Sustainable Production and Consumption 56 (2025) 343–363

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Life cycle sustainability assessment of staple food processing: A double and dynamic materiality approach☆

Mwewa Chikonkolo Mwape[a,*], Aditya Parmar[b,e], Franz Roman[a], Naushad M. Emmambux[c], Yaovi Ouézou Azouma[d,1], Oliver Hensel[a]

[a] *Department of Agricultural and Biosystems Engineering, University of Kassel, Nordbahnhoftstraße 1a, Witzenhausen 37213, Germany*
[b] *Faculty of Engineering & Science, Natural Resources Institute, Food and Markets Department, University of Greenwich, ME4 4TB, UK*
[c] *Department of Consumer and Food Sciences, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa*
[d] *Ecole Supérieure d'Agronomie, Université de Lomé, Lomé BP 1515, Togo*
[e] *International Center for Living Aquatic Resources Management (ICLARM-WorldFish), Penang, Malaysia*

ARTICLE INFO

Editor: Alejandro Gallego Schmid

Keywords:
LCSA
Staple foods
Double materiality
Dynamic materiality
MEFA
Global warming potential (GWP)
Python modeling
ESG

ABSTRACT

Globally, 70 % of people are fed through peasant food systems that are responsible for growing 50 % of the world's food calories on 30 % of the land. In the global south, particularly in Sub-Saharan Africa, small-scale farming serves as a crucial lifeline for the food and income needs of local populations. Yet, it remains under-funded and under-researched in the context of sustainable development. Even if the traditional Life Cycle Sustainability Assessment offers a holistic approach to evaluating the impacts of staple food processing across environmental, economic, and social dimensions, its inability to track dynamic materiality limits its application in evaluating future impacts. Therefore, this study aimed to provide a comprehensive Life Cycle Sustainability Assessment framework for staple food processing, using cassava to produce gari, a staple food for more than 300 million West Africans, as a case study. This framework integrates Material and Energy Flow Analysis techniques to trace resource use and emissions. The research incorporated Environmental, Social and Governance pillars; double materiality, evaluating both the direct and indirect impacts of processing activities, alongside dynamic materiality to capture evolving environmental, financial, and social factors through scenarios. Python computational modeling was used to perform these complex analyses, ensuring accuracy and adaptability. The findings highlight significant energy inefficiencies (6.67 kWh kg^{-1}) coupled with a high Global Warming Potential (GWP) of 9.02 $kgCO_2eq$ kg^{-1} and production costs of \$0.56 kg^{-1}. The most significant opportunities for improvement were identified in optimizing energy consumption and transforming waste into biogas. The dynamic model revealed that integrating renewable energy sources could substantially reduce environmental impacts and increase the Net Profit Margin from 34.43 to 52.52 %, as proposed in the energy transition from woodfuel and gasoline to a Hybrid Solar and Biogas energy system. This study contributes to the growing body of literature on Life Cycle Sustainability Assessment by applying a comprehensive framework to staple food processing. The findings offer valuable insights into the environmental, social, and economic trade-offs in food processing systems, providing practical recommendations for improving sustainability throughout the food supply chain. Extended studies using these methods on other staples are highly recommended.

1. Introduction

At the expense of 30 % of global greenhouse gas emissions (GhG), the agricultural sector uses 24.5 million cubic kilometres of water (70 % of fresh water) and 59.2 million square kilometres of land (40 % of total land) to produce food (Oksana and Dmytro, 2021; Wei et al., 2024). In 2023, however, over 735 million people went hungry, even as 14 % of the food (worth \$400 billion) was lost before reaching the markets, and another 17 % was wasted in households and markets due to post-harvest wastage and dietary habits, further deepening the global food insecurity

---

☆ This article is part of a Special issue entitled: 'CBE and Global South' published in Sustainable Production and Consumption.

* Corresponding author.

E-mail address: chikonkolo@uni-kassel.de (M.C. Mwape).

[1] Deceased.

https://doi.org/10.1016/j.spc.2025.04.002
Received 12 November 2024; Received in revised form 31 March 2025; Accepted 2 April 2025

(FAO, 2023; FAO, IFAD, UNICEF, WFP, 2024). Additionally, the projected 9 billion people on the planet by 2050 will need 60 % more food (Chaplinsky, 2012).

To meet global food demand sustainably, methods of sustainable agriculture are necessary for ensuring a safe and secure food supply chain that does not exceed the planet's natural resource capacity. The concept of sustainable agriculture has been studied for several decades, as different societies increasingly understand the finite supply of our natural resources for promoting development (Wei et al., 2024). It has been highlighted that achieving global Sustainable Development Goals (SDGs) and preventing catastrophic climate change require a rapid shift to sustainable food systems and healthy diets. However, in order to transition the global food system toward sustainability, challenges must be addressed, as well as putting in place comprehensive, scientifically verified interventions across all food systems at the planetary scale to serve as substantial climate change deterrent tools (Rockström et al., 2020).

In the context of sustainable development, small to medium-scale food systems, which produce half of the world's food calories, remain underfunded and understudied, despite being responsible for feeding over 70 % of the world's population. This is particularly true in the global south, especially in Sub-Saharan Africa, where small-scale farming is essential to providing local populations with much-needed food and income (Dhillon and Moncur, 2023).

Therefore, building climate resilience in these smallholder-managed agricultural systems and promoting the broad adoption of innovative farming practices, such as post-harvest waste reduction innovations, is critical to efforts to develop rural economies, ensure nutrition and quality food security, and eradicate rural poverty. At harvest, most staples in developing countries such as cassava roots, deteriorate quickly due to high moisture content and need to be dehydrated sustainably (shelf life of 1-2 days) (Kashala-Abotnes et al., 2019).

However, building sustainability and resilience requires numerous interventions, such as increasing the amount of climate financing packages available to developing nations from the current 1.7 % global average, as well as promoting research for the implementation of sustainable innovations (UNSDG, 2023). The lack of credible data jeopardizes sustainable innovation development and climate financing, mostly in developing countries. Accurate operation status (including material and energy flows), financial data, and evaluation of environmental, social, and governance impacts, along with honest reporting, are crucial for making sound decisions and allocating resources effectively. Without them, it is difficult to track and report success, attract investment, and ensure accountability. This data gap exacerbates the discrepancy between adoption and innovations development (Grinspan and Worker, 2021; UNEP, 2024). Addressing these sustainability data challenges is crucial for enhancing trust, developing innovative and efficient technologies and their governing policies, improving the efficacy of climate finance, and meeting global climate and SDG targets (Fanzo et al., 2021; Schneider et al., 2023).

Given the current circumstances, it is essential to thoroughly analyze the agricultural processes using cradle-to-grave methods, covering every phase from farming to final preparation for consumption. One practical approach is to implement the Life Cycle Sustainability Assessment (LCSA), which integrates environmental, economic, and social pillars of sustainability. This assessment evaluates a product's Environmental, Social, and Economic Impacts (ESEI) at every stage of its lifecycle, encompassing raw material extraction, processing, manufacturing, distribution, consumption, and disposal or recycling. Decision-makers can compare two processes or goods using LCSA and select the one with the least adverse environmental impact (R. Kumar et al., 2023). Fig. 1 highlights the LCSA framework along with all the techniques (flows) based on the International Organization for Standardization (ISO) 14040 (ISO, 2023; Olalekan et al., 2023; Voglhuber-Slavinsky et al., 2022).

Building on the aforementioned concerns, this study emphasizes the application of LCSA as a foundational framework, with a specific focus on the need for comprehensive sustainability assessments in agricultural production. Although LCSA provides a solid foundation for assessing the economic, social, and environmental effects, the governance pillar is omitted from its traditional framework, which limits its ability to adequately represent the dynamic interaction of these elements. The effectiveness of LCSA in evaluating sustainability has been demonstrated in several studies; however, it often overlooks comprehensive resource flow analysis and the dynamic nature of environmental, social, and governance materiality (ESG), as well as the consequences of technology. Furthermore, other researchers have highlighted methodological issues in evaluating the LCSA of the development and adoption of new technologies in the context of changing climate policy (Djekic et al., 2019; Padilla-Rivera et al., 2023).

To create a more comprehensive sustainability assessment framework for the food processing industry, the aforementioned LCSA drawbacks highlight the potential benefits of combining additional strategies, such as Material and Energy Flow Analysis (MEFA) and the Python script-automated ESG frameworks, including double and dynamic materiality. This would highlight the following; process costs, material flow analysis per process (stage), energy demand/source at each stage, human to equipment interaction, raw materials/final products market price/demand dynamics, ESG inward and outward impacts, the impacts of renewable energy-based technological innovation advancements, and

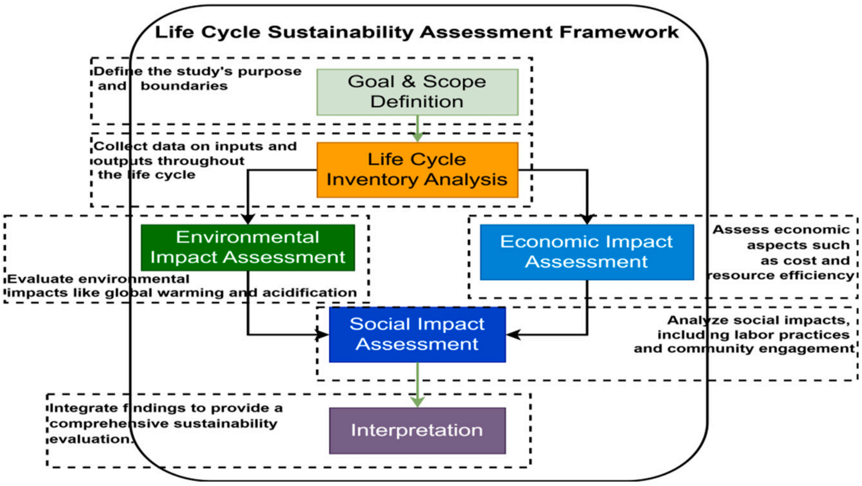


Fig. 1. Life Cycle Sustainability Assessment framework based on (ISO, 2023).

waste recycling (Circularity).

To test the adaptability of the proposed framework, a case study was conducted on the processing of cassava from the farm to the final product (gari). The literature review that follows highlights significant gaps, critically evaluates earlier studies on LCSA and related approaches, and lays the groundwork for the integrated model that is proposed and applied in this work.

2. Literature review

Vulnerability to climate change which is said to be a question of Diversity, Equality, and Inclusion (DEI), because the rich in societies who are responsible for the most greenhouse gases are often less vulnerable to its consequences which are severe in the Global South, is influenced by a complex web of interrelated ESG elements. As a result, reliable information regarding the sustainability status of a process, product, or organization is more crucial than ever for making informed decisions or forming informed opinions.

The LCSA, which encompasses environmental, economic, and social dimensions, has emerged as a comprehensive framework for evaluating and reporting the overall sustainability of diverse systems, including agricultural practices. It employs extensive farm processes to assess the entirety of impacts, spanning from the extraction and cultivation of raw materials to processing, distribution, and ultimate waste management (Alejandrino et al., 2021; Schau and Alberto-Quintana, 2024). Using LCSA, researchers can evaluate and report labor/social conditions, GhG, resource inefficiencies, and economic viability throughout the supply chain. By taking a comprehensive approach, decision-makers can evaluate various production methods and implement strategies that could enhance sustainability while meeting not only food demands but also quality standards outlined by Quality Management Systems (QMS), which are essential for supporting the growing global population (Jungbluth et al., 2018; Siva et al., 2016).

Various authors have, however, asserted that traditional, linear methods of evaluating and reporting food systems are inadequate for identifying, reporting, and resolving the complex, interconnected material issues of modern food production, consumption, and sustainability policy requirements. For example, in their systematic review of 71 publications applying LCSA in the agro-food sector, Matos et al. (2024) found that Life Cycle Assessment (LCA) was the most frequently used tool, with limited applications of Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA), emphasizing environmental impact assessments. In addition, Cucurachi et al. (2019) thoroughly reviewed of LCA techniques applied in food systems, highlighting the intricacy of food supply chains and their effects on the environment worldwide. The efficiency of the LCA methodology in evaluating environmental impacts across the production, distribution, and consumption stages was methodically described. Nevertheless, the study pays little attention to the economic and social aspects. In a related study, the standardized ISO 14040/14044 LCA has been further applied to evaluate the sustainability status of food processing from the perspective of agricultural practices, packaging materials, and food wastes. The research provided insights into the environmental performance of food technologies, neglecting the economic, social, and governance impacts (IBP, 2025). Similarly, (LCA) is used by the Sustainable Food Processing Group at ETH Zurich to assess and reduce the environmental impact of food production, focusing on factors such as water use, greenhouse gas emissions, and energy efficiency. To further integrate sustainability and nutrition, they developed Nutritional Life Cycle Assessment (N-LCA), which evaluates the environmental and nutritional impacts of food systems across different regions. However, while N-LCA provides valuable insights, it does not comprehensively address social and economic sustainability aspects, such as governance, labor conditions, affordability, and community well-being, which are essential for a holistic sustainability assessment (ETH, 2025).

To address food system challenges, Moores et al. (2024) proposed a framework rooted in circularity, sustainability, and ecosystems concepts, aiming to guide innovation using LCA, S-LCA, and LCC (ISO 14044) protocols. They evaluated the Sustainable Nutrition Security and Food System Sustainable frameworks for environmental and social assessments at the product level, examining seven foods produced in Norway. Both frameworks provided comprehensive sustainability assessments but struggled to distinguish between social and ethical issues due to data limitations. Easier-to-use frameworks often sacrificed depth and comprehensiveness (Bhérer-Breton et al., 2025).

In contrast to its position as a staple crop in Sub-Saharan Africa, research on cassava farming and its value chain has concentrated primarily on its industrial applications, such as the production of ethanol and starch. For regional food security, particularly in West Africa, cassava plays a crucial role (Mwape et al., 2025). However, due to the scarcity of studies on these subjects, sustainability assessments often overlook the impacts of household consumption, traditional processing techniques, smallholder livelihoods, and food security on the environment, society, and economy. For example, investigations into circular economy techniques reveal the potential for waste valorization; however, traditional studies indicate that the production of gari from cassava is associated with high energy consumption and emissions, highlighting a significant gap (Mwape et al., 2025). At the same time, LCSA has been used to evaluate the environmental, economic, and social impacts of cassava, often as static snapshots. Studies have focused on the effects of climate change on cassava yields and food security. For example, a survey on the valorization of root and tuber crop wastes found that a cassava starch factory could save approximately 124 t of carbon dioxide (tCO_2) per year by recovering waste heat energy, highlighting the significance of energy, emissions, and costs in production (Aguilar-Rivera, 2024). Similarly, in Guangxi, China, a study on the manufacture of cassava ethanol evaluated environmental emissions from several fermentation techniques using survey data and LCA-based simulations (Zhan et al., 2022). It examined how alcohol production affected emissions and energy consumption, emphasizing the importance of integrating modeling and plant data to identify ways to reduce energy consumption and mitigate environmental impacts. The study highlights the potential for reducing carbon emissions and conserving energy, and suggests that future research should encompass all pillars of LCSA for cassava processing at both commercial and traditional/household stages.

Another noteworthy study examined the environmental effects of cassava flour production in Southwestern Nigeria. The study focused on major impact categories, including global warming potential and eutrophication. This study provided valuable insights into the environmental impact of cassava flour manufacturing, highlighting areas for improvement in energy and resource utilization. However, it focused exclusively on environmental concerns, with little investigation of the economic and social elements (Olaniran et al., 2017).

Cassava processing technologies have been extensively investigated, with a focus on sustainability and efficiency. Research on starch extraction has stressed environmental and energy issues while ignoring social and economic factors (Hansupalak et al., 2016; Tran et al., 2012). The Cassava Processing Technology Toolkit assessed both conventional and modern approaches, but it did not include emerging technologies or LCA-based impacts comparisons (Taat, 2024). Despite increasing energy efficiency by 10-15 % through the optimization of cassava flour production with a modified flash dryer, 49 % of enterprises abandoned the practice due to high operational costs, underscoring the risks of overlooking the impact of the dynamic financial risk on adoption (Tran et al., 2022).

Regarding the financial and cultural dimensions, studies from LCSA have frequently concentrated on specific factors, often overlooking others. For example, Nimoh et al. (2020) reported profit margin of 22 % in the cassava business, specifically transitioning from fresh cassava to processed gari. In contrast, Nnaji and Akanno (2022) highlighted the environmental impact of cassava effluent on the soil quality. This includes significant concentrations of pollutants, such as hydrogen cyanide and heavy metals, that surpass permissible discharge thresholds. The processing methods of cassava exhibit considerable variability based on cultural and ethnic preferences, which poses challenges to the widespread adoption of uniform nutrient rich cassava varieties and innovative processing techniques and equipment. For example, in Africa, traditional methods entail sophisticated skills passed down through generations and are firmly embedded in cultural customs (Hahn, 2023). This affects productivity, quality, market acceptance, and the long-term viability of gari production (Bechoff et al., 2019; Ezeocha et al., 2019).

The comprehensive review's key findings emphasize the increasing application of LCSA in agricultural processing. However, there is a notable imbalance as most studies target only one pillar (environmental, economic, or social) and overlook the others. There is limited integration of policy frameworks with social, economic, and governance factors, and few studies evaluate the full farm-to-product lifecycle of staple foods, such as gari.

Research on emerging processing technologies such as renewable energy-powered cookstoves, reengineered flash dryers, and biorefineries often overlooks their long-term sustainability. Comparisons between processing stages are also rare. Additionally, traditional staple food processing for household consumption, particularly for cassava, maize, and rice in the Global South, is often overlooked in favour of industrial applications such as ethanol, starch, and animal feed production. The failure to consider raw material and market price dynamics further weakens long-term sustainability predictions.

Key sustainability aspects, such as health and food safety (SDG 3), gender equality in processing (SDG 5), poverty reduction (SDG 1), industrial innovation (SDG 9), and the impact of modernization on employment (SDG 8), are often overlooked. Without comprehensive sustainability evaluations, staple food processing struggles to access green finance mechanisms, such as green bonds and ESG-linked investments. Smallholder enterprises remain undervalued in sustainability markets due to a lack of solid data on profit margins, returns on investment, and input/output efficiency. Furthermore, weak institutional support and governance (SDG 16) hinder policy-driven progress in sustainable staple food processing.

Another significant drawback in LCSA is the absence of MEFA and QMS across processing stages. MEFA provides a systematic approach to quantifying input-output linkages, identifying efficiency gaps, and revealing environmental trade-offs. Integrating MEFA and LCSA can improve sustainability assessments for material, energy, and waste-intensive operations like cassava drying and milling, in line with circular economy concepts (Laner and Rechberger, 2016; Taulo and Sebitosi, 2016). Conformity to quality standards and traceability can be enhanced throughout the MEFA by integrating a QMS within the MEFA. Internet of Things (IoT) based approaches have been found to have a significant positive impact on supply chain transparency and quality management (Verna et al., 2024).

