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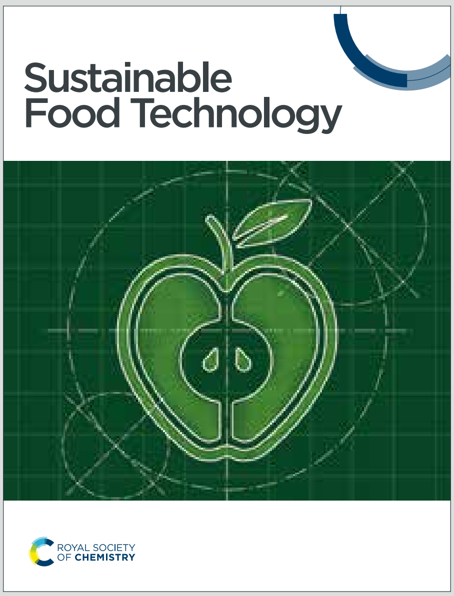

Sustainability Spotlight Statement

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Sub-Saharan Africa faces major food security challenges due to post-harvest losses (PHL) in roots, tubers, and plantains (RTPs), which are vital calorie sources. Traditional artisanal processing of RTPs into semolina such as gari, attiéké, and tapioca offers a sustainable solution by reducing PHL, extending shelf life, and increasing market value. The process involves peeling, grating, fermenting, squeezing, and heat treatment, with fermentation playing a key role in safety and flavor. This method not only minimizes waste but also empowers women-led rural enterprises and improves local nutrition. To scale this approach, supportive policies, infrastructure investment, and digital traceability (like IoT and blockchain) are essential. By leveraging traditional knowledge and technology, SSA can enhance food security, boost rural economies, and build a more resilient food system advancing key Sustainable Development Goals (SDGs) like Zero Hunger, Gender Equality, and Responsible Consumption.

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Artisanal production of semolina: an agro-industrial prospect for the reduction of post-harvest losses of roots, tubers, and plantains in Sub-Saharan Africa.

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Abstract

The region of sub-Saharan Africa faces major food and nutrition security challenges because of post-harvest losses (PHL), which affect its essential roots, tubers, and plantains (RTPs) as calorie sources. The combination of inefficient supply chains, inadequate infrastructure, equipment, and these losses creates serious economic and nutritional consequences.

The evaluation examines the scalability of traditional food crop processing into semolina in Sub-Saharan Africa (SSA) to fight PHL while creating economic opportunities for rural communities. The inclusion criteria required studies demonstrating artisanal RTP processing into semolina in sub-Saharan Africa while showing the traditional food crops associated with PHL origins.

The research data demonstrated that different production methods exist across various regional and cultural groups. The studies reveal that RTP semolina production involves five fundamental steps: peeling, grating, fermentation and squeezing, and finally heat treatment through roasting or steaming. The research demonstrates that fermentation is a crucial process that shapes final product characteristics and operating conditions by reducing toxic cyanogenic compounds and creating distinctive semolina flavours. The artisanal processing method decreases post-harvest losses through its ability to lengthen product shelf life and create higher market value from processed products. The socio-economic advantages of artisanal production include greater earnings for predominantly women producers and better availability of nutritious food in local communities. Implementing integrated policies is essential for establishing a sustainable food system to support artisanal semolina production and consumption of m'bahou, attiéké, gari, and tapioca. Using systems such as the Internet of Things (IoT) or blockchain to ensure the traceability of traditional food crops from farm to consumer could also help reduce PHL significantly.

Keywords: Agro-industry; Attiéké; Gari; M'bahou; Post-harvest losses; Semolina; Tapioca.

1.0.Introduction

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Sub-Saharan Africa is at a crossroads characterized by increasing urbanization and rapidly changing dietary habits [1]. As urban centers expand and populations seek to diversify their diets, RTPs remain fundamental pillars of food security and local economies in the region [2,3]. Rich in energy and essential nutrients, these crops form the basis of the diets of millions of people and play a crucial role in traditional and emerging farming systems [4–7].

