder farmers. Establishing and strengthening moringa farmer-based organizations is a key leverage point in this sustainability assessment since it can improve coordination among farmers for seed collection, help access markets, and facilitate access to resources such as farming inputs and training. These findings can only be revealed with a holistic approach and exhibit the importance of developing interventions that avoid shifting sustainability burdens.

This study also identified several potential avenues for advancing LCSA applications in smallholder-driven agri-food systems. While selecting economic value as a functional unit was appropriate for this study, future research could further explore its implications in LCSA on agri-food systems, particularly regarding price fluctuations and their potential interactions across different sustainability dimensions. Moreover, methodologies that capture interactions among variables could enhance the interpretability of LCSA results, particularly in SLCA, where smallholder indicators interact in complex ways. Consequently, future studies might apply econometric methods to identify causal relationships alongside conducting uncertainty analyses for SLCA results. Additionally, analyzing panel data on social indicators could offer deeper insights into the temporal aspects of social sustainability. Incorporating additional well-being indicators, such as Food Consumption Scores and total monthly household expenditure per capita, into the SLCA framework could provide a more comprehensive understanding of social impacts. Finally, future research on the organizational structure and dynamics of farmer-based groups in SLCA is also recommended, as it is pertinent to advancing sustainability in smallholder dominated agri-food supply chains.

In conclusion, this research makes notable contributions to sustainability assessments by conducting a new LCSA case study on a multifunctional crop, adopting economic value as a functional unit, focusing on the smallholder perspective, and introducing new well-being indicators to the SLCA framework. Each of these contributions can enhance aspects of LCSA when evaluating the sustainability of multifunctional smallholder farming systems. Integrating the Characteristic Object Method (COMET) with LCSA for the first time was another salient feature of our analysis. Future studies can build on these findings to develop more comprehensive sustainability metrics and strategies, supporting global efforts to create more resilient, sustainable, and equitable agri-food supply chains.

CRediT authorship contribution statement

Yoel Gebrai: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gideon Danso-Abbeam:** Writing – review & editing, Supervision, Methodology. **Kebreab Ghebremichael:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **James R. Mihelcic:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.10.017.

Data availability

The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information files.

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