Furthermore, traditional LCSA techniques often overlook double and dynamic materiality. Double materiality is a concept in sustainability and financial reporting that considers both the economic impacts of ESG issues on a system and the system's impacts on the environment and society. Identifying the specific ESG issues of a process or organization through stakeholder engagement and a thorough understanding is critical for successfully conducting the double materiality. The evaluation of the financial and environmental materiality of the issues on the system and the systems operations impacts on the environment and society involves analysing the risks and opportunities (Baumüller and Sopp, 2022; Gourdel et al., 2024; Svensson, 2024) This viewpoint is crucial for staple food processing, because sustainability assessments must evaluate economic viability and risks, labor circumstances, and changing climate change/sustainability frameworks. Dynamic materiality, which examines how sustainability concerns evolve over time, is crucial for understanding market fluctuations, regulatory changes, and socio-techno-economic shifts. It acknowledges that ESG issues can develop and become financially significant as circumstances change. This concept emphasizes the risk of present non-issues turning critical in the future due to shifts in legislation, technology, labor, market upheavals, energy sources, climatic conditions, seasons, or changing stakeholder expectations. Triggers and trends, such as new registrations, scientific innovations, climatic conditions, or societal shifts, can increase the prominence of specific ESG issues; thus, firms must remain forward-thinking by implementing relevant and proactive policies (Arias et al., 2024). Without this methodology, assessments fail to capture long-term industry resilience. Integrating these principles into LCSA can help bridge the gap between research and real-world investment decisions, promoting green bonds, ESG-linked investments, identifying current and future business and technology risks, and facilitating climate adaptation in line with the COP 29 green bond financing regulations.

Traditional LCSAs rely on static datasets and generic effect variables, which reduce prediction accuracy. Python-based computational tools can help improve LCSA models by incorporating real-time market data, regulatory changes, and environmental trends (Sánchez-Gendriz et al., 2025). Python can model MEFA for various processing technologies, run simulations to evaluate sustainability uncertainties, optimize energy efficiency for staple food processing under different policy scenarios, and compare traditional vs. modernized processing systems for economic viability. Python, for example, can simulate cassava processing efficiency under varied energy sources and conditions, and examine employment shifts related to modernization. Such computer tools increase the depth and accuracy of sustainability assessments (Mwape et al., 2025; Sun et al., 2025).

Therefore, the purpose of this study was to fill these gaps and enhance knowledge of staple food sustainability assessment by integrating LCSA with MEFA, incorporating double and dynamic materiality, and utilizing Python computational tools for data automation, analysis, simulation, and visualization. The goal was to identify opportunities for enhancing energy and material efficiency, thereby reducing the negative environmental, social, and economic impacts. Unlike traditional LCSA studies, which often focus on static environmental impacts, this novel approach enabled real-time scenario modeling, dynamic and double materiality risk assessment, and alignment with global sustainability targets (SDGs 1, 3, 5, 8, 9, 10, 12, 13, 16, and 17) and reporting. This was accomplished through a case study of cassava processing into gari (granulated and roasted cassava) at three cooperative facilities in Togo, from harvesting to ready-to-eat product (market). To achieve the stated aims, the following research questions were addressed;

1. Life cycle and sustainability impacts

- What are the key environmental, economic, and social impacts of staple food processing across its life cycle?
- How can LCSA be effectively applied to evaluate the entire supply chain of staple food products?

2. Material and energy flow analysis

- What are the primary sources of material and energy inefficiencies in staple food processing systems?
- How does the integration of MEFA and QMS with LCSA facilitate the identifying of opportunities for enhancing resource efficiency?

3. Double and dynamic materiality

- How does the concept of double materiality, which considers both direct and indirect impacts, enhance the assessment of sustainability in staple food processing?
- How can dynamic materiality be applied to adopt the LCSA model to reflect changing environmental, technological, policy, and social factors over time?

4. Computational modeling with Python

- How can Python and machine learning-based computational modeling improve the accuracy and scalability of sustainability assessments in staple food processing?
- What advantages does Python offer in simulating scenarios and optimizing resource flows in food processing systems?

5. Policy and practical implications

- What insights can be derived from the integrated LCSA model to inform policy and improve sustainability practices in the staple food industry?
- How can the results guide stakeholders (producers, processors, policymakers) in adopting more sustainable practices?

The methodology and materials used in Section 3 were developed based on the literature review presented in Section 2, which highlights the research gaps addressed in this study. In Section 4, the results obtained are discussed, and conclusions and recommendations are provided in Section 5.

3. Methods

The three partner facilities under observation provided the materials used in this investigation. These included cookstoves, fresh cassava, water, wood fuel, and tools (such as knives, hoes, and other processing equipment). All materials used were quantified using the procedures outlined below and in Appendix A in the supplementary materials. All materials and energy flows (wood fuel) were weighed before and after each successive process using weighing scales, and temperatures were captured using the data loggers.

3.1. Description of the study area

The study was conducted in collaboration with cooperative partners via the University of Lome in Ganave (Yoto Prefecture), Vogan (Vo Prefecture), and Topko in the Lacs Prefecture of the Maritime region in Togo, as highlighted in Fig. 2. The primary focus was on the traditional cassava-to-gari production at the small-scale cooperative stage, which is prevalent in Togo. The processing stages analyzed include harvesting, transportation, peeling, washing, grating, fermentation, de-watering, sieving, roasting, sieving and grading, and finally packaging (Abass et al., 2012; Agricdemy, 2022; Ajewole and Adeosun, 2018; Ajibola et al., 1987; Jekayinfa and Olajide, 2007).

3.2. Application of LCSA in cassava to gari process sustainability analysis

The LCSA saved as the foundation, guiding the use of MEFA, materiality assessment, and scenario analysis (Padilla-Rivera et al., 2023). To fully integrate MEFA in the LCSA, this study employed the field-based mixed research methods applying quantitative measurements, observational data, and survey responses (Kurtaliqi et al., 2024; Pérez Bentancur and Tiscornia, 2024; Polisetty et al., 2024). The quality of the materials at each stage was measured using the physicochemical analysis, as highlighted by (Mwape et al., 2023b).

Double Materiality was employed to assess the financial and environmental impacts on the facilities and society. Dynamic Materiality was used to analyze the potential dynamic changes that could accompany the energy transition from gasoline and woodfuel to solar PV and biogas produced from process wastes (biomass and effluents). Calculations were automated using Python to process the data rapidly and facilitate flexible analysis for materiality outcomes. Fig. 3 highlights the conceptual framework for integrating MEFA, QMS, double and dynamic materiality into LCSA.

Key metrics, including GWP, financial, and health effects on humans (primarily on women and children), as well as social consequences, are among the outputs from these assessments that are visualized to aid in

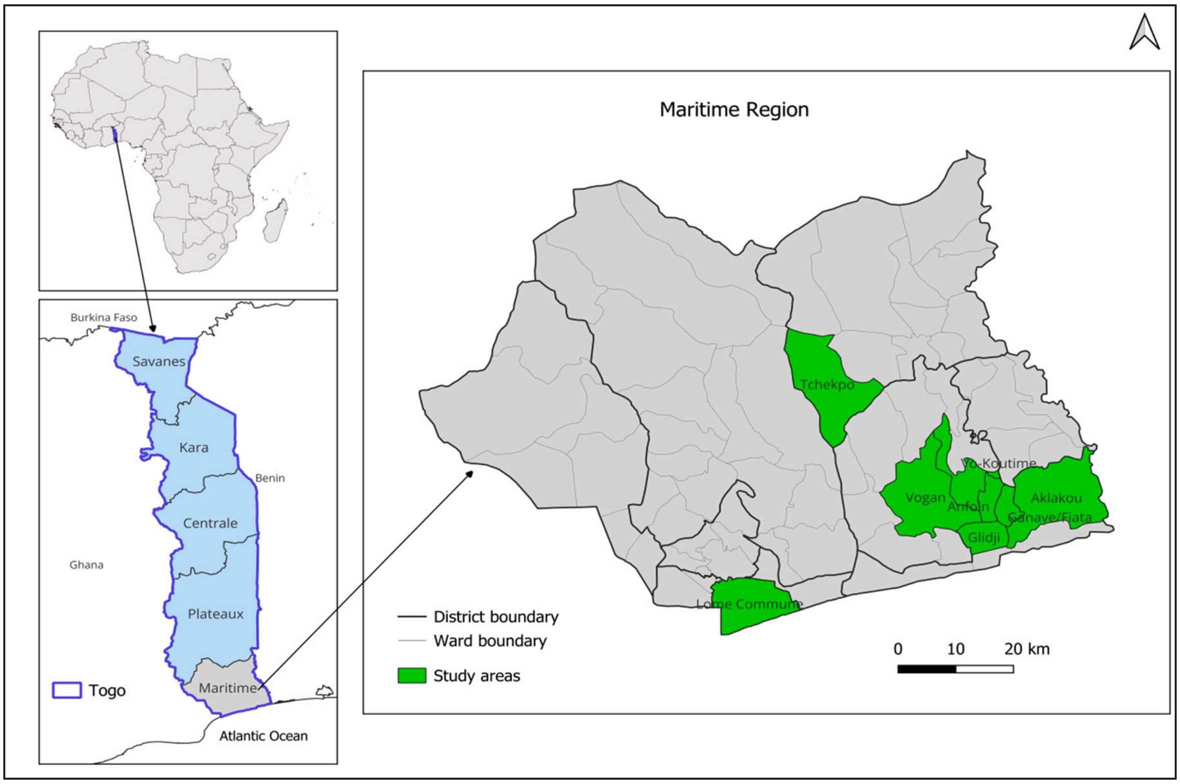


Fig. 2. Location of the study: Maritime region, Togo, West Africa (by Gebremeskel, Haftom Hagos).

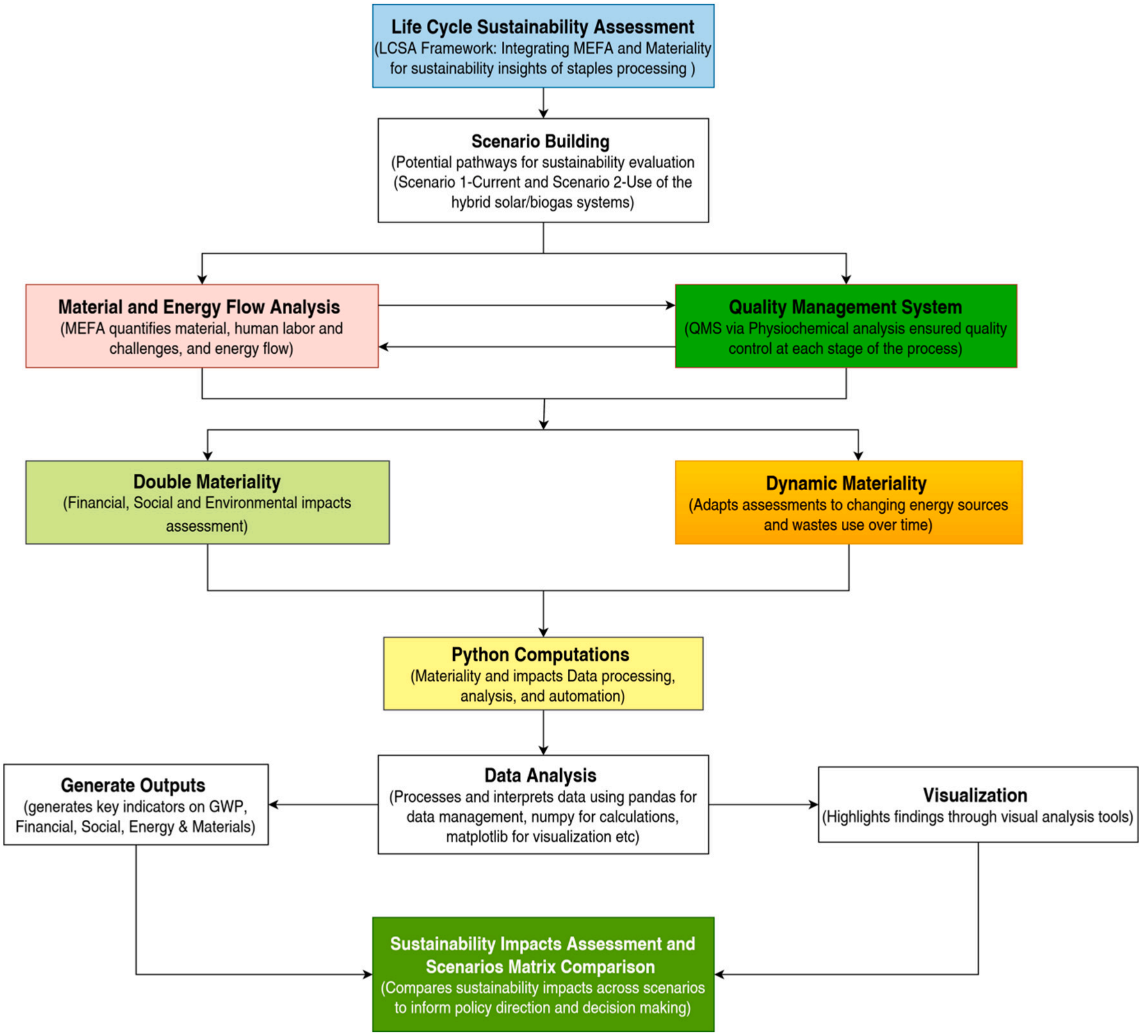


Fig. 3. Conceptual framework for integrating Material and Energy Flow Analysis/Quality Management System (QMS) (MEFA/QMS), dynamic materiality, and double materiality in Life Cycle Sustainability Analysis (LCSA).

comprehension and decision-making. This integrated approach provides a comprehensive evaluation of current and future dynamic sustainability consequences, enabling scenario comparison and informed decision-making.

In order to facilitate comprehensive data correction and analysis, a mixed-methods research approach was adopted. Qualitative data were gathered through structured questionnaires, detailed in Supplementary Materials S1 (LCSA/MEFA FORM 1-from harvesting to packaging), S2 (LCSA/MEFA FORM 2 at Roasting stage), and S3 (LCSA/MEFA FORM 3: Market-Place- prices). These instruments helped in capturing the narrative insights on operational procecesses, material usage, and social, economic, health and governance factors. Concurrently, quantitative data including material and energy weights, spatial dimensions, energy consumption, temperature regimes and time-were recorded using calibrated instruments and data loggers. The data were initially recorded in Excel and subsequently automated via Python to enhance efficiency and accuracy. This integrated approach improves the reliability of the findings and provided a holistic view of the research.

Appendix A (S4) provides a comprehensive methodology, explicitly detailing all the mathematical calculations considered when automating in Python.

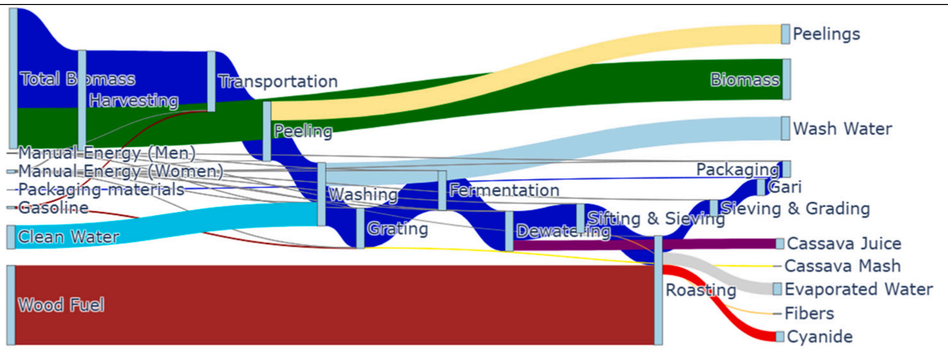
4. Results and discussions

4.1. Overview of material, energy, and emission flows

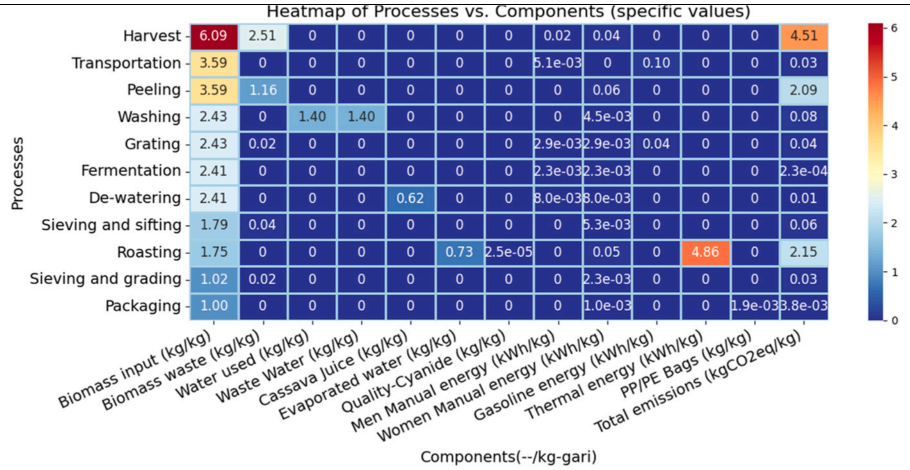
The MEFA of the cassava to gari processing system reviews different patterns in material throughput, energy consumption, and waste/emission generation at each stage. The Sankey diagram (Fig. 4(a), based on Script 2) depicts the system's numerous stages, each of which contributes to the overall energy requirement, material transformation, and adverse environmental impacts.

This data takes into consideration all inputs and outputs to produce 1 kg of gari from cassava. Table S1 in the supplementary materials (S5) displays the aggregated data from the three facilities. The materials, energy, human hours, and productivity recorded in this study are within the reported figures by other researchers (Bouniol et al., 2024, 2020).