However, despite their vital importance, SSA's RTPs sector is seriously affected by massive PHL [6]. These losses, which can reach alarming percentages, estimated at 30-40% of total production in some locations throughout the value chain from farm to consumer, are multifactorial [6,8,9]. They are mainly due to biological factors (rotting, sprouting), technical aspects (often rudimentary farming practices, inadequate harvesting and handling technologies, poor storage conditions), and socio-economic factors (limited access to markets, storage infrastructure, and processing technologies) [10–13]. The socio-economic consequences of these losses are devastating: reduced income for farmers, reduced food availability, increased vulnerability of populations, waste of precious resources, and damage to regional food security [13,14]. PHLs do not contribute to the sustainable development of emerging countries as defined by the United Nations, jeopardizing global efforts to eradicate hunger by 2030 while promoting sustainable agriculture [15].

Faced with this critical problem, a reorientation of the management system is required to explore innovative and sustainable agro-industrial solutions to add value to RTPs while drastically reducing post-harvest losses. In this context, the production of semolina from the processing of these crops is emerging as a promising avenue [16]. Locally produced from roots (such as cassava), tubers (such as yams), or plantains, semolina (such as *attiéké*, gari, tapioca, and *m'bahou*) is easy to prepare, nutritious, and meets the logistical and economic constraints of local and international producers and consumers [6]. Semolina, a dry and stable product, offers the advantage of long-term preservation, diversification of culinary uses, and creation of added value within local value chains, thereby strengthening culinary and cultural sovereignty and food security [17].

To ensure the reliability of this work, only studies published in French or English between 2000 and 2024 that dealt with semolina production processes (*attiéké*, *gari*, *tapioca*, or *m'bahou*), the PHL of RTPs, the challenges of agro-industrialization, and the development of sustainable agriculture in Sub-Saharan Africa were included. Research on inaccessible or concerned with other cereals, fruits, and vegetables was excluded. This approach enabled a focus on recent,

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peer-reviewed bibliographic data, while reflecting the current realities of this part of the continent. The results will guide all stakeholders, including policymakers, researchers, and practitioners.

This study proposes to explore the causes of post-harvest losses and the potential of local semolina production as a viable agro-industrial alternative to reduce losses of traditional food crops in Sub-Saharan Africa. It aims to synthesise available scientific and technical knowledge, identify challenges and opportunities, and contribute to the development of effective strategies for adding value to these important crops that play a central role in food security and local economies. Considering all this data, this review aims to inform the various stakeholders of the key role that semolina production could play in the sustainable transformation of the traditional food crop sector in Sub-Saharan Africa, by combining it with innovative traceability systems.

2.0.Post-harvest losses of roots, tubers, and plantains in sub-Saharan Africa.

According to the FAO report "Agricultural Production Statistics 2000-2021"[5], the world production of roots and tubers was estimated at 800 million tonnes in 2021. Africa and Asia were the primary producers, with about 340 million tonnes, accounting for almost 80% of world production. Potato was the most produced tuber in this category, with 376 million tonnes, followed by cassava with 315 million tonnes. Cassava (*Manihot esculenta*) production increased significantly by 79% compared to 2000, reflecting its growing importance as a staple food, particularly in sub-Saharan Africa. Significant roots and tubers such as sweet potato, yam, and taro contributed to world production, albeit in smaller quantities. Sweet potato production fell by 36% between 2000 and 2021, while yam and taro production increased by 90% and 17%, respectively. Despite these production levels, the region faces significant post-harvest losses threatening millions of smallholder farmers' food security and economic stability.

