

Participatory Modelling of the Water-Energy-Food Nexus: A Case Study of a Cassava Processing Hub in Oyo State, Nigeria

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Abstract

Cassava production plays a crucial role in providing food and income for smallholder farmers, and raw materials for agro-processors in Nigeria. However, interlinked pressures on water, energy, waste management, and local environmental systems are increasingly constraining their expansion. This study examines the dynamics that impact the sustainable growth of a cassava processing hub in Oyo State, Nigeria. The processors collectively manage approximately 6-9 tons of cassava per processing cycle, reflecting a small- to medium-scale processing operation. The hub is established on a shared land area of 4,180.64m², enabling access to pay-as-you-use equipment and infrastructure that would otherwise be too costly for smaller-scale processors. Hence, a participatory system dynamics modelling approach was employed using qualitative insights from Focus Group Discussions (FGDs) with cassava processors. These insights were used to develop a System Dynamics Model (SDM) in Stella Architect, by applying the Limits to Growth system archetype, represented through Causal Loop Diagrams (CLDs). The CLDs illustrate how initial expansion in processing capacity is constrained by resource dependencies and negative environmental feedback. The SDM reveals how feedback loops, time delays, and non-linear relationships link water use, energy demand, processing capacity, and waste discharge. Results indicate that while processors pursue expansion through a reinforcing production loop, this growth is systematically constrained by five balancing loops: environmental impact (B1), water resource dependency (B2), energy resource dependency (B3), waste management limitations (B4), and escalating operational costs (B5). By explicitly identifying these structural constraints and their interactions, the study advances system-level understanding of sustainability challenges in cassava processing hubs. The study concludes that unlocking resilient, inclusive, and sustainable growth requires coordinated interventions, including communal wastewater infrastructure, resource-efficient technologies, strengthened governance among processors, and improved access to training and knowledge through a combination of processors' collective efforts and support from Oyo State government extension services and development agencies. These insights position participatory system dynamics modelling as a practical decision-support tool for guiding sustainable agro-processing development.

Keywords: Cassava, limits to growth, wastewater, participatory modelling

Introduction

The integration of water, energy, and food systems through the Water-Energy-Food (WEF) Nexus framework provides critical insights into the complex and interdependent challenges associated with resource use and sustainability. The nexus approach emphasizes the synergies and trade-offs involved in managing water, energy, and food resources, with the overarching aim of improving resource-use efficiency, equity, and environmental sustainability (Allouche, 2024; Zhang et al., 2024). Within the context of cassava processing, this framework enables an examination of how water use, energy demand, and food security outcomes interact within

localized processing hub. A cassava processing hub serves as a shared facility for agro-processors to aggregate and process cassava, using common infrastructure to ensure processing efficiency, increase market access, and improve their livelihoods.

Cassava processing activities are particularly sensitive to WEF nexus dynamics. Inefficient water management during washing and fermentation, heavy reliance on firewood and diesel-powered equipment, and post-harvest losses represent key nexus challenges. Conversely, opportunities exist through improved processing technologies, renewable energy integration, and the valorization of cassava by-products such as peels. Recent studies have highlighted how disruptions in water availability and energy supply can significantly constrain cassava processing operations (Adekanye et al., 2013; Omotosho and Ewemoje, 2020). Empirical studies that holistically examine how cassava processors navigate the interconnected challenges of water use, energy efficiency, and food system sustainability remain limited. Situating cassava processing dynamics in Egbeda Local Government Area within the WEF Nexus framework provides valuable insights into system interactions, constraints, and leverage points to enhance sustainability and resilience in local food networks.

Methodology

A Collaborative Learning School (CLS) engagement was conducted from April to May 2025 in collaboration with executives and members of the cassava processors situated in Egbeda Local Government Area (LGA) Oyo State, Nigeria. The discussions explored the dynamics of the WEF subsystems. The outcomes captured the collective perspectives of processors related to reinforcing and balancing feedback relationships among water use, energy demand, and food (cassava) processing activities. Qualitative information from a Focus Group Discussion (FGD) during the CLS served as the foundation for developing a System Dynamics Model (SDM) using Stella Architect (Version 4.1.1). However, the primary modelling output for this phase is the Causal Loop Diagram (CLD), which visualizes the key feedback loops shaping cassava processing within the WEF nexus.

Results and Discussion

The CLD in Fig. 1 presents an integrated view of how production, resources, environmental, regulations, and economic constraints interact within cassava processing systems. The system consists of one major reinforcing loop and several balancing loops that highlight natural limits.

Core Production Loop (R1- Reinforcing Loop)

The core production loop describes the production engine of cassava processing. Increased investment boosts the availability of raw cassava, labor, and processing capacity. Higher capacity results in greater processed output (Garri/Fufu/starch), leading to higher income. Rising income fuels further investment, either individually or through pooled funds among association members in the processing hub. This creates a self-reinforcing cycle of expansion and growth in the processing hub. This loop explains why cassava processing enterprises tend to scale rapidly when resources are available.

Environmental Impact Loop (B1- Balancing Loop)

This loop describes a natural break on uncontrolled growth in the hub, thereby highlighting the environmental limits of cassava processing (Table 2). Although labor → processing capacity → processed output are positive links in the core production loop (R1), they behave differently in this environmental impact loop (B1) because health risks reduce labor availability. As production increases in the hub, effluent discharge also rises, leading to water and soil contamination. This amplifies health risks within the host community of the processing hub. Health impacts emerge only after prolonged exposure, meaning processors often perceive

Fig 1. The CLD integrated view of the reinforcing loop and balancing loops

Conclusion and Recommendations

Addressing the constraints identified in the SDM requires a combination of infrastructure investment, resource-efficient technologies, and strategic governance. These measures are essential for unlocking resilient, inclusive, and sustainable growth in cassava processing hubs. The framework highlights policy interventions that sustain productivity while mitigating environmental degradation. A key priority is collective wastewater management. Processors should coordinate efforts to prevent effluent discharge from causing environmental harm. Instead, cassava wastewater can be transformed into an economic resource through biodigesters, generating biogas and organic fertilizer. This approach not only curbs pollution but also creates new income streams.

The Ministry of Environment and relevant agencies have a critical role to play in building capacity. Training programs for processors on proper effluent discharge and waste treatment practices can strengthen compliance and reduce health risks in host communities. Regulatory oversight, combined with technical support, ensures that environmental safeguards are effectively implemented in the processing hub.

Model validation further demonstrates the value of efficiency improvement scenarios. These help processors and policymakers identify leverage points for enhancing sustainability. Integrated WEF resource management emerges as a strategic pathway, ensuring that water and energy constraints are addressed holistically while maintaining food processing productivity.

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