The heatmap in Fig. 4(b) and (c) (script 3) highlights the exact stage-wise breakdown of specific resources spent to produce a kg of gari (-/kg-gari) quantitatively. During the initial harvesting step, considerable amounts of biomass waste were generated, primarily in the form of cassava residual plant matter left in the field. When organic wastes decompose, they produce significant volumes of CO_2eq, contributing to the overall carbon footprint of the system. Other researchers suggest that uncontrolled biomass decomposition from agricultural residue can release up to 30-50 % of their carbon content as CO_2, contributing significantly to agricultural production-related GWP, highlighting the

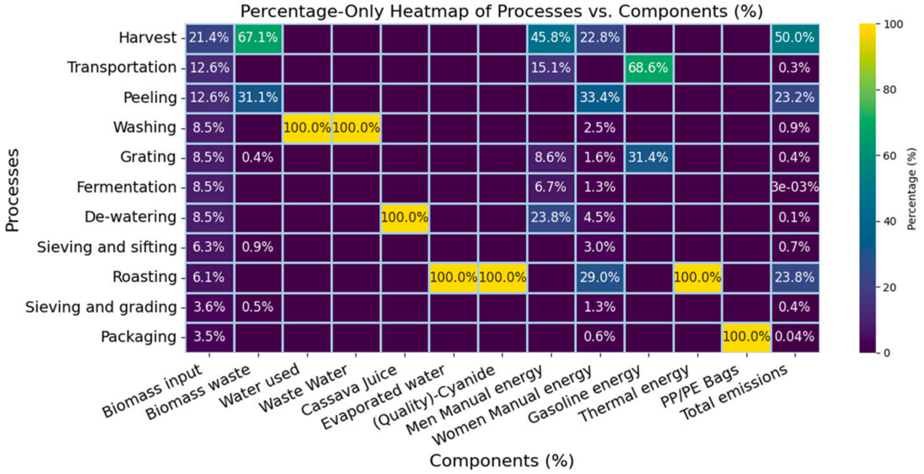


(a) Cassava to gari Material and energy flow sankey diagram



Processes	Biomass input (kg/kg)	Biomass waste (kg/kg)	Water used (kg/kg)	Waste Water (kg/kg)	Cassava Juice (kg/kg)	Evaporated water (kg/kg)	Quality-Cyanide (kg/kg)	Men Manual energy (kWh/kg)	Women Manual energy (kWh/kg)	Gasoline energy (kWh/kg)	Thermal energy (kWh/kg)	PP/PE Bags (kg/kg)	Total emissions (kgCO2eq/kg)
Harvest	6.09	2.51	0	0	0	0	0	0.02	0.04	0	0	0	4.51
Transportation	3.59	0	0	0	0	0	0	5.1e-03	0	0.10	0	0	0.03
Peeling	3.59	1.16	0	0	0	0	0	0	0.06	0	0	0	2.09
Washing	2.43	0	1.40	1.40	0	0	0	0	4.5e-03	0	0	0	0.08
Grating	2.43	0.02	0	0	0	0	0	2.9e-03	2.9e-03	0.04	0	0	0.04
Fermentation	2.41	0	0	0	0	0	0	2.3e-03	2.3e-03	0	0	0	2.3e-04
De-watering	2.41	0	0	0	0.62	0	0	8.0e-03	8.0e-03	0	0	0	0.01
Sieving and sifting	1.79	0.04	0	0	0	0	0	0	5.3e-03	0	0	0	0.06
Roasting	1.75	0	0	0	0	0.73	2.5e-05	0	0.05	0	4.86	0	2.15
Sieving and grading	1.02	0.02	0	0	0	0	0	0	2.3e-03	0	0	0	0.03
Packaging	1.00	0	0	0	0	0	0	0	1.0e-03	0	0	1.9e-03	3.8e-03

(b) Cassava to gari Material and energy flow heatmap-Specific materials based



Processes	Biomass input	Biomass waste	Water used	Waste Water	Cassava Juice	Evaporated water	(Quality)-Cyanide	Men Manual energy	Women Manual energy	Gasoline energy	Thermal energy	PP/PE Bags	Total emissions
Harvest	21.4%	67.1%						45.8%	22.8%				50.0%
Transportation	12.6%							15.1%		68.6%			0.3%
Peeling	12.6%	31.1%							33.4%				23.2%
Washing	8.5%		100.0%	100.0%					2.5%				0.9%
Grating	8.5%	0.4%						8.6%	1.6%	31.4%			0.4%
Fermentation	8.5%							6.7%	1.3%				3e-03%
De-watering	8.5%				100.0%			23.8%	4.5%				0.1%
Sieving and sifting	6.3%	0.9%							3.0%				0.7%
Roasting	6.1%					100.0%	100.0%		29.0%		100.0%		23.8%
Sieving and grading	3.6%	0.5%							1.3%				0.4%
Packaging	3.5%								0.6%			100.0%	0.04%

(c) Cassava to gari Material and energy flow heatmap-% Specific materials based

Fig. 4. MEFA visualization: (a) Material and energy flow sankey diagram, (b) Material energy flow heatmap (specific values based) and Material energy flow heatmap (specific values in %).

repercussions for the environment and the economy (Kinne et al., 2018; Phiri et al., 2024; Shah et al., 2023). In order to carry out the Life cycle Sustainability Assessment of production processes of staple foods conclusively, it is strongly advised to use thorough and schematic methodologies that include all levels of Material and Energy Flow (MEF) (Visentin et al., 2020).

Peeling and washing processes generate additional material losses, particularly in the form of biomass waste (peels) and wastewater resulting from the use of water for washing. The peeling stage alone generated nearly 31 % of the system's total biomass waste. The careful handling of these peels, which contain residual cyanide, is crucial for both environmental and food safety. Similarly, if wastewater is not properly treated before release, it may pose an environmental risk.

Roasting was found to be the most energy-intensive step. Cassava mash was roasted to an average temperature of 142 °C. The necessity to remove water from the cassava to achieve the appropriate moisture content for storage drives the energy usage during this phase. This water loss helps remove the cyanide, which evaporates at certain temperatures, in addition to being essential for drying. This stage is essential for guaranteeing the quality and safety of the finished product, as cassava naturally contains substances that can cause cyanogenesis. Other studies conducted have demonstrated that roasting or cooking cassava at temperatures higher than 100 °C can considerably lower the amount of cyanide present (Bradbury et al., 2005; Mwape et al., 2023b). This highlights the importance of integrating the QMS at every stage in the MEFA as also concluded by other researchers in the metal processing industries (Li et al., 2022). The amount of thermal energy required for the roasting process is a significant factor in the system's energy consumption and CO_2 emissions. At this point, using conventional cookstoves that burn biomass inefficiently increases emissions and raises the carbon footprint (Hayyat et al., 2024).

Conversely, processes such as grating, dewatering, sifting, and sieving depend more on manual labor and mechanical power. Although these stages use less energy than roasting, they nevertheless increase overall energy consumption, particularly in regions where manual labor and simple mechanical devices are commonly employed. The procedures, as will be explained below, are both labor-intensive and labor-insensitive.

There is a substantial correlation between the system's energy consumption and emissions profile. The need for greener energy sources is underscored by the fact that CO2 emissions are most pronounced during processes that require significant energy, such as roasting and harvesting. High energy-consuming processes are also high emitters and costly (Huang and Ren, 2024). Energy consumption and emissions/the carbon footprint of most of the staple food production, may be decreased by integrating other renewable energy sources, such as solar energy for

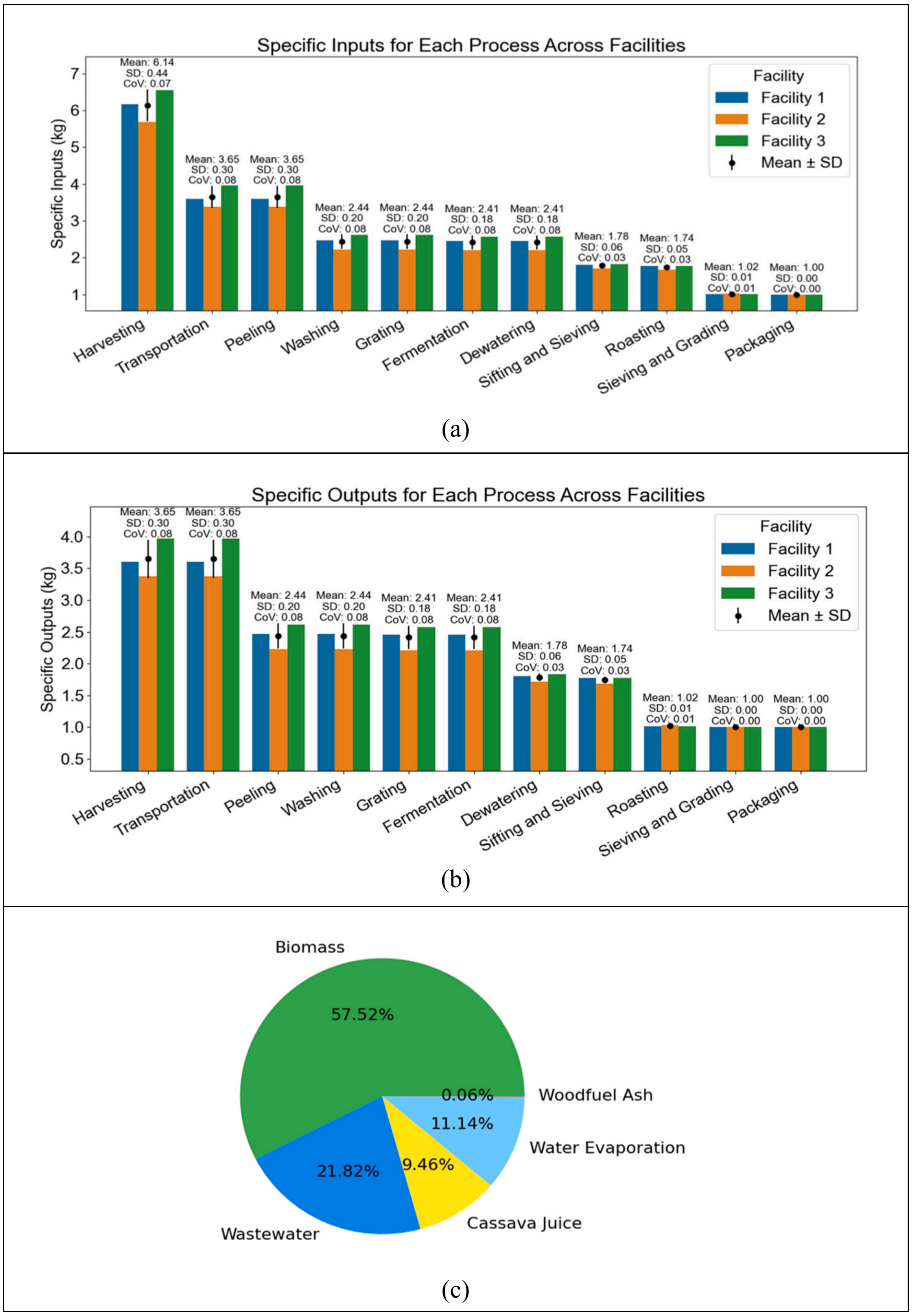


Fig. 5. (a) Material Flow Analysis of the cassava process to gari; (b) Wastes distribution and (C) wastes distribution.

mechanical and roasting processes, and utilization of biomass wastes from the systems for biogas production.

This overview provides a summary of the material and energy flows across the cassava processing system. Subsequent sections will delve into a detailed analysis of each stage, offering insights into potential optimization strategies, including the use of other renewable energy sources to reduce the environmental impacts.

4.2. Material flow analysis (MFA) and waste distribution across stages

This section describes the primary material flows, including Inputs (Fig. 5(a)), outputs (Fig. 5(b)), and waste streams (Fig. 5(c)). It highlights the potential environmental implications and identifies opportunities for enhancing process efficiency. For average scripted specific material flow data across all facilities, refer to the supplementary materials (S6), specifically Table S2 from Script 1. During harvesting, cassava roots were separated from the rest of the plant. Specifically at the harvest stage, 6.14 kg of whole plant (roots, leaf materials, and stems) was required to produce 3.65 kg of cassava roots as specific raw input material. This resulted in 2.49 kg biomass wastes including cassava leaf, stalks and straw, presenting 68.22 % cassava root mass which is consistent with figures reported by other researchers (Nizzy and Kannan, 2022; Veiga et al., 2016).

Supplementary materials in Tables S2 show the specific material consumption for all facilities, while S3, S4, and S5 (highlighted as S7 in supplementary materials) provide the same information in a Table for each respective facility. Table S6 presents the actual average waste in kilograms per stage for all facilities (see Supplementary material S8). While there was no research publication to compare to the specific raw material consumption in terms of the whole plant (harvested biomass) required to produce a kg of gari from the literature, this study's findings on the specific root-raw material requirements are in line with the 3.57 to 3.71 kg published by (Akinoso and Kasali, 2012), but 8.5 % lower than the 4 kg reported by (Jekayinfa and Olajide, 2007). The minor differences could be attributed to the varying harvesting periods that affect the moisture contents or the cultivar variations (Afek and Kays, 2003).

Tables S7, S8, and S9 highlight actual MFA data in facilities 1 to 3, respectively (see supplementary materials in S9), whereas Table S10 represents the average (S10). As can be observed from the bar charts in Fig. 5 (a) and (b) and Tables S7, S8, and S9, the Coefficient of Variation (CoV) of the MFA was less than 10 %, indicating that the inputs and outputs were consistent across the facilities. A lower CoV (below 10 %) suggests less variability and greater consistency in the data sets being compared (Jalilibal et al., 2021).

Biomass solid wastes made up the majority (57 %) as the waste distribution pie chart in Fig. 5(c) illustrates. Some transformative processes, such as peeling, de-watering, and roasting, were identified as the primary contributors to waste, as evident in the differences between the input and output materials in Fig. 5(a) and (b). The peeling procedure generated a substantial amount of cassava peel waste, accounting for 32.31 % of the harvested roots. Peels were spotted being fed to some livestock at several areas. In several sites, livestock animals were spotted drinking from waste water poured into small trenches, which has the possibility of exposing animals to cyanide. Additional research is needed to determine the safety of utilizing peels as feed in terms of cyanide exposure. The measured figures of peel wastes are in line with the 20 to 35 % highlighted (Oghenejoboh et al., 2021).

Approximately 69.66 % of effluent waste was produced during washing (water consumption-induced) and 30.34 % from the de-watering operations (cassava juice). Researchers have highlighted that wastewater generated during the cassava processing exhibits elevated levels of total dissolved solids (TDS), chemical oxygen demand (COD), starch concentration, and biological oxygen demand (BOD) with negative environmental impacts on the soil, water and air (Nizzy and Kannan, 2022). All wastes were left to rot or burn at each of the facilities under study, except for one site, where some wastes were dried for use as fuel. This biomass, if left to decompose, can emit significant amounts of kgCO_2eq, contributing to the carbon footprint (Kumar Sarangi et al., 2023; Vahdati et al., 2018). The waste generation, distribution, and disposal observed in this study align with those of other researchers (Asante, 2022; Olajoke et al., 2019).

Roasting was responsible for 11 % of the total cassava material loss due to moisture loss, resulting in a 41.71 % mass loss of the cassava mash during the sifting and sieving stage, primarily attributed to intense energy consumption. This is within the stated range of 25 % to 50 % loss and is primarily due to water evaporation from cassava mash (Dahdouh et al., 2021). The yield in this study was 28.00 % of the harvested root value of raw material and 16.33 % of the total cassava plant input. Understanding this data is critical for cassava processing planning and long-term profit maximization. The yield of gari varies depending on the cassava variety (Sobowale et al., 2016).

Knowledge of various cassava roots and waste productivity is crucial in raising awareness of their environmental impacts and designing mitigation strategies, in addition to being vital to energy engineers for wastes-to-energy planning. Cassava leaves could be used as vegetables for both human and animal consumption, and stalks could be replanted and used for other purposes (Nizzy and Kannan, 2022; Okike et al., 2022; Wu1 et al., 2017).

Peels could be used as a feedstock for biogas energy generation, which would assist in reducing energy poverty in rural areas and mitigate the effects of climate change (Luo et al., 2024). Other studies have emphasized additional environmentally friendly uses for cassava peels (J. A. Kumar et al., 2023; Okike et al., 2022). It is worthwhile to note that this study aggregated the waste impact per unit of the final product (specific material consumption) produced from fresh cassava, making it more precise for better tracking and management.

Opportunities for waste valorization, such as employing cassava biomass wastes, wash water, and juice for biogas production, offer a sustainable approach to reducing environmental impacts (SDG 13-climate action). By converting the final solid wastes into organic fertilizers, this process supports sustainable agriculture and responsible consumption (SDG 12). Additionally using biogas for roasting can enhance energy efficiency, lower CO_2 emissions, and reduce energy expenses, contributing to cleaner and more affordable energy solutions (SDG 7:affortable and clean energy) This shift toward a circular economy fosters resource efficiency and economic sustainability within the cassava value chain leading to profit maximization and job creation (SDG 8-decent work and economic growth) (UN, 2020).

4.2.1. Labor distribution

As shown in Fig. 6, a gender gap was evident at every facility examined in our study. A number of interconnected factors were identified as the cause of the observed discrepancy, which saw women make up nearly 80 % of the total compared to 20 % for men.

- Resource unavailability: lack of support and resources to enable women to acquire skills and the qualifications required for formal employment in other sectors.

- Economic pressure: Factors such as male migration for employment in larger towns and subsistence farming often leave women to fend for themselves and their children.
- Health and safety concerns: It is believed in the facilities that women are more responsible for maintaining the nutrition and food security/safety, and are more likely to participate in food processing at a higher rate.
- Social norms and gender roles: In line with traditional home roles, cultural norms frequently assign women primary responsibility for food processing duties.

Similarly, in many Asian countries, women contribute significantly

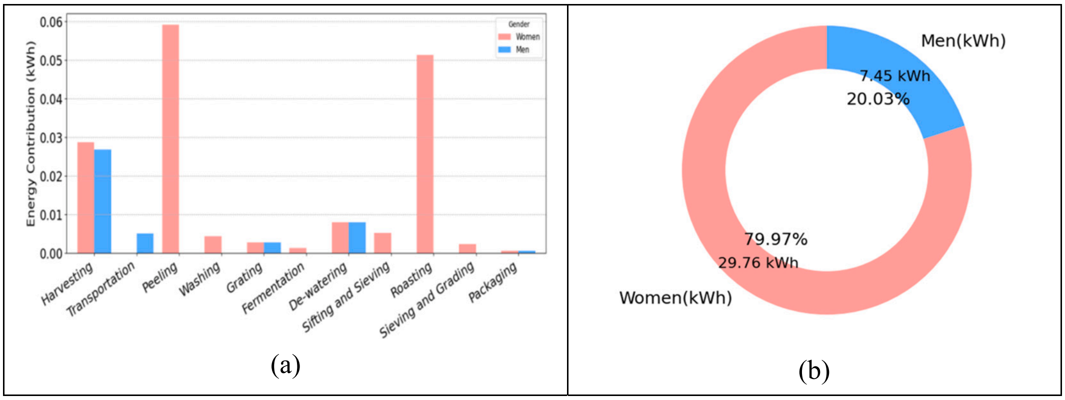


Fig. 6. Gender based participation and energy contribution

to the production of rice, especially during post-harvest processing stages like milling and sorting (Mishra et al., 2017). The other sector affected is the maize value chain. Further research is needed to investigate how gender influences the acceptance and adoption of mechanization in gari processing, as observed in the post-harvest waste reduction of the maize value chain (Lelea et al., 2022).

The differences in participation rates can be viewed in terms of gender roles, economic conditions, and cultural norms. Recognizing and resolving these variables enables the development of more egalitarian staple food production systems that acknowledge the contributions of all individuals, regardless of gender. This approach not only promotes gender equality but also helps communities enhance their food security and economic resilience.

Human power is critical at all key stages of the processing and plays a major role in the quality and efficient use of both materials and energy.