RTP's post-harvest losses constitute a significant challenge in SSA. Contrary to estimates of RTP production in many producing countries, there is a lack of actual, quantified data on post-harvest losses [18]. According to the FAO in its May report, "Reducing post-harvest losses for improved food and nutrition security in IGAD member states," losses in SSA are estimated to be between 40 and 50 percent for RTP and occur mainly during transport, storage, and processing [19,20]. They result from many factors, including rotting, pest infestation, poor storage conditions, lack of infrastructure, excess supply, lack of expertise about effective post-harvest management, and climatic conditions (**Figure 1**) [10]. Beyond their agricultural impact, these

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losses have economic, social, and environmental dimensions. They affect food availability and the economic stability of smallholder farmers.

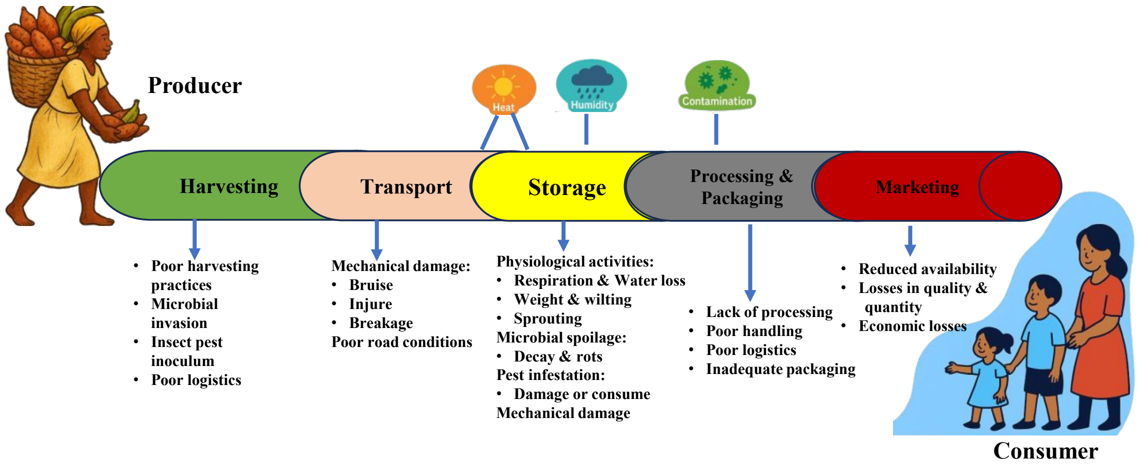

Figure 1. Steps involved in post-harvest losses from producer to consumer.

2.1. Post-Harvest Loss Causes

The PHL of RTPs, which can vary by crop and region in SSA, results from various factors that can be classified into biological, technical, and socio-economic.

2.1.1. Biological factors

Biological factors are one of the leading causes of PHL. They include rotting, sprouting, parasitic infestation, and pathogen contamination.

2.1.1.1. Rot

Microorganisms irreversibly damage food during microbial attacks, rendering it unacceptable due to rotting or producing toxic substances [11]. Root and tuber rots are often caused by fungi (such as *Ceratocystis fimbriata* (black rot), *Aspergillus niger* (dry rot), *Fusarium solani* (root and stem rot), *Plenodomus destruens* (foot rot), *Rhizopus stolonifer* (soft rot), *Lasiodiplodia theobromae* (stem end rot and dieback), and *Penicillium* spp. (blue mould)) [21,22]. Those losses due to yam dry rot, exacerbated by nematodes, can reach alarming levels [21,23]. Tubers like sweet potato and cassava are particularly susceptible to fungal and bacterial attack, especially under

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humid and hot storage conditions [24]. Mycotoxins, such as aflatoxin (a liver carcinogen), are also a major risk to PTRs, resulting in significant economic losses [11].