4.3. Energy flow analysis (EFA) and process temperatures by stage

4.3.1. Energy flow analysis

The amount of energy used varied significantly across the processes and facilities of staple food production. The production of one kilogram of gari needed an average of 6.67 kWh of SEC (facility 1: 3.67 kWh,

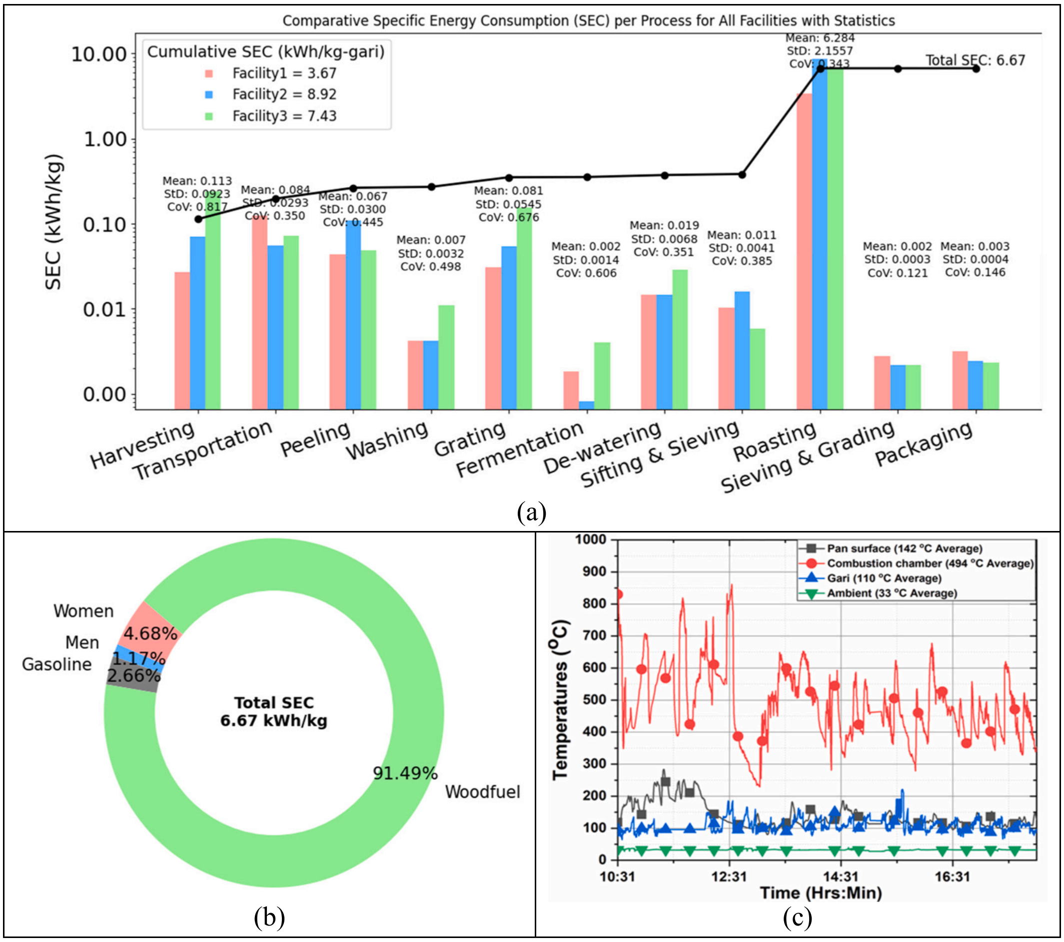


Fig. 7. Energy Flow Analysis ((a) comparative specific energy consumption (SEC) per process for all facilities, (b) Overall SEC contribution by source and (c) Roasting process temperature profiles.

facility 2: 8.92 kWh, and facility 3: 7.43 kWh), of which 91.49 % came from wood fuel (thermal energy), as Fig. 7(a) and (b) illustrate. The variation in the SEC per process is highlighted by the higher CoVs across the processes, as shown in Fig. 7(a), which range from 12 % to 82 %. Facility 2 utilized more energy than the rest, as explained in the next section. The energy demands of each process measured in all facilities are shown in the heatmap in Fig. S13 (S12 in supplementary materials), which displays the individual facility's energy consumption as presented in Tables S14, S15, and S16 (Script 4). The average energy demand is highlighted in Fig. S17 (Supplementary Materials, Section S15).

Comapred to the SEC, the higher CoV observed in energy demand, particularly in stages such as transportation, grading, and packaging, may reflect broader variations in overall energy use per process across each facility. For example, the distance covered to transport cassava in Facility 1 with higher quantities was longer than in other facilities, resulting in increased energy consumption. This fact indicates that energy consumption (demand) typically fluctuates significantly (dynamic material issue) over time due to changes in operational conditions (distance and capacity of materials), equipment, or human performance, as well as external influences such as demand peaks and variations in equipment or human availability. On the contrary, SEC is a more stable indicator because it is energy consumed per product output (efficiency relative to production) (Duarte et al., 2024; Lawrence et al., 2019).

Although manual energy accounted for only around 5 % of the overall energy, the processes were labor-intensive and required human effort at every stage. The significance of human resources in the processing of staple foods was demonstrated by the entirely manual, energy-dependent processes of harvesting, peeling, washing, sifting, sieving, and packaging (Tables S1 and S12).

Using approximately 94 % of the total energy, roasting was the most energy-intensive phase, as shown in Fig. 7(a), with supporting data provided in Table S12, labeled as S11 in the supplementary materials. Fig. 7(c) illustrates how the high temperatures needed for water evaporation during roasting under low-energy-efficient cookstoves (5.85 to 17.37 %; Fig. 7) used in the research regions may be the cause of this unit's high consumption.

In comparison to the 0.76 kWh kg-gari^{-1} recorded for high-level mechanized gari processing facilities in Nigeria, the facilities examined in this study utilized almost 80 % more energy based on the peeling to gari sieving/grading unit operations reported in earlier works. However, this study witnessed 5 % less consumption of 7.04 kWh kg-gari-1 reported for medium level mechanized and 15 % less of the 7.65 kWh kg-gari-1 low level mechanized units (Akinoso and Kasali, 2012). Disparities could be attributed to different energy sources with varying caloric contents (Imtiaz Anando et al., 2023).

4.3.2. *Process temperatures by stage*

The study's average roasting temperatures, as shown in Fig. 7(c), enabled the drawing of several scientific conclusions regarding the effectiveness of the stoves and heat transfer mechanisms. The cookstove chamber reached 494 °C, while the roasting pan only received 142 °C, or 29 % of the combustion chamber temperature, indicating a considerable loss of thermal energy, which suggests that the cookstove system has poor heat transfer efficiency (Mwape et al., 2023a). This discrepancy may suggest that poor insulation and insufficient heat transfer from the combustion zone to the cooking surface are likely causes.

Heat loss probably arose from convection, radiation, and sometimes inefficient airflow or open gaps. The stove's design exhibits low thermal efficiency, indicating that much of the energy produced from burning fuel is wasted instead of being effectively utilized for roasting, as indicated by scientific research (Berrueta et al., 2008; Kuye and Kumar, 2023). Improvements in heat retention, material conductivity, and stove design, particularly reducing heat loss through the stove structure, would be necessary to increase efficiency. This could indicate that the cookstoves used in the research areas resulted in significant energy losses and necessitating an evaluation of fuel consumption, energy efficiency, and associated emissions.

4.3.3. *Comparison of fuel usage, CO2 emissions, and efficiency among cookstoves*

The three key performance metrics of the cookstoves used in this study are highlighted in Fig. 8 (Script 5). The roasting process was accomplished in facilities 2 and 3 using traditional U-shaped cookstoves. As the bar chart illustrates, facility 2's specific fuel consumption was found to be greater (1.55 kg kg^{-1}) than that of facility (1.34 kg kg^{-1}). When comparing the semi-modernized cookstoves to those used in facility 1, the latter approximately consumed 40 % less fuel. Similar trends were observed in the emissions, with the semi-modernized cookstoves emitting 1.07 kgCO2eq kg-gari^{-1} and the U-shaped traditional cookstoves emitting an average of 2.52 kgCO2eq kg-gari^{-1}.

Variations in the energy efficiency of the cookstoves utilized could be the cause of the disparities in consumption and emissions. The average efficiency of the semi-modernized cookstoves was 17.37 %, whereas the traditional U-shaped cookstoves had an efficiency of 5.85 % and 8.35 %, respectively. The energy losses varied from 82.63 % to 94.15 %.

The low energy efficiency observed could be attributed to the wider spaces between the roasting pan seat and the U-shaped massive wall (U-shaped traditional cookstoves), and the lack of heat-insulating materials beneath the U-shaped wall, which serves as a combustion chamber. This is the case because, prior to moving on to the cassava mash, the heat must first heat the roasting pan's material and the cookstove's massive wall and body structures. As a heat sink, the earth may have contributed significantly to the system's equilibrium by absorbing residual energy (Berrueta et al., 2008). Other researchers have pointed out that stoves with smaller-mass components exposed to the fuel burning heat tend to be more fuel-efficient, produce fewer pollutants, and transfer heat to the food more quickly (Boafo-Mensah et al., 2020). The efficiencies achieved in this study are comparable to others (Boafo-Mensah et al., 2020; McCracken and Smith, 1998; Okafor and Unachukwu, 2012). The semi-modernized cookstoves offer a more sustainable choice for gari processing because higher efficiency is correlated with lower energy consumption and emissions.

These analyses suggest that higher energy consumption correlates with lower energy efficiency, leading to increased emissions, as shown in Fig. 8. The cookstoves' high energy consumption (wood fuel) and poor efficiency exacerbate the high emissions. This implies that the environmental effects of roasting procedures could be significantly reduced by transitioning to more energy-efficient and renewable energy-powered roasting cookstoves. The results of this study are consistent with those of other researchers who have shown that reducing energy use to perform the same quantifiable tasks leads to effective energy use and is beneficial for combating climate change (SDG 7-affordable and clean energy, climate action-SDG 13, and responsible consumption and production –SDG 12) (Piao and Managi, 2023; Wiese et al., 2024).

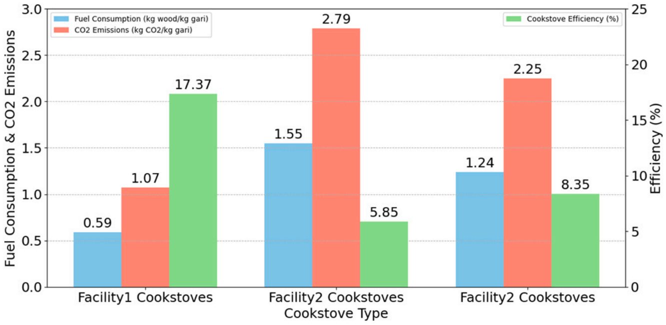


Fig. 8. Performance comparison of the cookstoves used in the 3 research facilities.

4.4. Global warming potential by process stage

The total GWP for the cassava processing chain was estimated to be 9.02 kgCO2eq kg-gari^{-1}. Fig. 9(a) and (b) show that harvesting, peeling, and roasting have the highest emissions, accounting for a significant portion of the overall GWP (50.05 %, 23.22 %, and 23.80 %, respectively). The biomass wastes at the harvesting and peeling stages, and the high woodfuel energy requirements for the roasting process, contributed significantly to the kgCO2eq. These findings are congruent with those of Kamyab et al. (2024), who identified the first and last stages of agricultural processing as key contributors to GWP.

Almost1 % of the GWP was linked to the combined waste from washing and dewatering. Given that the discharge from converting cassava into gari is known to be extremely polluting and could contribute to climate change, it is recommended that this effluent undergo treatment prior to disposed (Nnaji and Akanno, 2022).

The cyanide content initially at 32.13 ppm was found to be reduced to 4.72 ppm in gari. Even if no physiochemical analysis was carried out on wastes (only done on fresh cassava, fermented mash and gari), it has been reported that 90 % and one-third of the cyanogens and original linamarin present in cassava tubers were removed during fermentation and washing stages, respectively (Nnaji and Akanno, 2022). Therefore, emphasis should be placed on wastewater disposal to reduce soil contamination and disturbances to biodiversity.

This study throughly examines the environmental effects of processing cassava into gari, demonstrating how every stage of the process, from harvesting to packaging, significantly increases the overall GWP per kilogram of gari produced. Even without specific data on the GWP of one kilogram of gari produced in West Africa, specifically in Togo, the GWP obtained in this study is less than the 11.05 kgCO2eq noted by Olaniran et al. (2017) for the production of unfermented cassava flour in Southwest Nigeria. Excluding the harvesting process, other reports from Thailand, Vietnam, and Colombia have found 0.093 to 0.539 kgCO2eq emissions per kg of cassava starch (Lansche et al., 2020; Tran et al., 2015). The differences in GWP can be attributed to the distinctive processes involved in cassava starch production and gari production, as well as the integration of biogas production into starch production using wastewater and solid waste, significantly reducing the GWP.

Understanding the opportunities for emission reduction, particularly at high-end emission stages (harvesting, peeling, and roasting), may be incentivized if financial analysis is conducted at each stage with a double materiality approach. Future studies should investigate and compare the GWP based on kgCO$_2$eq per hectare, following the techniques of other studies such asthose on conventional and organic potato cultivation (R. Kumar et al., 2023).

4.5. Double materiality in cassava processing to gari: environmental (cumulative GWP), financial, and social impacts

4.5.1. Financial and environmental materiality

From the financial cost centre perspective highlighted in Fig. 10(b), the cost of fresh cassava accounted for the highest expenditure at 42.42 % of the total cost of $0.056 per kg of gari, followed by woodfuel and human labor. The selling price of gari is crucial for the overall financial viability of the business with financial dynamics directly impacting the net profit margins. As shown in Fig. 10(c), the achieved Return on Capital (ROC) margin was 52.52 %, indicating a substantial profit generation in relation to capital expenditure.

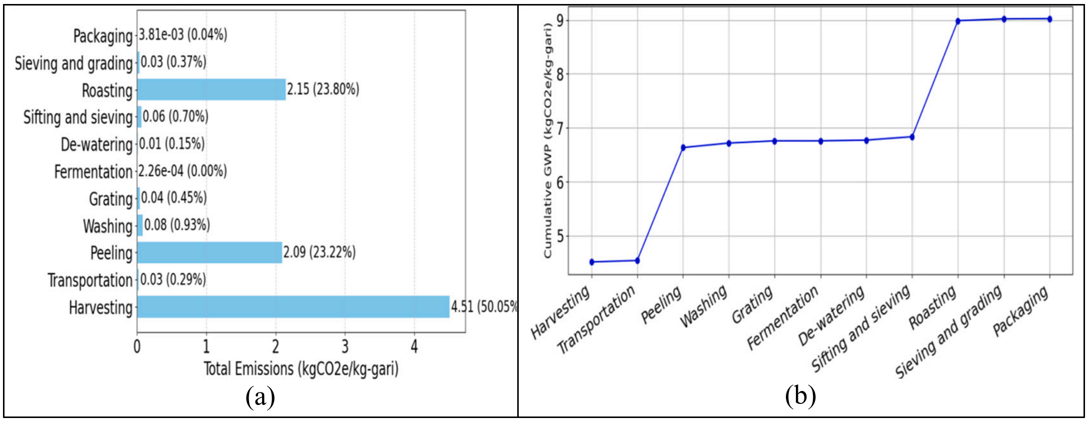
Although the ROC in this study is higher than the 25.65 % and 29 % reported by Esheye (2021) in Nigeria and Nimoh et al. (2020) in Ghana, respectively, it is lower than the 67 % reported by Agbekpornu (2014) and does not meet the 85.61 % highlighted by (Tran et al., 2022). The disparities in margins could be attributed to the various variable costs of fresh cassava and labor, which are largely site, regional, and nation-specific, as well as the type of cookstoves utilized, and the availability and distances of cassava from farms. For example, the labor expenses of all three facilities analyzed in this study were cheaper since the majority of the laborers were also members of cooperatives and operated on a Sweat Equity Cooperative Model (SECM) (Suttor, 2018).

It has been highlighted that the prices of cassava and market prices of gari change frequently, mostly depending on factors such as the cassava harvest yield (influenced by rainfall and the cassava disease), seasons, and location (Allado et al., 2024; RT, 2021; TE, 2022). This was observed during the analysis of seasonal dynamics in materiality, as reflected in production and market prices, as shown in Table S18 (supplementary material S16), where the low peak in cassava prices resulted in an almost 32 % increase. The market price per bowl increased from its lowest of $1.69 bowl^{-1} ($0.85 kg^{-1}) to about $2.18 ($1.09 kg^{-1}).

4.5.2. Link between financial and environmental materiality (global warming potential/operational costs)

This analysis has shown that emissions pose the greatest financial concerns in addition to environmental challenges. Fig. 10(a) and Table S13 (Supplementary material S13) (Script 7) in the supplementary materials highlight that cassava raw material procured and processed from harvesting, was the most costly and also the most GWP emitting followed by the roasting stage (Note that the cost of the raw material was divided equally across all stages because it was processed till the energy). The cumulative costs and the GWP in Fig. 10(a) clearly illustrate the contribution of each stage.

The Stages with higher emissions and higher financial costs, such as harvesting and roasting, were found to be directly correlated, highlighting the possibility of co-benefits in terms of cost savings and



(a) (b)

Fig. 9. Global warming potential in cassava processing by process stage, (a) total emissions by process, (b) cumulative GWP by process (data in Table S11 and script 3-S12 in supplementary materials).

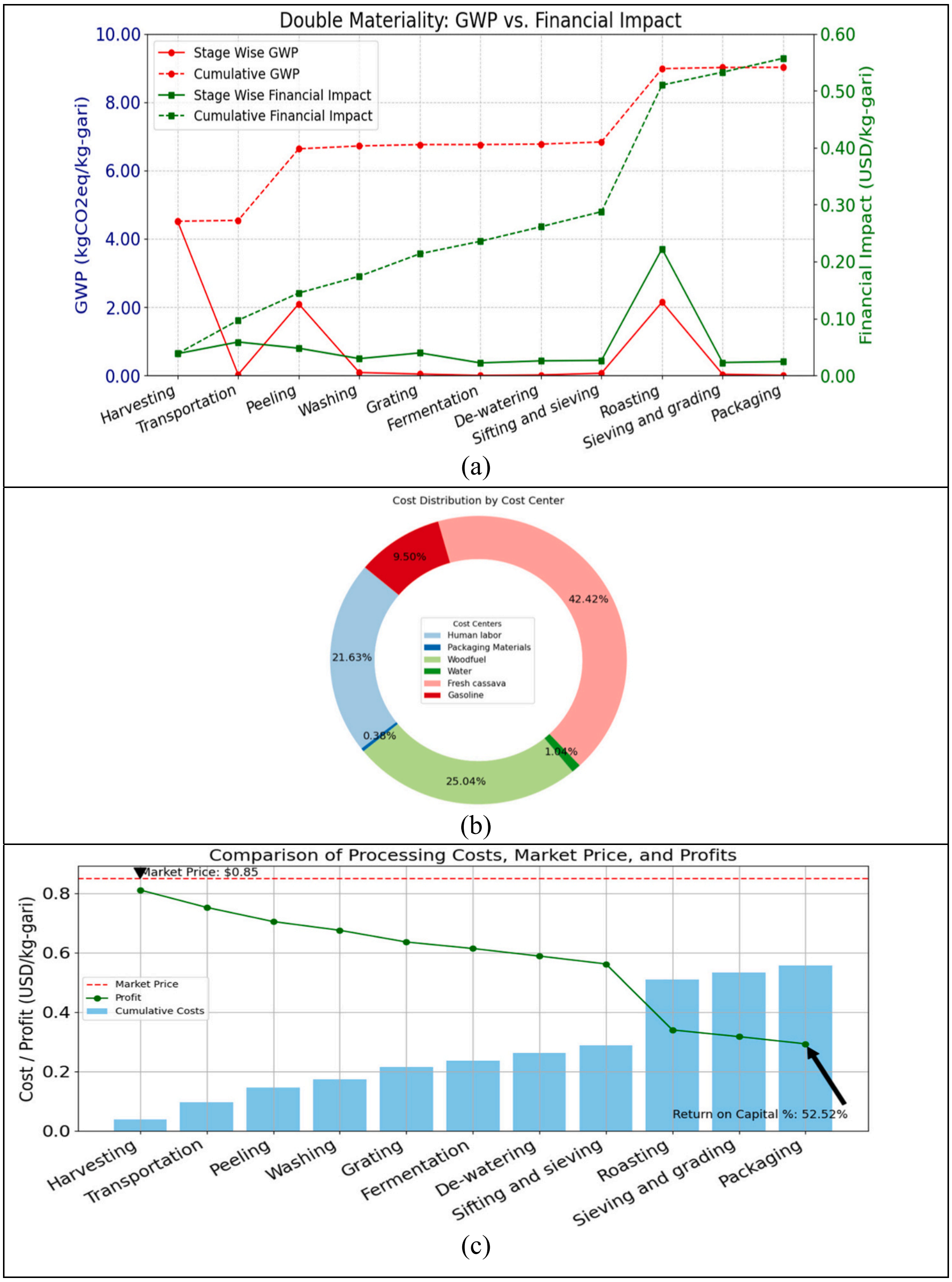


Fig. 10. Double materiality in cassava processing; (a) Global warming potential Vs Financial impacts, (b) Cost distribution by cost center and (c) comparison of processing costs, market price and profits.

emissions reduction. This scenario, where energy-intensive processes are most likely high-emission and cost-intensive, has also been highlighted in the beverage industry (Sovacool et al., 2021).

Increased regulatory pressure on a global scale to combat climate change and adaptation through programs like carbon pricing or more stringent emissions laws once implemented in developing nations in the near future may result in extra costs for cassava processors.

By switching to alternative, sustainable energy sources like solar and biogas, and utilizing more efficient cookstoves, co-benefits can be realized. Furthermore, significant reductions in emissions and energy cost savings can be achieved by processing biomass and effluent wastes into biogas or other sustainable products. Biogas digestate has a high nutrient content and can be applied as an organic fertilizer. The production of biogas from cassava wastes has long been emphasized as a robust approach with the potential to sustainably lower operating expenses and environmental effects (Tran et al., 2022). Conversely, addressing GWP by adopting energy-efficient technologies could help reduce long-term financial risks, positioning the staple food processing sector for better sustainability credentials and access to environmentally conscious markets.

To reduce energy usage and CO_2 emissions from traditional roasting techniques, it's crucial to switch to more sustainable options. Solar-powered roasting technologies are a potential solution, providing a renewable and cost-effective way to reduce reliance on fossil fuels and inefficient biomass (Mwape et al., 2025). Furthermore, utilizing more sustainable biomass sources, such as agro-waste pellets and sustainably sourced wood fuel, can enhance efficiency while minimizing environmental degradation. Biogas, created from organic waste, has the potential to be a greener alternative, offering a circular solution that combines waste management and energy production. By implementing these energy-efficient solutions, the roasting process can become more sustainable, leading to reduced emissions and increased long-term economic and environmental benefits.

4.5.3. Social materiality

The elevated levels of worker engagement in gari production, particularly in rural areas where job opportunities are scarce, reflect the social and material aspects present within the industry. Over ten persons were involved in the harvesting process, which primarily relies on human labor. Its labor-intensive character helps local economies by giving rural residents the much-needed jobs and means of livelihood. The results in this section compare social and material elements in traditional cassava processing to gari across the three monitored facilities. The evaluation highlights key factors, including high labor demand and roles, environmental practices, economic access, and cultural influences. These findings highlight common obstacles as well as specific prospects for long-term improvements, such as the adoption of new processing equipment in gari production.

i. Gender roles and access to resources

With more than 79 % women-driven labor force, this study has highlighted how gender insensitive this sector is. Despite their vital roles, women highlighted that they encountered issues such as a lack of access to financing and current processing tools and technologies. This restriction of access not only affects productivity but also perpetuates gender disparities, since women may be paid less than their male counterparts or excluded from decision-making roles. Other scholars have reported on these gender dynamic concerns in agricultural labor, showing that to some extent, even remedies implemented, such as access to resource endowment, aren’t functioning (Abdisa et al., 2024). This could be attributed to the lack of focus on real issues, such as addressing the policy and technologies’ gendering (Clay and Yurco, 2024).

ii. Health and safety concerns

Workers across all facilities complained about smoke and excessive heat from cookstoves. This poses substantial health hazards because extended exposure to smoke from the roasting stage, as well as physical strain and stress from repetitive chores like peeling and sieving, can induce respiratory and musculoskeletal ailments. Other research has thoroughly documented these dangers. For instance, it was discovered that workers in cassava processing are at a higher risk of getting respiratory ailments due to smoke inhalation from traditional roasting processes (Parmar et al., 2019).

iii. Traditional vs modern technology

The idea of introducing new equipment for roasting cassava raised some worries. The participants interviewed emphasized the importance of integrating traditional knowledge and skills in gari preparation to maintain the product’s quality, taste, and cultural value. Some operational techniques, such as roasting methods and fermentation times, varied among facilities. The distinctive flavor and texture of gari are reportedly enhanced by manual methods that have been passed down over the years, such as hand-roasting and fermenting in cassava, which are frequently used in traditional ways and increase its marketability in local marketplaces. Other authors from different regions have extensively reported this dynamic issue (Awoyale et al., 2021; Owusu-Darko et al., 2024).

iv. Waste management and environmental sustainability

It was found that facilities that kept livestock provided some biomass waste from the peeling and harvesting processes to the animals. Some people made firewood out of the leftover stems. Other researchers have also highlighted on activity (Jumare I et al., 2024).

This study has demonstrated that gari processing encompasses social, environmental, and financial aspects that are intricately intertwined. By lowering the GWP, financial investments targeted at reducing energy use can help alleviate the environmental impacts. These same investments, however, may require adjustments in labor force participation, which would impact workers’ livelihoods. For example, adopting more technically advanced roasting systems, such as cookstoves driven by solar energy, may require and encourage a greater number of technically qualified males to participate than females, which would lower the income for women.

Cassava processors, like other staple food processing systems owners, must balance between their financial success with environmental and social responsibilities. A comprehensive approach considering the tradeoffs across these dimensions is essential for developing a long-term, robust, sustainable business model.

As a result, considering of social materiality is critical in staple food production, as it demonstrates how dynamic interactions between people and new technological breakthroughs create positive, holistic, and dynamic changes in societies as an inseparable whole. Efficient processes with lower GWP could directly result in financial gains, resulting in greater financial benefits and fewer climate change implications for everyone (Leonardi et al., 2012).

4.5.4. Governance

Despite having nearly 80 % female members, all but one cooperative was headed by men, highlighting a gender insensitivity. The chairperson normally had the power to organize and manage the decision-making process, and most farms and land were owned by men. Systemic constraints still prevent women from participating in sustainable staple food processing practices, although effective governance is essential to guaranteeing equitable access to resources and technology. Organizational and policy-level governance frameworks often overlook gender differences in property ownership, loan availability, and participation in capacity-building programs. As a result, it is extremely challenging for women to adopt new roasting technologies and benefit from sustainability programs. The findings in this study align with the other researchers who have highlighted that, despite considerable improvements, gender inequality is not sufficiently addressed by the majority of climate change policies and activities (Bryan et al., 2024). Gender-responsive policies addressing these obstacles must be integrated into governance structures to promote fairness and inclusivity in a just transition to sustainable solutions. Most of the global south governments’ initiatives to support women’s empowerment have a lot of room for improvement (Li et al., 2022). This entails easing access to training, offering targeted financial support, and guaranteeing women’s participation in decision-making processes. Governments and organizations can empower women and promote the wider adoption of sustainable energy solutions by strengthening their governance structures to be more gender-aware and inclusive.

4.5.5. Promoting gender inclusivity: actionable recommendation for sustainable practices

Gender dynamics have significant influence in the adoption of sustainable staple food processing and the achievement of the SDGs. To address existing imbalances, targeted interventions are essetial, including legislation that guarantees women equal access to resources such as financing, land, and technology, along with capacity-building programs tailored to their specific needs. Furthermore, decision-making roles should be more inclusive, with international regulations promoting women’s leadership at both the local and industrial levels. The following are the key actionable policy recommendations proposed in this study:

- Develop gender-sensitive training programs to address the gender gap in innovative technology adoption, aligning with SDG 9 and promoting gender equity (SDG 5).

- Promoting women's leadership: Implement education/training programs to increase female participation in decision-making roles (SDG 4).
- Streamline carbon trading mechanisms: by focusing on impactful small-holder solutions, such as sustainable food processing, and aligning them to green funding, and promote climate action-SDG-13, reduce hunger-SDG 2, and poverty-SDG 1 for good health and well-being (SDG 3.
- Implement financial support mechanisms, such as low-interest loans and subsidies, to encourage women to adopt sustainable technologies and promote decent work and economic growth (SDG 8).
- Promote Collaboration: Collaboration with industry stakeholders can help overcome structural hurdles and integrate gender equity into sustainability initiatives, promoting partnerships that align with the goals (SDG 17).
- Empowering women with access to resources: Provide equal access to loans, land, and renewable technology for women. This has the capacity to reduce social and economic inequalities (SDG 10) and promote the use of sustainable yet affordable energy (SDG 7).

If appropriately executed, these recommendations can offer stakeholders doable steps to reduce gender inequality and encourage more sustainable and inclusive practices that support responsible production and consumption (SDG 12). These can be translated into the creation of sustainable cities and communities (SDG 11), which support justice, peace, and robust institutions (SDG 16) (UN, 2020).

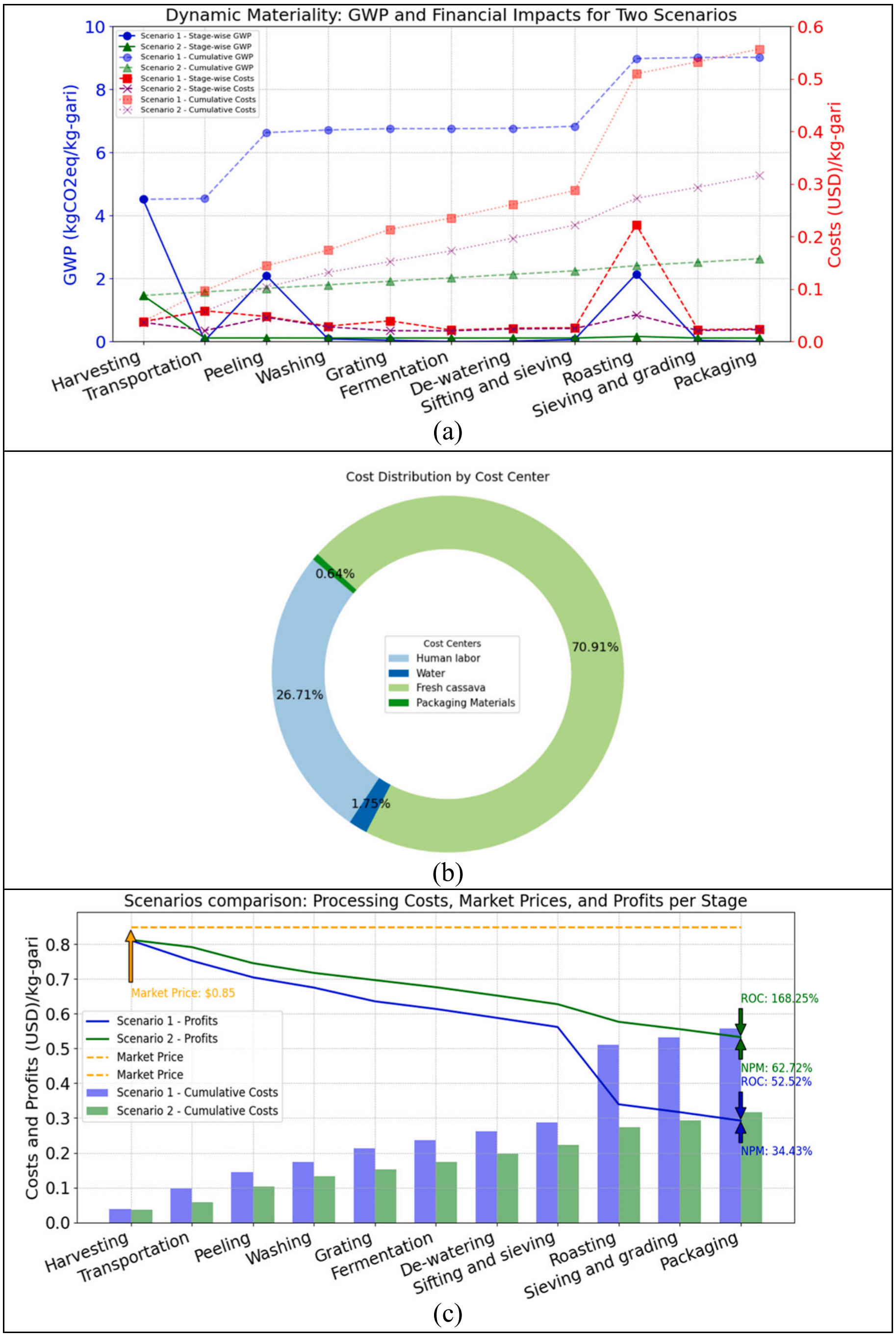


Fig. 11. Dynamic materiality in cassava processing; (a) GWP and Financial, (b) Change in costs distribution, (c) Scenarios comparison processing costs, market prices and profits per stage.

4.6. Dynamic materiality: evaluating environmental and operational shifts from traditional practices to hybrid solar-biogas-powered roasting (HSB)

The comparison of HSB and woodfuel energy in this study reveals how the dynamic materiality issues of each energy source and associated GHG-emitting wastes change, impacting both financial results and environmental sustainability, as highlighted in Fig. 11.

4.6.1. Global warming potential and financial performance

In contrast to traditional energy sources used in cassava processing, such as woodfuel and gasoline, introducing an HSB system signifies a substantial shift in materiality. By decreasing reliance on solid-biomass fuel-based systems and non-renewable resources, such as gasoline, the HSB system addresses both financial and environmental sustainability by combining solar photovoltaic (PV) energy with biogas generated from process effluent and organic waste.

The HSB (scenario 2) and woodfuel/gasoline (scenario 1) are compared in Fig. 11(a) with respect to their GWP and financial performance. By utilizing e-transportation and converting the majority of waste into biogas for use at the roasting stage as part of the HSB, it is anticipated that scenario 2 could produce 70.62 % fewer GWP per kilogram of gari produced. This dramatic reduction illustrates the environmental advantage of the HSB system, which is attributed to the use of solar energy (carbon neutral during operation), and biogas, which produces fewer emissions than gasoline or woodfuel combustion (Jameel et al., 2024; Smith et al., 2024). It also highlights the dynamics of the energy transition.

The biogas component of the hybrid system is critical for lowering the GWP. It could even be considered carbon-neutral or even carbon negative because the methane that would otherwise be emitted by decaying organic waste is transformed and used as energy. Methane has a GWP 25 times more than CO_2 over a 100-year period. Converting it into energy instead of releasing it into the atmosphere can greatly reduce the GWP of the cassava processing system by cutting CO_2 emissions by 50 to 60 % compared to woodfuel and fossil fuel systems (Jaro et al., 2021; Nature, 2021; Olukanni and Olatunji, 2018; Tripathi et al., 2019).

In addition to addressing dynamic materiality, the hybrid solar/biogas system prevents future environmental expenses associated with cassava processing. The greenhouse gas pollution associated with fossil fuels and woodfuel will become a more significant concern as international laws on carbon emissions become stricter and carbon markets evolve. This could take the form of emission caps, carbon taxes, and other regulations that force high-emitting businesses to pay a price (Filonchyk et al., 2024; IPPC, 2022; UNFCCC, 2023). The operating expenses of the woodfuel/gasoline system would increase in such a case, thereby decreasing the long-term viability of the business plan. The HSB system, by contrast, positions cassava processors to future-proof their operations.

4.6.2. Financial dynamic materiality: effects on operational costs and returns

From the financial perspective illustrated in Fig. 11(c) (Data in Table S18(a) and S19), highlighted as S16 in the supplementary materials based on Script 8, the proposed scenario 2 has a substantially lower operating cost per unit of gari produced than the traditional system (scenario 1). This is largely driven by the fluctuating prices of gasoline and the increasing scarcity of woodfuel, which is currently being experienced and accounts for almost 35 % of the total costs ($0.19 per kilogram of gari produced). On the other hand, the hybrid system results in an overall reduction of $0.24 (44 % of the scenario 1 costs) per kg of gari produced by lowering the operating costs to $0.32 per kg.

The dynamic relationship between sustainability and profitability is further highlighted in the analysis of the ROC and the NPM under both scenarios. Fig. 11(c) demonstrates that proposed scenario 2 has a higher ROC and NPM than the current situation (scenario 1). This could be attributed to lower energy and labor expenditures, which significantly reduce costs throughout the transportation and roasting stages. Fig. 11(b) illustrates the dynamic shift in cost regimes, with the primary cost share of fresh cassava rising to 70.91 % from 42.42 % in scenario 1. The highlighted change could be caused by a shift in main costs, which is aided by free energy available from the HSB. It suggests that the operating investment is predicted to create a return of 194.28 % of the entire investment cost in scenario 2, compared to only 65.01 % in scenario 1. This demonstrates the impact of dynamic materiality on costs and revenues resulting from planned adjustments to energy and waste management in the cassava processing system. This dynamic change could be further supported by the volatility of fresh cassava market prices in the research areas.

The proposed system's lower operating costs can be attributed to the elimination of recurring energy costs (Kpodar and Liu, 2022). It was discovered during the field investigations that the cost structure of the traditional cassava processing system is heavily reliant on fuel costs, which are vulnerable to market and weather/season volatility. In contrast, the solar energy component of the proposed hybrid system incurs no ongoing fuel expenses, whereas biogas, produced from cassava waste, requires no additional input beyond maintenance.