2.1.1.2.Physiological activities

Several physiological mechanisms controlled by respiration can occur in RTPs during storage, causing changes in the sensory and nutritional properties of the food. Natural respiration, which promotes the processes of ripening, senescence, wilting, and germination in RTPs, is responsible for a significant proportion of weight loss through the heat it generates. These changes can increase the susceptibility of the food to mechanical damage or infection by pathogens, and reduce nutritional value and consumer acceptance [11]. Premature germination of tubers, such as potatoes and yams, leads to quality deterioration and weight loss due to the mobilization of nutrient reserves [25]. Sprouting is often favored by inappropriate temperatures and humidity during storage [26]. Losses due to sprouting can be significant, especially if tubers are not stored under optimal conditions. According to Adeniyi and Ayandiji[18], a significant proportion of PHL of plantain in the Cote d'Ivoire and Nigeria, estimated at 35%, is due to the rapid ripening of this fruit, and most products made from it can only be stored for a few days. The bio-deterioration of sweet potato is responsible for about 32.5% of post-harvest losses of this tuber [21]. Degebasa[19] and Liu et al.[26] also report that maturity at harvest and tuber stress influence the degree of sprouting and reduce natural dormancy. Considering storage conditions, increased respiration (use of sugar converted from starch) during sprout growth, and moisture loss, damaged and diseased tubers sprout earlier than healthy tubers.

2.1.1.3.Pest infestation

Insect pests such as weevils, moths, rodents, and birds cause significant damage to RTP stocks. Their consumption of feed results in direct losses, not to mention the contamination caused by hair, feathers, excrement, and the unpleasant odors of urine and pheromones [11]. Nematodes, in particular, are responsible for yam dry rot, which exacerbates post-harvest losses [21,23]. Insect pests such as *Euzopherodes vapidella* contribute significantly to yam deterioration [27].

2.1.2. Technical factors

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Technical factors are crucial in PHL, primarily due to poor storage conditions and inadequate infrastructure, and suboptimal handling practices.

2.1.2.1.Poor storage conditions and inadequate infrastructure

Traditional storage structures commonly used in sub-Saharan Africa fail to adequately protect crops from pests and environmental hazards, compounded by critical deficits in infrastructure. Variations in temperature and humidity during storage accelerate losses, particularly in humid tropics, where inadequate facilities at harvest trigger rapid deterioration of produce[21]. Nwankwo and Chiekezie[28] documented cassava losses reaching 35% in Nigeria due to deficient storage systems, while Degebasa[19] highlighted physical damage to potato tubers from improper bag stacking and insufficient ventilation during storage, leading to bruising. These conditions exacerbate physiological stress in tubers, increasing water loss and quality decline[29]. Furthermore, the absence of essential infrastructure, such as modern storage silos and rural roads, severely limits farmers' capacity to preserve and market harvests[30]. This is evidenced by Chiekezie et al.[31] reporting 266,116 kg of cassava post-harvest losses, predominantly during harvesting (55%) and processing (33%) phases. These findings align with Adeniyi and Ayandiji[18], who attributed 46.45% of plantain losses to transportation gaps and 33.60% to marketing constraints.

2.1.2.2.Suboptimal handling practices

Farmers often lack training in proper handling and storage practices. Kuyu et al.[32], show that inappropriate harvesting techniques damage tubers, accelerating their deterioration. In addition, mechanical damage during harvesting and transport creates entry points for pathogens, increasing the risk of rot [19]. Kouadio et al.[33] Also, improper handling during storage and transport, combined with inadequate temperature control, exacerbates yam losses. Similarly, Sugri and Johnson[34], indicate that post-harvest losses for plantain in various African states are often due to inadequate harvesting, transport, and storage practices.

2.1.3. Socio-economic factors

Socioeconomic factors, such as limited market access and low-value addition, exacerbate post-harvest losses.

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2.1.3.1.Limited access to markets

The remoteness of production areas from urban markets, combined with poor transport infrastructure, leads to significant losses. Farmers are often forced to sell their produce at low prices to avoid degradation, reducing their income and ability to invest in better conservation practices [35]. In Nigeria, for example, these constraints can reach 50-60% [31]. Lack of market access and high temperatures contribute to increased losses, especially in countries such as Ghana [36,37].