Although it was not part of this research, the high initial capital expenditure associated with solar PV system installation and biogas plant construction initially raises scenario 2 costs. However, operational expenditure gradually reduces, leading to substantial long-term savings, as shown in Fig. 11. This structural shift reflects the principle of dynamic materiality, highlighting the dynamic materiality of energy decisions in the agro-processing sector. Although the initial capital expenditures of most of the renewable energy sources are significant, they reduce over time as operating savings and environmental advantages mount (Egli, 2020; Kpodar and Liu, 2022). Furthermore, as carbon-intensive energy sources become more expensive due to regulatory frameworks like carbon pricing and emissions trading schemes, the financial attractiveness of solar and biogas systems increases (Sterner, 2024; Tran et al., 2022; van den Bergh and Savin, 2021). This shift highlights the increasing material significance of environmental performance.

The proposed hybrid system also reduces financial risks connected with fuel shortages and price volatility, particularly in areas where fuel access is becoming an urgent concern (Pawar et al., 2024). Therefore, while the traditional system appears less capital-intensive upfront, the hybrid system delivers greater long-term financial resilience.

4.6.3. Sustainability implications

The current system emits high levels of carbon and contributes to deforestation due to its reliance on unsustainably harvested wood fuel. This causes biodiversity loss and releases CO_2 from trees, exacerbating the climatic impact. Aside from the obvious financial and operational issues, the current system is unsustainable in terms of the environment. Operations that rely on high-emission energy sources may face reputational concerns and regulatory challenges as the global focus on climate change grows.

The transition to renewable energy sources in the hybrid system would significantly reduce emissions, aligning the cassava processing business with global climate targets and enhancing its sustainability. The system promotes a circular economy paradigm by converting cassava waste into biogas, reducing waste, and increasing resource efficiency. This decreases the environmental impact of cassava processing while also creating a closed-loop energy system. The hybrid system preserves forests, protects biodiversity, and reduces CO_2 emissions from deforestation by reducing the need for unsustainable wood fuel utilization.

From a dynamic materiality standpoint, as consumer and investor demand for sustainable practices grows, implementing a low-carbon, resource-efficient energy system would strengthen the business market position and boost access to green finances. This long-term sustainability will also assure compliance with increasing environmental standards, thereby future-proofing the businesses.

4.7. Broader implications and cross-sector transferability

The study's methodology, which includes MEFA, QMS, double and dynamic materiality, and a Python computational LCSA-strengthened framework, is not limited to the staple food processing industry. These frameworks are broadly applicable in various industries, processes, or businesses with complex supply chains, resource-intensive production, and environmental concerns. This is also very key to tackling covid-19 look alike challenges and calamities (Mwape et al., 2024).

MEFA is a proven method for evaluating the flow of materials and energy between various systems, such as waste management, manufacturing, agriculture, and energy generation. For every industry seeking to enhance its sustainability performance, the capacity to monitor inputs, outputs, and resource efficiencies is extremely pertinent. The integration of QMS to MEFA techniques results in a robust system that not only dynamically assesses the quantity of the material and energy flow, but also the quality (Papageorgiou et al., 2024; Siva et al., 2016). Double materiality ensures that MEFA accounts for both the impact of sustainability factors on a system or business performance and the system or business's impact on the environment and society, making it relevant for corporate and regulatory reporting for all situations (Dyczkowska and Szalacha, 2025). Meanwhile, dynamic materiality allows MEFA to adapt to evolving sustainability risks and opportunities, ensuring continuous alignment with stakeholder expectations and policy changes. This makes MEFA and double/dynamic materiality integrated LCSA an essential tool for processes or industries seeking to improve resource efficiency while addressing sustainability challenges holistically.

The Python-based computational modeling employed in this study also offers a scalable and customizable approach that can be applied to various industries. Whether applied to circular economy strategies in manufacturing, energy optimization in industrial processes, or waste reduction in urban systems, the flexibility of computational modeling ensures its relevance across sectors. This enables researchers and policymakers to optimize, simulate, and visualize sustainability pillars (energy efficiency, GhG emissions, economic, policy implications, social, and governance) in real-time. This approach ensures data-driven decision-making, making sustainability solutions more adaptable, globally relevant, and actionable across diverse sectors, including manufacturing, energy, and agriculture. The developed scripts and algorithms could be integrated into AI tools for more advanced predictions, automation, and decision-making (Alenezi and Akour, 2025; Chen et al., 2021; Rashid and Kausik, 2024).

Furthermore, this study contributes to global discussions about circular economic models and climate resilience. It has demonstrated how material risks, such as waste generated by many staple food systems, can be repurposed for waste-to-energy, with the benefits of reducing greenhouse gas (GHG) emissions, generating income, and lowering production costs (EEA, 2024; Yang et al., 2022). Biogas by-products, for example, can be utilized as organic fertilizer. As countries strive to achieve Sustainable Development Goals (SDGs) 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production), and 13 (Climate Action), waste-to-energy innovations provide a scalable pathway for reducing environmental impacts while supporting economic development in agro-industrial sectors (Sharma et al., 2025).

This study demonstrates how these frameworks can be applied in the processing of staple foods, highlighting their potential to inform sustainability assessments and decision-making in various industries and geographical areas. This flexibility enhances the study's global applicability and provides a solid foundation for subsequent research aimed at maximizing sustainability across various sectors. By applying these principles across diverse agricultural value chains, processes or industries, stakeholders can accelerate the transition toward more inclusive, low-carbon, and resource-efficient systems and products globally (Herrero et al., 2020).

5. Conclusions

This study illustrates the efficacy of employing the MEFA and QMS frameworks, in conjunction with the principles of double and dynamic materiality, to comprehensively analyze the LCSA- including material flow, energy usage and efficiency, global warming potential (GWP), and financial services- of the often neglected small-scale staple food production systems, utilizing cassava processing to gari as a case study. The double materiality has been successfully demonstrated through the creative application of Python-based tools to construct models and visualization diagrams, such as Sankey diagrams and heatmaps, considering not only the immediate financial costs and global warming potential (GWP), but also the long-term environmental and social implications of resource utilization and emissions. This might help in predicting the social and financial impacts that are highly uncertain and context-dependent. The dynamic materiality component highlights how these effects evolve over time as the cassava processing system is adapted to utilize different energy sources under varying conditions. These techniques highlight how the traditional LCSA, often based on static life cycle inventories and impact assessments that mostly just reflect current or historical data, could be transformed to fully capture the real-time or future dynamic changes in markets, technology, policy, or social trends. This might promote short-term to real-time processes efficiency schemes, adjustments, and adaptability.

MEFA, QMS, double and dynamic materiality, and a Python computational LCSA reinforced framework are all part of the study's methodology, which is not exclusive to the staple food processing sector. These frameworks are widely applicable to a diverse range of enterprises, processes, and industries that involve resource-intensive production, complex supply chains, and environmental concerns.

The innovative development of scripts tailored to specific staple foods, utilizing existing open-source and free Python-based tools, enabled tracking and visualization of material and energy flows. This process revealed inefficiencies and waste across multiple processing stages, while also providing insights into the potential for circularity. It considers the identification of the GWP, revealing that transitioning from gasoline and woodfuel to renewable energy sources such as hybrid solar-biogas can dramatically reduce CO2 emissions.

By considering double materiality, this study connects the immediate and long-term economic benefits of renewable energy transitions with their environmental advantages, providing a comprehensive evaluation of the cassava-to-gari value chain.

From an energy and material standpoint, the MEFA techniques enabled the isolation of specific stages in the process, such as the fresh cassava input materials and the woodfuel at the roasting stage, where emissions were highest. The shift from using inefficient wood-fueled cookstoves to hybrid systems underscores the need for a sustainable energy transition that addresses the overuse of local biomass resources without replenishment, particularly in developing countries. The double materiality further highlighted that high GHG-emitting materials are also financially draining, further connecting the multifaceted nature of high GWP sources. The dynamic materiality in this context demonstrates that, while the initial cost of installing renewable energy may be higher, the long-term benefits, both financially and environmentally, are enormous.

The Python-based visualization tools also make an important contribution by enabling government departments responsible for agricultural extension and business services, or individual users, to dynamically model multiple energy scenarios, which aids in decision-making processes that consider both current and future implications. These staple food-specific models offer a straightforward approach for stakeholders to evaluate the dual and dynamic materiality of energy and material flows in small-scale agricultural systems.

Although this study provides a comprehensive overview of staple food processing using cassava as a case study, further investigation is needed to assess the scalability and replication of the proposed energy transitions. Subsequent investigations must focus on the long-term sustainability and financial feasibility of these alternative energy sources. The suggested frameworks (MEFA, Double and Dynamic Materiality reinforced LCSA) and Python tools in this study should be applied to various systems, from cradle to grave. Additionally, it is essential to monitor the social and governance implications of several issues, including the physical effects of manual labor, exposure to smoke, heat intensity, and cyanide concentration. Education level effects could also be considered.

The study has highlighted that in ESG reporting, dynamic and double materiality are crucial because they provide a thorough, forward-looking, and stakeholder-inclusive approach. For instance, converting cassava waste into biogas can lead to lower emissions and energy expenses, increased profits, and the opportunity to generate more employment. Companies should implement a comprehensive ESG framework that utilizes both Dynamic and Double Materiality. By addressing changing ESG risks and considering both financial and impact perspectives, organizations can improve their decision-making, enhance transparency, and foster trust among stakeholders. Utilizing tools such as QMS, MEFA, and Python automation simplifies reporting and ensures compliance with global standards like the International Sustainability Standards Board (ISSB) and the Corporate Sustainability Reporting Directive (CSRD).

Given the significance of resolving both double and dynamic materiality, there is an urgent need to develop policies that will incentivise the energy transition in staple food production, such as the removal or reduction of import taxes on renewable energy systems. This would promote not only instant financial benefits but also align with long-term environmental sustainability goals. Targeted policy interventions that support renewable energy infrastructure development and farmer and processor education are essential for fostering this transition and are directly aligned with SDGs 1, 2, 3, 5, 6, 7, 8, and climate action SDG 13.

By exploring both the dynamic financial and environmental aspects of cassava processing through the lens of double and dynamic materiality, this study lays the groundwork for a more holistic, real-time, and sustainable approach to small-scale staple food production and other processes. A future without the integration of real-time Financial and Environmental Metering of energy-hungry processes is business as usual and counterproductive to the attainment of the SDGs.

CRediT authorship contribution statement

Mwewa Chikonkolo Mwape: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aditya Parmar:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition. **Franz Roman:** Writing – review & editing, Visualization, Validation, Data curation. **Naushad M. Emmambux:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Yaovi Ouézou Azouma:** Investigation. **Oliver Hensel:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Funding

The authors gratefully acknowledge financial support for the Sun-Gari project from the German Federal Ministry of Education and Research (Grant code: FKZ 03F0683A) and the European Union's Long-Term Joint European Union-African Union Research and Innovation Partnership on Renewable Energy (LEAP-RE) under Grant Agreement No. 963530.

Declaration of competing interests

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

Acknowledgments

We are very grateful for the field coordination provided by the University of Lome. We also thank the following organizations for their participation in this research: Cooperative des Femmes NOVIVA Tokpo, Agro-Pastoral in Ganave, Coopérative d'Action pour le Développement (CAD) in Wogba, Vagan, Togo, and the National Institute for Scientific and Industrial Research, Lusaka, Zambia.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2025.04.002.

Data availability

The corresponding author remains available to share the datasets used or analyzed in the current study upon request.

References

Abass, A., Braima, J., Richardson, O., Fannah, S., Maziya-Dixon, B., Sanni, L., Osei-Sarfoh, A., Fomba, S., Lukombo, S., 2012. Producing Gari from Cassava: an illustrated guide for smallholder cassava processors [WWW Document]. International Institute of Tropical Agriculture (IITA). In: https://www.researchgate.net/publication/288609121_Producing_Gari_from_Cassava_An_illustrated_guide_for_smallholder_cassava_processors. (Accessed 21 February 2022).

Abdisa, T., Mehare, A., Wakeyo, M.B., 2024. Analyzing gender gap in agricultural productivity: evidence from Ethiopia. J. Agric. Food Res. 15, 100960. https://doi.org/10.1016/J.JAFR.2023.100960.

Afek, U., Kays, S.J., 2003. Postharvest physiology and storage of widely used root and tuber crops. Hortic. Rev. (Am. Soc. Hortic. Sci.) 253–316. https://doi.org/10.1002/9780470650837.CH7.

Agbekpornu, H., 2014. Economic returns of gari processing enterprises in the Mampong Municipality, Ghana. Int. J. Agric. Innov. Res. 2, 502–509.

Agricdemy, 2022. Gari processing: equipment required and techniques [WWW Document]. In: https://agricdemy.com/post/gari-processing-business. (Accessed 19 November 2022).

Aguilar-Rivera, N., 2024. Life cycle assessment of valorization of root and tuber crop wastes for bio-commodities and biofuels: cassava as a case study. In: Roots, Tubers, and Bulb Crop Wastes: Management by Biorefinery Approaches, pp. 333–350. https://doi.org/10.1007/978-981-99-8266-0_15.

Ajewole, P.O., Adeosun, 2018. Design Analysis of a Cassava Mash Roaster, GSJ.

Ajibola, O.O., Ige, M.T., Makanjuola, G.A., 1987. Preliminary studies of a new technique of cassava mash gelatinization. J. Agric. Eng. Res. 36, 97–100. https://doi.org/10.1016/0021-8634(87)90116-8.

Akinoso, R., Kasali, W.O., 2012. Energy expended in processing Gari (Cassava Flakes) *Manihot esculenta* crantz, using three levels of mechanization. Pak. J. Sci. Ind. Res. Ser. B Biol. Sci. 55, 114–116. https://doi.org/10.52763/pjsir.biol.sci.55.2.2012.114.116.

Alejandrino, C., Mercante, I., Bovea, M.D., 2021. Life cycle sustainability assessment: lessons learned from case studies. Environ. Impact Assess. Rev. 87, 106517. https://doi.org/10.1016/J.EIAR.2020.106517.

Alenezi, M., Akour, M., 2025. AI-driven innovations in software engineering: a review of current practices and future directions. Appl. Sci. 15, 1344. https://doi.org/10.3390/APP15031344, 2025, Vol. 15, Page 1344.

Allado, S.S., Adjata, K.D., Pita, J.S., Atass, K., Dansou-Kodjo .A., S, Mivedor, tu, Tozo, K., Allado, S.S., Adjata, K.D., Pita, J.S., Atass, K., Dansou-Kodjo .A., S, Mivedor, tu, Tozo, K., 2024. East African cassava mosaic virus and East African cassava mosaic cameroon virus: two species emerging in Togo. Agric. Sci. 15, 864–876. https://doi.org/10.4236/AS.2024.158048.

Arias, D., Barriola, X., Loza Adaui, C.R., 2024. Corporate purpose and early disaster response: providing evidence of dynamic materiality? Bus. Strateg. Environ. 33, 4598–4612. https://doi.org/10.1002/BSE.3707.

Asante, E., 2022. Environmentally Sustainable Cassava Processing in Ghana: Trade-offs Between the Different United Nations Sustainable Development Goals.

Awoyale, W., Alamu, E.O., Chijioke, U., Tran, T., Takam Tchuente, H.N., Ndjouenkeu, R., Kegah, N., Maziya-Dixon, B., 2021. A review of cassava semolina (gari and eba) end-user preferences and implications for varietal trait evaluation. Int. J. Food Sci. Technol. https://doi.org/10.1111/ijfs.14867.

Baumüller, J., Sopp, K., 2022. Double materiality and the shift from non-financial to European sustainability reporting: review, outlook and implications. J. Appl. Acc. Res. 23, 8–28. https://doi.org/10.1108/JAAR-04-2021-0114.

Bechoff, A., Tomlins, K.I., Chijioke, U., Ilona, P., Bennett, B., Westby, A., Boy, E., 2019. Variability in traditional processing of gari: a major food security product from cassava. Food Chain 8 (1), 39–57. https://doi.org/10.3362/2046-1887.18-00015.

Berrueta, V.M., Edwards, R.D., Masera, O.R., 2008. Energy performance of wood-burning cookstoves in Michoacan, Mexico. Renew. Energy 33, 859–870. https://doi.org/10.1016/j.renene.2007.04.016.

Bhérer-Breton, P., Woodhouse, A., Åby, B.A., Bos-Brouwers, H., Kok, M., Olsen, H.F., 2025. Implementing sustainability frameworks at a product-level – exploring the usability. Environ. Sustain. Indic. 25, 100593. https://doi.org/10.1016/J.INDIC.2025.100593.

Boafo-Mensah, G., Darkwa, K.M., Laryea, G., 2020. Effect of combustion chamber material on the performance of an improved biomass cookstove. Case Stud. Therm. Eng. 21, 100688. https://doi.org/10.1016/J.CSITE.2020.100688.

Bouniol, A., Adinsi, L., Hotegni, F., Delpech, A., Akissoé, N., Fliedel, G., Tran, T., Dufour, D., 2020. Assessment of the Processing Ability of Improved Cassava Varieties Into a Traditional Food Product (Gari) in Benin.

Bouniol, A., Ceballos, H., Bello, A., Teeken, B., Olaosebikan, D.O., Owoade, D., Afolabi, A., Fotso Kuate, A., Madu, T., Okoye, B., Ofoeze, M., Nwafor, S., Onyemauwa, N., Adinsi, L., Forsythe, L., Dufour, D., 2024. Varietal impact on women's labour, workload and related drudgery in processing root, tuber and banana crops: focus on cassava in sub-Saharan Africa. J. Sci. Food Agric. 104, 4498–4513. https://doi.org/10.1002/JSFA.12936.

Bradbury, J.H., Cardoso, A.P., Mirione, E., Ernesto, M., Massaza, F., Cliff, J., Haque, M. R., 2005. Processing of cassava roots to remove cyanogens. J. Food Compos. Anal. 18, 451–460. https://doi.org/10.1016/j.jfca.2004.04.002.

Bryan, E., Alvi, M., Huyer, S., Ringler, C., 2024. Addressing gender inequalities and strengthening women's agency to create more climate-resilient and sustainable food systems. Glob. Food Sec. 40, 100731. https://doi.org/10.1016/J.GFS.2023.100731.

Chaplinsky, M., 2012. Feeding the world sustainably. UN Chron. 49, 15–17. https://doi.org/10.18356/89C2A819-EN.

Chen, M., Tworek, J., Jun, H., Yuan, Q., Pinto, H.P. de O., Kaplan, J., Edwards, H., Burda, Y., Joseph, N., Brockman, G., Ray, A., Puri, R., Krueger, G., Petrov, M., Khlaaf, H., Sastry, G., Mishkin, P., Chan, B., Gray, S., Ryder, N., Pavlov, M., Power, A., Kaiser, L., Bavarian, M., Winter, C., Tillet, P., Such, F.P., Cummings, D., Plappert, M., Chantzis, F., Barnes, E., Herbert-Voss, A., Guss, W.H., Nichol, A., Paino, A., Tezak, N., Tang, J., Babuschkin, I., Balaji, S., Jain, S., Saunders, W., Hesse, C., Carr, A.N., Leike, J., Achiam, J., Misra, V., Morikawa, E., Radford, A., Knight, M., Brundage, M., Murati, M., Mayer, K., Welinder, P., McGrew, B., Amodei, D., McCandlish, S., Sutskever, I., Zaremba, W., 2021. Evaluating Large Language Models Trained on Code.

Clay, N., Yurco, K., 2024. Beyond the 'gender gap' in agriculture: Africa's Green Revolution and gendered rural transformation in Rwanda. J. Rural. Stud. 112, 103444. https://doi.org/10.1016/J.JRURSTUD.2024.103444.

Cucurachi, S., Scherer, L., Guinée, J., Tukker, A., 2019. Life cycle assessment of food systems. One Earth 1, 292–297. https://doi.org/10.1016/J.ONEEAR.2019.10.014.

Dahdouh, L., Escobar, A., Rondet, E., Ricci, J., Fliedel, G., Adinsi, L., Dufour, D., Cuq, B., Delalonde, M., 2021. Role of dewatering and roasting parameters in the quality of handmade gari. Int. J. Food Sci. Technol. 56, 1298–1310. https://doi.org/10.1111/ijfs.14745.

Dhillon, R., Moncur, Q., 2023. Small-scale farming: a review of challenges and potential opportunities offered by technological advancements. Sustainability 15, 15478. https://doi.org/10.3390/SU152115478, 2023, Vol. 15, Page 15478.

Djekic, I., Pojić, M., Tonda, A., Putnik, P., Kovačević, D.B., Režek-Jambrak, A., Tomasevic, I., 2019. Scientific challenges in performing life-cycle assessment in the food supply chain. Foods 8. https://doi.org/10.3390/FOODS8080301.

Duarte, J.E., Rosero-Garcia, J., Duarte, O., Duarte, J.E., Rosero-Garcia, Javier, Duarte, Oscar, 2024. Analysis of variability in electric power consumption: a methodology for setting time-differentiated tariffs. Energies 17, 842. https://doi.org/10.3390/EN17040842, 2024, Vol. 17, Page 842.

Dyczkowska, J., Szalacha, P., 2025. Double materiality concept in practice: impact in a construction company. In: Management Decision. https://doi.org/10.1108/MD-06-2024-1350 ahead-of-print.

EEA, (European Environment Agency), 2024. Capturing the climate change mitigation benefits of circular economy and waste sector policies and measures — European Environment Agency [WWW Document]. https://www.eea.europa.eu/publications/capturing-the-climate-change-mitigation. (Accessed 3 April 2025).

Egli, F., 2020. Renewable energy investment risk: an investigation of changes over time and the underlying drivers. Energy Policy 140, 111428. https://doi.org/10.1016/J.ENPOL.2020.111428.

Esheye, S.E., 2021. Economic analyses of gari processing in Ebonyi State, Nigeria. Niger. Agric. J. 52, 237–241.

ETH, 2025. Life cycle assessment – sustainable food processing | ETH Zurich [WWW Document]. https://sfp.ethz.ch/research/life-cycle-assessment.html?utm_source=chatgpt.com. (Accessed 18 February 2025).

Ezeocha, C.V., Ihesie, L.C., Kanu, A.N., 2019. Comparative evaluation of toasting variables and the quality of gari produced by different women in Ikwuano LGA, Abia State, Nigeria. J. Food Process. Preserv. 43, e14060. https://doi.org/10.1111/JFPP.14060.

Fanzo, J., Haddad, L., Schneider, K.R., Béné, C., Covic, N.M., Guarin, A., Herforth, A.W., Herrero, M., Sumaila, U.R., Aburto, N.J., Amuyunzu-Nyamongo, M., Barquera, S., Battersby, J., Beal, T., Bizzotto Molina, P., Brusset, E., Cafiero, C., Campeau, C., Caron, P., Cattaneo, A., Conforti, P., Davis, C., DeClerck, F.A.J., Elouafi, I., Fabi, C., Gephart, J.A., Golden, C.D., Hendriks, S.L., Huang, J., Laar, A., Lal, R., Lidder, P., Loken, B., Marshall, Q., Masuda, Y.J., McLaren, R., Neufeld, L.M., Nordhagen, S., Remans, R., Resnick, D., Silverberg, M., Torero Cullen, M., Tubiello, F.N., Vivero-Pol, J.L., Wei, S., Rosero Moncayo, J., 2021. Viewpoint: rigorous monitoring is necessary to guide food system transformation in the countdown to the 2030 global goals. Food Policy 104, 102163. https://doi.org/10.1016/j.foodpol.2021.102163.

FAO, (Food and Agriculture Organization of the United), 2023. FAO Publications Catalogue 2023. FAO Publications Catalogue 2023. https://doi.org/10.4060/CC7285EN.

FAO, IFAD, UNICEF, WFP, WHO, 2024. In Brief to The State of Food Security and Nutrition in the World 2024 – Financing to End Hunger, Food Insecurity and Malnutrition in all its Forms. Rome. The State of Food Security and Nutrition in the World 2024. https://doi.org/10.4060/CD1254EN.

Filonchyk, M., Peterson, M.P., Zhang, L., Hurynovich, V., He, Y., 2024. Greenhouse gases emissions and global climate change: examining the influence of CO2, CH4, and N2O. Sci. Total Environ. 935, 173359. https://doi.org/10.1016/J.SCITOTENV.2024.173359.

Gourdel, R., Monasterolo, I., Dunz, N., Mazzocchetti, A., Parisi, L., 2024. The double materiality of climate physical and transition risks in the euro area. J. Financ. Stab. 71, 101233. https://doi.org/10.1016/J.JFS.2024.101233.

Grinspan, D., Worker, J., 2021. Implementing Open Data Strategies for Climate Action: Suggestions and Lessons Learned for Government and Civil Society Stakeholders. World Resources Institute. https://doi.org/10.46830/WRIWP.19.00093.

Hahn, S.K., 2023. Research methodology in teacher education - Dr. T. Sharon Raju, Dr. D Nagaraja Kumari - Google Books [WWW Document]. In: https://books.google.de/books?hl=en&lr=&id=_jxHEQAAQBAJ&oi=fnd&pg=PA1&dq=•%09Hypothesis:+A+hypothesis+directs+a+research+study%27s+design,+data+collection,+and+analysis+procedures+by+offering+a+precise+and+verifiable+assertion+regarding+the+anticipated+re. (Accessed 25 February 2025).

Hansupalak, N., Piromkraipak, P., Tamthirat, P., Manitsorasak, A., Sriroth, K., Tran, T., 2016. Biogas reduces the carbon footprint of cassava starch: a comparative assessment with fuel oil. J. Clean. Prod. 134, 539–546. https://doi.org/10.1016/J.JCLEPRO.2015.06.138.

Hayyat, U., Khan, M.U., Farooq, M., Sultan, M., Amjed, M.A., Liu, G., Chunyu, X., Riaz, F., Alkhedher, M., 2024. Recent developments and challenges in biomass cookstove. Energy Rep. 12, 2193–2208. https://doi.org/10.1016/J.EGYR.2024.08.016.

Herrero, M., Thornton, P.K., Mason-D'Croz, D., Palmer, J., Benton, T.G., Bodirsky, B.L., Bogard, J.R., Hall, A., Lee, B., Nyborg, K., Pradhan, P., Bonnett, G.D., Bryan, B.A., Campbell, B.M., Christensen, S., Clark, M., Cook, M.T., de Boer, I.J.M., Downs, C., Dizyee, K., Folberth, C., Godde, C.M., Gerber, J.S., Grundy, M., Havlik, P., Jarvis, A., King, R., Loboguerrero, A.M., Lopes, M.A., McIntyre, C.L., Naylor, R., Navarro, J., Obersteiner, M., Parodi, A., Peoples, M.B., Pikaar, I., Popp, A., Rockström, J., Robertson, M.J., Smith, P., Stehfest, E., Swain, S.M., Valin, H., van Wijk, M., van Zanten, H.H.E., Vermeulen, S., Vervoort, J., West, P.C., 2020. Innovation can accelerate the transition towards a sustainable food system. Nat. Food 1, 266–272. https://doi.org/10.1038/s43016-020-0074-1, 2020 1:5.

Huang, Z., Ren, X., 2024. Impact of natural resources, resilient economic growth, and energy consumption on CO2 emissions. Resour. Policy 90, 104714. https://doi.org/10.1016/J.RESOURPOL.2024.104714.

IBP, (Fraunhofer Institute for Building Physics), 2025. Life cycle assessment of food - Fraunhofer IBP [WWW Document]. https://www.ibp.fraunhofer.de/en/expertise/life-cycle-engineering/applied-methods/life-cycle-assessment-of-food.html. (Accessed 18 February 2025).

Imtiaz Anando, A., Ehsan, M.M., Karim, M.R., Bhuiyan, A.A., Ahiduzzaman, M., Karim, A., 2023. Thermochemical pretreatments to improve the fuel properties of rice husk: a review. Renew. Energy 215, 118917. https://doi.org/10.1016/J.RENENE.2023.118917.

IPPC, (The Intergovernmental Panel on Climate Change), 2022. The evidence is clear: the time for action is now. We can halve emissions by 2030 [WWW Document]. https://www.ipcc.ch/2022/04/04/ipcc-ar6-wgiii-pressrelease/. (Accessed 26 September 2024).

ISO, (International Organization for Standardization), 2023. ISO 14040:2006 - environmental management — life cycle assessment — principles and framework [WWW Document]. https://www.iso.org/standard/37456.html. (Accessed 2 February 2025).

Jalilibal, Z., Amiri, A., Castagliola, P., Khoo, M.B.C., 2021. Monitoring the coefficient of variation: a literature review. Comput. Ind. Eng. 161, 107600. https://doi.org/10.1016/J.CIE.2021.107600.

Jameel, M.K., Mustafa, M.A., Ahmed, H.S., Mohammed, A. jassim, Ghazy, H., Shakir, M. N., Lawas, A.M., Mohammed, S. khudhur, Idan, A.H., Mahmoud, Z.H., Sayadi, H., Kianfar, E., 2024. Biogas: production, properties, applications, economic and challenges: a review. Results Chem. 7, 101549. https://doi.org/10.1016/J.RECHEM.2024.101549.

Jaro, R.H., Icalina, M.A.A., Talemporos, R.T., Napiňas, P.M., Potato, D.N.C., Manuel, L. G., Cubio, G.M., Ido, A.L., Arazo, R.O., 2021. Biogas production from waste pulps of cassava (*Manihot esculenta* Crantz) via anaerobic digestion. Energy Ecol. Environ. 6, 204–212. https://doi.org/10.1007/S40974-020-00182-2/TABLES/5.

Jekayinfa, S.O., Olajide, J.O., 2007. Analysis of energy usage in the production of three selected cassava-based foods in Nigeria. J. Food Eng. 82, 217–226. https://doi.org/10.1016/J.JFOODENG.2007.02.003.

Jumare I, Fatimah, Madihah, Salleh, M., Ihsan, N., Hussin, H., Jumare I, F., Salleh, M.M., Ihsan, N., Hussin, H., 2024. Cassava waste as an animal feed treatment: past and future. Rev. Environ. Sci. Biotechnol. 23, 839–868. https://doi.org/10.1007/S11157-024-09701-7, 2024 23:3.

Jungbluth, N., Keller, R., Meili, C., 2018. Life cycle assessment of a detailed dairy processing model and recommendations for the allocation to single products. Int. J.

Life Cycle Assess. 23, 1806–1813. https://doi.org/10.1007/S11367-017-1392-X/TABLES/7.

Kamyab, H., SaberiKamarposhti, M., Hashim, H., Yusuf, M., 2024. Carbon dynamics in agricultural greenhouse gas emissions and removals: a comprehensive review. Carbon Lett. 34, 265–289. https://doi.org/10.1007/s42823-023-00647-4.

Kashala-Abotnes, E., Okitundu, D., Mumba, D., Boivin, M.J., Tylleskär, T., Tshala-Katumbay, D., 2019. Konzo: a distinct neurological disease associated with food (cassava) cyanogenic poisoning. Brain Res. Bull. https://doi.org/10.1016/j.brainresbull.2018.07.001.

Kinne, B.J., Bearce, D., Chow, W., Cranmer, S., Dorussen, H., Duffield, J., Gartzke, E., Huth, P., Jupille, J., Kahler, M., Kono, Y., Leeds, A., Maoz, Z., McKibben, H., Montgomery, A., Murdie, A., Peinhardt, C., Poast, P., Sandler, T., Schneider, G., Signorino, C., Tir, J., Ward, M., Warren, C., Westerwinter, O., Takeda, M., Scoggins, C., Kapti, E., Yang, K.-C., Ogunkoya, F., Kaplan, J., Sandlin, E., 2018. Defense cooperation agreements and the emergence of a global security network. Int. Organ. 72, 799–837. https://doi.org/10.1017/S0020818318000218.

Kpodar, K., Liu, B., 2022. The distributional implications of the impact of fuel price increases on inflation. Energy Econ. 108, 105909. https://doi.org/10.1016/J.ENECO.2022.105909.

Kumar Sarangi, P., Subudhi, S., Bhatia, L., Saha, K., Mudgil, D., Prasad Shadangi, K., Srivastava, R.K., Pattnaik, B., Arya, R.K., 2023. Utilization of agricultural waste biomass and recycling toward circular bioeconomy. Environ. Sci. Pollut. Res. 30, 8526–8539. https://doi.org/10.1007/S11356-022-20669-1/TABLES/2.

Kumar, J.A., Sathish, S., Prabu, D., Renita, A.A., Saravanan, A., Deivayanai, V.C., Anish, M., Jayaprabakar, J., Baigenzhenov, O., Hosseini-Bandegharaei, A., 2023a. Agricultural waste biomass for sustainable bioenergy production: feedstock, characterization and pre-treatment methodologies. Chemosphere 331, 138680. https://doi.org/10.1016/J.CHEMOSPHERE.2023.138680.

Kumar, R., Bhardwaj, A., Singh, L.P., Singh, G., 2023b. Quantifying ecological impacts: a comparative life cycle assessment of conventional and organic potato cultivation. Ecol. Model. 486, 110510. https://doi.org/10.1016/J.ECOLMODEL.2023.110510.

Kurtaliqi, F., Lancelot Miltgen, C., Viglia, G., Pantin-Sohier, G., 2024. Using advanced mixed methods approaches: combining PLS-SEM and qualitative studies. J. Bus. Res. 172, 114464. https://doi.org/10.1016/J.JBUSRES.2023.114464.

Kuye, A., Kumar, P., 2023. A review of the physicochemical characteristics of ultrafine particle emissions from domestic solid fuel combustion during cooking and heating. Sci. Total Environ. 886, 163747. https://doi.org/10.1016/J.SCITOTENV.2023.163747.

Laner, D., Rechberger, H., 2016. Material Flow Analysis, pp. 293–332. https://doi.org/10.1007/978-94-017-7610-3_7.

Lansche, J., Awiszus, S., Latif, S., Müller, J., 2020. Potential of biogas production from processing residues to reduce environmental impacts from cassava starch and crisp production—a case study from Malaysia. Appl. Sci. 10, 2975. https://doi.org/10.3390/APP10082975, 2020, Vol. 10, Page 2975.

Lawrence, A., Thollander, P., Andrei, M., Karlsson, M., 2019. Specific energy consumption/use (SEC) in energy management for improving energy efficiency in industry: meaning, usage and differences. Energies 12, 247. https://doi.org/10.3390/EN12020247, 2019, Vol. 12, Page 247.

Lelea, M.A., Garbaba, C.A., Guluma, A., Hensel, O., 2022. Gendering post-harvest loss research: responsibilities of women and men to manage maize after harvest in southwestern Ethiopia. Food Sec. 14, 951–963. https://doi.org/10.1007/S12571-022-01259-Y/FIGURES/2.

Leonardi, P.M., Nardi, B.A., Kallinikos, J., 2012. Materiality and Organizing: Social Interaction in a Technological World, Materiality and Organizing: Social Interaction in a Technological World. Oxford University Press. https://doi.org/10.1093/ACPROF:OSO/9780199664054.001.0001.

Li, P.C., Shih, H.C., Ma, H. wen, 2022. Applying probabilistic material flow analysis for quality control and management of waste recycling in steelmaking. Waste Manag. 144, 67–75. https://doi.org/10.1016/J.WASMAN.2022.03.011.

Luo, T., Shen, B., Mei, Z., Hove, A., Ju, K., 2024. Unlocking the potential of biogas systems for energy production and climate solutions in rural communities. Nat. Commun. 15, 1–10. https://doi.org/10.1038/s41467-024-50091-9, 2024 15:1.

Matos, C., Junkes, V.H., Lermen, F.H., Magalhães, R.F. de, Matias, G. de S., Ribeiro, J.L. D., Lenzia, G.G., Siqueiraa, H.V., 2024. Life cycle sustainability assessment of the agri-food chain: empirical review and bibliometrics. Production 34. https://doi.org/10.1590/0103-6513.20230043.

McCracken, J.P., Smith, K.R., 1998. Emissions and efficiency of improved woodburning cookstoves in Highland Gatemala. Environ. Int. 24, 739–747. https://doi.org/10.1016/S0160-4120(98)00062-2.

Mishra, A.K., Khanal, A.R., Mohanty, S., 2017. Gender differentials in farming efficiency and profits: the case of rice production in the Philippines. Land Use Policy 63, 461–469. https://doi.org/10.1016/J.LANDUSEPOL.2017.01.033.

Moores, A., Charalampopoulos, D., Williams, A., Schmidt Rivera, X., 2024. Incorporating circularity, sustainability, and systems thinking into an assessment framework for transformative food system innovation. Front. Sustain. Food Syst. 8, 1502468. https://doi.org/10.3389/FSUFS.2024.1502468/BIBTEX.

Mwape, M.C., Parmar, A., Ouézou Azouma, Y., Agboka, K., Hoedt, H., Scheffler, W., Precoppe, M., Mehlomakulu, N., Nkosi, S., Emmambux, N.M., Diale, M., Hensel, O., 2023a. Evaluation of temperature and energy requirements for gari processing at standard quality parameters in Togo. Tropentag. https://www.tropentag.de/2023/abstracts/links/Mwape_hCawoeHe.php.

Mwape, M.C., Parmar, A., Roman, F., Azouma, Y.O., Emmambux, N.M., Hensel, O., 2023b. Determination and modeling of proximate and thermal properties of de-watered Cassava Mash (*Manihot esculenta* Crantz) and Gari (Gelatinized cassava mash) traditionally processed (In Situ) in Togo. Energies 16, 6836. https://doi.org/10.3390/EN16196836, 2023, Vol. 16, Page 6836.