2.1.3.2.Low product value

RTPs are often undervalued in the market due to their high perishability, which limits incentives to invest in preservation and processing technologies. The low value of RTP products, such as flour, crisps, or drinks, is a significant challenge for the agri-food sector in Africa, which can be supported by the analysis of several studies on the characteristics, preservation practices, and market demand for these products, which are indicators of commercial outlets.

The low value added of tubers can be attributed to problems related to product quality and preservation. Research has shown that the storage time of untreated tubers can lead to significant weight losses of up to 43%, while properly treated tubers lose only 17% of their weight [38]. It is also important to note that the quality of tubers such as cassava is influenced by various factors, including the variety grown and ecological conditions [39,40]. Therefore, it is necessary to favor adapted varieties and develop effective preservation techniques to improve cassava's value.

According to the data collected, there is a growing demand for alternatives to imported wheat flour. However, national production of tubers such as cassava and sweet potato is still insufficient to meet the needs of the industrial market [41]. Despite their high nutritional potential, tuber-based products have failed to penetrate the market due to increasing wheat imports and an ill-defined substitution strategy [41]. In addition, efforts must be made to process these products, particularly by producing better-quality bread flour [41,42].

The value of products such as plantain also appears to be under-exploited. The processing of plantain into products such as chips, juice, and semolina could benefit from research into methods to prevent browning and recover extraction residues[43]. In addition, the use of

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innovative approaches, such as traditional storage in refrigerated pots, could help to preserve these products better, thereby improving their quality and competitiveness in the market [44].

2.1.3.3.Poverty and lack of finance

According to Anyoha et al.[10], the leading cause of post-harvest losses in cassava in Imo State, Nigeria, is a lack of finance. Small-scale producers, who make up the majority of farmers in SSA, often lack the financial resources to invest in modern storage infrastructure or processing technologies [45]. This forces them to resort to inefficient, traditional practices, perpetuating loss cycles.

2.2.Impact of post-harvest losses

The impact of PHL on roots and tubers in SSA is seen in two main areas: food security and farmers' incomes.

2.2.1. Social Impact

Post-harvest losses of RTPs in SSA directly impact food security, mainly by reducing the availability of staple foods. Roots and tubers such as cassava, yams, sweet potatoes, and plantains are staple foods for much of the sub-Saharan population. However, their high perishability and poor storage and transport conditions result in significant losses.

2.2.1.1.Threats to food security

Post-harvest losses (PHL) in Roots, Tubers, and Plantains (RTPs), reaching up to 50% of production or 20% according to Rwubatse et al.[46], severely reduce food availability in sub-Saharan Africa (SSA), where over 250 million people faced undernourishment in 2019[47]. Staple crops like cassava, vulnerable to deterioration within 1 to 3 days post-harvest[48], exemplify this crisis. These losses not only diminish food quantity but also degrade nutritional quality, exacerbating malnutrition as pests and poor storage contaminate calorie- and nutrient-dense RTPs essential for rural populations[48,49]. Consequently, urban and peri-urban households increasingly rely on imported processed foods to meet demand for convenient diets[50], while rural communities become dependent on volatile global markets. This import dependency

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exposes populations to price shocks and supply-chain disruptions, undermining local food sovereignty. As Thomas et al.[51] emphasize, strengthening post-harvest systems is critical to enhancing food access, stabilizing farmer livelihoods, and securing sustainable food systems across SSA.

2.2.1.2.Impact on Sustainable Development Goals (SDGs)

Cultivating plantains, sweet potatoes, cassava, yams, taro, and potatoes is critical to achieving the Sustainable Development Goals (SDGs), especially Goal 2, which aims to end hunger and promote sustainable agriculture [20] Root and tuber crops are recognized for their resilience and adaptability to various climates. They also make significant nutritional contributions, which enhance food security in vulnerable regions [52].