Mwape, M.C., Mpofu, N.S., Malanda, C.H., Kimutai, I.K., 2024. Early impacts of COVID-19 pandemic on the crude oil prices and demand in Sub-Saharan Africa: a review. Int. J. Energy Res. 2024, 5548311. https://doi.org/10.1155/2024/5548311.

Mwape, M.C., Kulig, B., Nurkhoeriyati, T., Roman, F., Parmar, A., Emmambux, N.M., Hensel, O., 2025. Modeling and optimization of energy efficiency and product quality in staple food roasting using machine learning: a case study on cassava processing. Therm. Sci. Eng. Prog. 103258. https://doi.org/10.1016/J.TSEP.2025.103258.

Nature, 2021. Control methane to slow global warming — fast. Nature 596, 461. https://doi.org/10.1038/D41586-021-02287-Y.

Nimoh, F., Richmond Anaman, R., Asiamah, M.T., Yeboah, B., Agyekum, I., Kpe, P.D.K., Kouao, D.K., 2020. Financial performance and constraints in gari production in Kumasi, Ghana. Afr. J. Food Agric. Nutr. Dev. 20, 16085–16098. https://doi.org/10.18697/AJFAND.92.18410.

Nizzy, A.M., Kannan, S., 2022. A review on the conversion of cassava wastes into value-added products towards a sustainable environment. Environ. Sci. Pollut. Res. 29, 69223–69240. https://doi.org/10.1007/S11356-022-22500-3, 2022 29:46.

Nnaji, C.C., Akanno, C.C., 2022. Assessment of environmental degradation due to processing of cassava into garri flakes using pollution indices. Environ. Process. 9, 1–18. https://doi.org/10.1007/S40710-022-00594-8/TABLES/3.

Oghenejoboh, K.M., Orugba, H.O., Oghenejoboh, U.M., Agarry, S.E., 2021. Value added cassava waste management and environmental sustainability in Nigeria: a review. Environ. Challenges 4, 100127. https://doi.org/10.1016/J.ENVC.2021.100127.

Okafor, I.F., Unachukwu, G.O., 2012. Performance evaluation of nozzle type improved wood cook stove. J. Sustain. Agric. 6, 195–203.

Okike, I., Wigboldus, S., Samireddipalle, A., Naziri, D., Adesehinwa, A.O.K., Adejoh, V. A., Amole, T., Bordoloi, S., Kulakow, P., 2022. Turning waste to wealth: harnessing the potential of cassava peels for nutritious animal feed. In: Root, Tuber and Banana Food System Innovations: Value Creation for Inclusive Outcomes, pp. 173–206. https://doi.org/10.1007/978-3-030-92022-7_6/TABLES/8.

Oksana, T., Dmytro, G., 2021. Earth's water distribution. In: Encyclopedia of the UN Sustainable Development Goals, pp. 1–14. https://doi.org/10.1007/978-3-319-70061-8_103-1.

Olajoke, A., Folasade Oyenike, A., Olayemi, A., Adetunji, O., 2019. Environmental impact of cassava processing on residents of surulere local government area, Oyo State, Nigeria. Civil Environ. Res. 11, 37–45. https://doi.org/10.7176/CER.

Olalekan, E.I., Emily, I., Toheeb, J., Rukayat, M.-S., Oladoyinbo, W., Aregbeshola, A.A., Victoria, O., Ortiz, C.C., 2023. Life cycle sustainability assessment. In: Encyclopedia of Sustainable Management, pp. 1–11. https://doi.org/10.1007/978-3-030-02006-4_289-1.

Olaniran, J.A., Jekayinfa, S.O., Agbarha, H.A., 2017. Life cycle assessment of cassava flour production: a case study in Southwest Nigeria. J. Eng. Technol. Res. 9, 6–13. https://doi.org/10.5897/JETR2015.0580.

Olukanni, D.O., Olatunji, T.O., 2018. Cassava waste management and biogas generation potential in selected local government areas in Ogun State, Nigeria. Recycling 3, 58. https://doi.org/10.3390/RECYCLING3040058, 2018, Vol. 3, Page 58.

Owusu-Darko, P.G., Golly, M.K., Owusu-Mensah, E., 2024. History of eating customs, food traditions, and dietary taboos across Western Africa: an overview on health implications, safety measures, and regulatory frameworks. In: Nutritional and Health Aspects of Food in Western Africa: A volume in Elsevier Traditional and Ethnic Food Series, pp. 9–30. https://doi.org/10.1016/B978-0-443-27384-1.00001-2.

Padilla-Rivera, A., Hannouf, M., Assefa, G., Gates, I., 2023. A systematic literature review on current application of life cycle sustainability assessment: a focus on economic dimension and emerging technologies. Environ. Impact Assess. Rev. 103, 107268. https://doi.org/10.1016/J.EIAR.2023.107268.

Papageorgiou, A., Björklund, A., Sinha, R., de Almeida, M.L.R., Steubing, B., 2024. Coupling material and energy flow analysis with life cycle assessment to support circular strategies at the urban level. Int. J. Life Cycle Assess. 29, 1209–1228. https://doi.org/10.1007/S11367-024-02320-Y/TABLES/4.

Parmar, A., Tomlins, K., Sanni, L., Omohimi, C., Thomas, F., Tran, T., 2019. Exposure to air pollutants and heat stress among resource-poor women entrepreneurs in small-scale cassava processing. Environ. Monit. Assess. 191. https://doi.org/10.1007/S10661-019-7811-7.

Pawar, R., Dalsania, K.P., Sircar, A., Yadav, K., Bist, N., 2024. Renewable energy hybridization: a comprehensive review of integration strategies for efficient and sustainable power generation. Clean Techn. Environ. Policy 2024, 1–18. https://doi.org/10.1007/S10098-024-02951-7.

Pérez Bentancur, V., Tiscornia, L., 2024. Iteration in mixed-methods research designs combining experiments and fieldwork1,2. Sociol. Methods Res. 53, 729–759. https://doi.org/10.1177/00491241221082595/ASSET/IMAGES/LARGE/10.1177_00491241221082595-FIG4.JPEG.

Phiri, R., Mavinkere Rangappa, S., Siengchin, S., 2024. Agro-waste for renewable and sustainable green production: a review. J. Clean. Prod. 434, 139989. https://doi.org/10.1016/J.JCLEPRO.2023.139989.

Piao, X., Managi, S., 2023. Household energy-saving behavior, its consumption, and life satisfaction in 37 countries. Sci. Rep. 13, 1–13. https://doi.org/10.1038/s41598-023-28368-8, 2023 13:1.

Polisetty, A., Chakraborty, D., G, S., Kar, A.K., Pahari, S., 2024. What determines AI adoption in companies? Mixed-method evidence. J. Comput. Inf. Syst. 64, 370–387. https://doi.org/10.1080/08874417.2023.2219668.

Rashid, A. Bin, Kausik, M.A.K., 2024. AI revolutionizing industries worldwide: a comprehensive overview of its diverse applications. Hybrid Adv. 7, 100277. https://doi.org/10.1016/J.HYBADV.2024.100277.

Rockström, J., Edenhofer, O., Gaertner, J., DeClerck, F., 2020. Planet-proofing the global food system. Nat. Food 1, 3–5. https://doi.org/10.1038/S43016-019-0010-4.

RT, (Republic of Togo), 2021. Support for the development of the cassava sector in Togo - Ministry of Agriculture, Village Hydraulic and Rural Development [WWW Document]. NEWS. https://agriculture.gouv.tg/appui-au-developpement-de-la-filiere-manioc-au-togo/. (Accessed 25 September 2024).

Sánchez-Gendriz, I., Pulgar-Pantaleon, E.M., Hamilton, S., Filho, F.C., Guedes, L.A., Soares, R., Peixoto, S., 2025. Python-based acoustic detection of *Penaeus vannamei* feeding behavior. Aquaculture 595, 741645. https://doi.org/10.1016/J.AQUACULTURE.2024.741645.

Schau, E.M., Alberto-Quintana, G., 2024. Sustainability | special issue: life cycle sustainability assessment: implementation and future perspectives [WWW Document]. Sustainability. https://www.mdpi.com/journal/sustainability/special_issues/IAZ3E73RB1. (Accessed 11 November 2024).

Schneider, K.R., Fanzo, J., Haddad, L., Herrero, M., Moncayo, J.R., Herforth, A., Remans, R., Guarin, A., Resnick, D., Covic, N., Béné, C., Cattaneo, A., Aburto, N., Ambikapathi, R., Aytekin, D., Barquera, S., Battersby, J., Beal, T., Molina, P.B., Cafiero, C., Campeau, C., Caron, P., Conforti, P., Damerau, K., Di Girolamo, M., DeClerck, F., Dewi, D., Elouafi, I., Fabi, C., Foley, P., Frazier, T.J., Gephart, J., Golden, C., Fischer, C.G., Hendriks, S., Honorati, M., Huang, J., Kennedy, G., Laar, A., Lal, R., Lidder, P., Loken, B., Marshall, Q., Masuda, Y.J., McLaren, R., Miachon, L., Muñoz, H., Nordhagen, S., Qayyum, N., Saisana, M., Suhardiman, D., Sumaila, U.R., Cullen, M.T., Tubiello, F.N., Vivero-Pol, J.L., Webb, P., Wiebe, K., 2023. The state of food systems worldwide in the countdown to 2030. Nat. Food 4, 1090–1110. https://doi.org/10.1038/s43016-023-00885-9, 2023 4:12.

Shah, M.A., Hayder, G., Kumar, R., Kumar, V., Ahamad, T., Kalam, M.A., Soudagar, M.E.M., Mohamed Shamshuddin, S.Z., Mubarak, N.M., 2023. Development of sustainable biomass residues for biofuels applications. Sci. Rep. 13, 1–18. https://doi.org/10.1038/s41598-023-41446-1, 2023 13:1.

Sharma, R., Choudhary, P., Thakur, G., Pathak, A., Singh, S., Kumar, A., Lo, S.-L., Kumar, P., 2025. Sustainable management of biowaste to bioenergy: a critical review on biogas production and techno-economic challenges. Biomass Bioenergy 196, 107734. https://doi.org/10.1016/J.BIOMBIOE.2025.107734.

Siva, V., Gremyr, I., Bergquist, B., Garvare, R., Zobel, T., Isaksson, R., 2016. The support of Quality Management to sustainable development: a literature review. J. Clean. Prod. 138, 148–157. https://doi.org/10.1016/J.JCLEPRO.2016.01.020.

Smith, B.L., Sekar, A., Mirletz, H., Heath, G., Margolis, R., 2024. An Updated Life Cycle Assessment of Utility-scale Solar Photovoltaic Systems Installed in the United States. Denver.

Sobowale, S., Awonorin, S., Shittu, T., Oke, M., Adebo, O., 2016. Estimation of material losses and the effects of cassava at different maturity stages on garification index. J. Food Process. Technol. 7, 554. https://doi.org/10.4172/2157-7110.1000554.

Sovacool, B.K., Bazilian, M., Griffiths, S., Kim, J., Foley, A., Rooney, D., 2021. Decarbonizing the food and beverages industry: a critical and systematic review of developments, sociotechnical systems and policy options. Renew. Sust. Energ. Rev. 143, 110856. https://doi.org/10.1016/J.RSER.2021.110856.

Sterner, T., 2024. Carbon pricing reduces emissions. Nature 632, 31–32. https://doi.org/10.1038/d41586-024-02293-w, 2024 632:8023.

Sun, J., Ru, J., Cribbs, A.P., Xiong, D., 2025. PyPropel: a Python-based tool for efficiently processing and characterising protein data. BMC Bioinformatics 26, 1–9. https://doi.org/10.1186/S12859-025-06079-3, 2025 26:1.

Suttor, G., 2018. Sweat equity: cooperative house-building in Newfoundland, 1920–1974. Hous. Stud. 1–2. https://doi.org/10.1080/02673037.2018.1419908.

Svensson, E., 2024. Materiality Matters: Unraveling the Impact of Double Materiality in Swedish Corporate Sustainability.

Taat, (Technologies for African Agricultural Transformation Programme), 2024. Cassava processing technology toolkit catalogue [WWW Document]. https://cgspace.cgiar.org/items/ab70a0c6-f7ce-4617-9313-61aa1c795842/full. (Accessed 18 February 2025).

Taulo, J.L., Sebitosi, A.B., 2016. Material and energy flow analysis of the Malawian tea industry. Renew. Sust. Energ. Rev. https://doi.org/10.1016/j.rser.2015.11.072.

TE, (The Economist), 2022. Le bol de Gari est plus cher - République Togolaise [WWW Document]. republicoftogo.com. https://www.republicoftogo.com/toutes-les-rubriques/medias/le-bol-de-gari-est-plus-cher. (Accessed 25 September 2024).

Tran, T., Da, G., Piyachomkwan, K., Moreno, M., Velez, G., Giraldo, A., Sriroth, K., Dufour, D., 2012. An assessment of environmental impacts of cassava starch extraction technologies [WWW Document]. https://www.researchgate.net/publication/274960587_An_assessment_of_environmental_impacts_of_cassava_starch_extraction_technologies/citations. (Accessed 18 February 2025).

Tran, T., Da, G., Moreno-Santander, M.A., Vélez-Hernández, G.A., Giraldo-Toro, A., Piyachomkwan, K., Sriroth, K., Dufour, D., 2015. A comparison of energy use, water use and carbon footprint of cassava starch production in Thailand, Vietnam and Colombia. Resour. Conserv. Recycl. 100, 31–40. https://doi.org/10.1016/J.RESCONREC.2015.04.007.

Tran, T., Abass, A., Taborda Andrade, L.A., Chapuis, A., Precoppe, M., Adinsi, L., Bouniol, A., Ojide, M., Adegbite, S.A., Lukombo, S.S., Sartas, M., Teeken, B., Kuate, A.F., Ndjouenkeu, R., Moreno, M., Belalcázar, J., López-Lavalle, L.A.B., Dufour, D., 2022. Cost-effective cassava processing: case study of small-scale flash-dryer reengineering. In: Root, Tuber and Banana Food System Innovations: Value Creation for Inclusive Outcomes, pp. 105–143. https://doi.org/10.1007/978-3-030-92022-7_4/FIGURES/12.

Tripathi, N., Hills, C.D., Singh, R.S., Atkinson, C.J., 2019. Biomass waste utilisation in low-carbon products: harnessing a major potential resource. NPJ Clim. Atmos. Sci. 2, 1–10. https://doi.org/10.1038/s41612-019-0093-5.

UN, 2020. THE 17 GOALS | sustainable development [WWW Document]. https://sdgs.un.org/goals. (Accessed 19 January 2021).

UNEP, (United Nations Environment Programme), 2024. The climate data challenge: the critical role of open-source and neutral data platforms – United Nations Environment – Finance Initiative [WWW Document]. https://www.unepfi.org/themes/climate-change/the-climate-data-challenge-the-critical-role-of-open-source-and-neutral-data-platforms/. (Accessed 31 October 2024).

UNFCCC, (UN Climate Chnage), 2023. COP28 agreement signals “beginning of the end” of the fossil fuel era [WWW Document]. COP28. https://unfccc.int/news/cop28-agreement-signals-beginning-of-the-end-of-the-fossil-fuel-era. (Accessed 26 September 2024).

UNSDG, (United Nations Sustainable Development Group), 2023. Towards sustainable food systems: how to feed, not deplete the world [WWW Document]. https://unsdg.un.org/latest/stories/towards-sustainable-food-systems-how-feed-not-deplete-world. (Accessed 31 October 2024).

Vahdati, M.M., Prakobboon, N., Shahrestani, M., 2018. An environmental impact assessment of the management of cassava waste: a case study in Thailand. Int. J. Biomass Renewables 7, 18. https://doi.org/10.61762/IJBRVOL7ISS2ART4868.

van den Bergh, J., Savin, I., 2021. Impact of carbon pricing on low-carbon innovation and deep decarbonisation: controversies and path forward. Environ. Resour. Econ. (Dordr) 80, 705–715. https://doi.org/10.1007/S10640-021-00594-6/METRICS.

Veiga, J.P.S., Valle, T.L., Feltran, J.C., Bizzo, W.A., 2016. Characterization and productivity of cassava waste and its use as an energy source. Renew. Energy 93, 691–699. https://doi.org/10.1016/J.RENENE.2016.02.078.

Verna, E., Genta, G., Galetto, M., 2024. Digital traceability of quality in the food processing industry. In: International Conference on Quality Engineering and Management, pp. 409–434. https://doi.org/10.1007/S12393-024-09392-4/FIGURES/4.

Visentin, C., Trentin, A.W. da S., Braun, A.B., Thomé, A., 2020. Life cycle sustainability assessment: a systematic literature review through the application perspective, indicators, and methodologies. J. Clean. Prod. 270, 122509. https://doi.org/10.1016/J.JCLEPRO.2020.122509.

Voglhuber-Slavinsky, A., Zicari, A., Smetana, S., Moller, B., Dönitz, E., Vranken, L., Zdravkovic, M., Aganovic, K., Bahrs, E., 2022. Setting life cycle assessment (LCA) in a future-oriented context: the combination of qualitative scenarios and LCA in the agri-food sector. Eur. J. Futures Res. 10, 1–23. https://doi.org/10.1186/S40309-022-00203-9.

Wei, W., Grieger, K., Cummings, C.L., Loschin, N., Kuzma, J., 2024. Identifying sustainability assessment parameters for genetically engineered agrifoods. Plants People Planet 6, 29–43. https://doi.org/10.1002/PPP3.10411.

Wiese, F., Taillard, N., Balembois, E., Best, B., Bourgeois, S., Campos, J., Cordroch, L., Djelali, M., Gabert, A., Jacob, A., Johnson, E., Meyer, S., Munkácsy, B., Pagliano, L., Quoilin, S., Roscetti, A., Thema, J., Thiran, P., Toledano, A., Vogel, B., Zell-Ziegler, C., Marignac, Y., 2024. The key role of sufficiency for low demand-based carbon neutrality and energy security across Europe. Nat. Commun. 15, 1–13. https://doi.org/10.1038/s41467-024-53393-0, 2024 15:1.

Wu1, Q., Xu2, H., Wang2, Q., Lin2, L., Li2, K., Zhang2, Z., 2017. A comprehensive review of the utilization of cassava (*Manihot esculenta* Crantz) leaf. Agric. Sci. Technol. 18, 2586.

Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A.I., Fawzy, S., Rooney, D.W., Yap, P.S., 2022. Circular economy strategies for combating climate change and other environmental issues. Environ. Chem. Lett. 21, 55–80. https://doi.org/10.1007/S10311-022-01499-6, 2022 21:1.

Zhan, L., Zhang, X., Zeng, Y., Li, R., Song, X., Chen, B., 2022. Life cycle assessment of optimized cassava ethanol production process based on operating data from Guangxi factory in China. Biomass Convers. Biorefinery 14, 26535–26552. https://doi.org/10.1007/S13399-022-03442-9/FIGURES/11.