The production of these crops directly supports food security by providing calorie-dense foods essential for large populations, especially in developing regions. Sweet potatoes and yams, for example, have been extensively promoted due to their high yields and nutritional value. These crops have the potential to reduce hunger levels if widely adopted by households [53,54]. Furthermore, studies highlight the importance of sweet potatoes for subsistence and for bolstering local economies, especially when smallholder farmers cultivate them [54,55]. The genetic diversity of these crops allows them to adapt better to climate change, thus contributing to the resilience of agricultural systems under varying conditions [56,57].

Additionally, cultivating these tuberous crops within agroecological frameworks is associated with benefits aligned with the SDGs. These practices improve soil quality, reduce reliance on chemical fertilizers, and promote environmental sustainability and enhanced agricultural productivity [55,58]. For instance, integrating sustainable practices into sweet potato and cassava cultivation can mitigate environmental degradation and foster healthier soil, supporting more sustainable agricultural methods [58,59].

Moreover, these crops' nutritional benefits provide a way to combat micronutrient deficiencies, a challenge highlighted in SDG 2. Incorporating biofortified varieties, such as orange-fleshed sweet potatoes, has been recognized as an effective strategy to address issues like vitamin A deficiency [60,61]. These crops are useful beyond direct food consumption because they can also

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be used to produce biofuels and other industrial products, which aligns with SDG 7, promoting affordable and clean energy [62].

Furthermore, intercropping these root and tuber crops with other food varieties enhances agricultural diversity and resilience against pests and diseases. This improves overall food systems and contributes to the socioeconomic stability of rural communities [54,63,64]. These integrative approaches are essential for achieving multiple SDGs because they ensure that agricultural practices are sustainable, inclusive, and equitable [65].

Emphasizing the cultivation of root and tuber crops, such as sweet potatoes, cassava, yams, and taro, is crucial for advancing the goals of the 2030 Agenda for Sustainable Development. They address immediate food security needs, promote sustainable agricultural practices, and improve nutritional outcomes. Thus, they provide resilience against economic and environmental challenges while supporting overall socioeconomic development [54,63,66]. Strategically integrating these crops into agricultural policies and programs is vital for achieving Sustainable Development Goal 2.

2.2.2. Economic impact

Post-harvest losses significantly impact farmers' incomes, especially for smallholder farmers who depend on crop sales for their primary source of income. This issue is particularly acute in the cultivation of root and tuber crops, such as taro, sweet potatoes, cassava, and yams. For example, viral diseases can devastate taro production, resulting in yield losses ranging from 20% to 60%. This significantly compromises farmers' financial viability and necessitates the implementation of effective management strategies to mitigate these losses [67,68]. Additionally, studies suggest that inadequate handling and storage practices after harvest can result in losses, further exacerbating economic challenges for small-scale farming operations [10,69].

The economic implications of post-harvest losses are evident in the analysis of specific crops, such as cassava. Cassava is vulnerable to excess supply, improper processing, and inadequate storage infrastructure, resulting in substantial waste and decreased income potential for farmers [10]. Statistical data suggests that post-harvest losses for cassava can exceed 30%, further illustrating the pressing economic challenges faced by these communities [70].

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Environmental factors such as high humidity and poor infrastructure further exacerbate the situation by accelerating the deterioration of storage quality for root and tuber crops. For example, poor storage conditions accelerate the physiological deterioration of taro, resulting in rapid quality loss and increased post-harvest waste [71,72]. Addressing these storage challenges is crucial. Adopting better preservation methods, such as treatments that delay enzymatic browning, could markedly improve the shelf life of crops and enhance farmers' economic returns [71,72].

2.2.2.1.Reduced income

Post-harvest physiological deterioration caused by physical damage during harvest reduces root and tuber quality, leading to price drops that directly lower farmer incomes. Global economic losses from this waste amount to $940 billion annually[10], as observed in plantain systems, where pre-harvest phytosanitary issues create economic gaps for dependent farmers[73], and cassava value chains where extreme perishability limits market access and income opportunities[48].

This income loss perpetuates a cycle of poverty: with 66% of West African employment tied to the food economy[50], farmers' inability to invest in improved practices or storage tech reduces long-term productivity. Consequently, diminished reinvestment capacity deepens rural poverty and food insecurity[46], trapping communities in financial vulnerability. This self-reinforcing dynamic disproportionately affects smallholders, who lose 15-35% of potential earnings from PHL, while weakening regional food systems' resilience.

2.2.2.2.Market instability

Market instability triggered by post-harvest losses (PHL) manifests through volatile price mechanisms and disrupted supply-demand equilibria. When PHL reduces available crop volumes, particularly perishable staples like cassava or plantain, local markets experience *supply shocks* that inflate consumer prices while depressing farmgate prices. This asymmetry erodes trader margins and discourages long-term contracts, fragmenting value chains[51]. Consequently, risk-averse investors avoid capital injection into agricultural cooperatives, processing facilities, or storage infrastructure[74]. The resulting underinvestment stifles productivity gains, entrenches subsistence farming models, and perpetuates rural economic stagnation. Critically, this cycle undermines SDG targets for poverty reduction (Goal 1) and

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sustainable agri-food systems (Goal 2), as confirmed by Thomas et al.'s analysis of West African economies[51].

3.0.A Technical analysis of unit operations and their impact on the properties: Overview of semolina made from cassava and plantain

Semolina is a granular product obtained by coarsely grinding starchy materials (cereals, roots, tubers, or fruits). It is intermediate in size between flour and whole grains, characterized by its grainy texture and ability to absorb liquids. Traditionally produced from durum wheat, it can also be made from tropical resources such as cassava, plantain, or yam, serving as a base for various food preparations like couscous and traditional dishes consumed mainly in Africa and South America[75–77]. It is a form of valorization aimed at reducing post-harvest losses thanks to its stability and versatility.

Gari, *tapioca*, and *attiéké* are three staple foods widely consumed in many parts of the world, particularly in Africa and South America, all of which are derived from cassava root. Cassava is a tuber exceptionally rich in starch, making it a primary source of energy for millions of people[78]. Although the raw material is the same, complex and varied processing methods result in finished products with distinct physical, organoleptic, and nutritional properties. Unlike these three products, *m'bahou* is a traditional Ivorian dish that uses another major starch, plantain, as its main ingredient[6]. **Figure 2** shows the artisanal production process for certain semolinas derived from cassava and plantain (*attiéké*, *gari*, *tapioca*, and *m'bahou*). These processes vary from region to region and directly influence all the characteristics of the semolina produced (**Table 1**). Artisanal methods, although mostly manual, can be optimized to improve product quality and safety while preserving their cultural identity. Understanding these processes is therefore crucial for the development and improvement of the quality of traditional semolina in Sub-Saharan Africa.

Table 1. Impacts of unit operations on semolina properties.

Process steps	**Impact on properties**			
	Nutritional	**Functional**	**Rheological**	**Sensory**

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Peeling and washing	Reduction of anti-nutrients and contaminants.	Increased contact surface for subsequent steps.	N/A	N/A
Grating	N/A	**Fine grating**		
		Increases water absorption capacity and swelling power.	Improves dispersion and texture.	Produces a smoother texture.
		Coarse grating		
		Reduces water absorption capacity and swelling power.	More granular texture.	Slightly coarse texture.
Fermentation	Reduction of cyanogenic glycosides (cyanide). Improves nutrient bioavailability.	Improves dispersibility and solubility.	**Fermentation too long**	
			Reduces maximum viscosity.	Risk of excessive acidity.
		Fermentation too short		Develops a slightly acidic flavour.
		Risk of poor dough formation.	Produces firmer semolina.	
Squeezing	Concentrates nutrients, but may result in a minor loss of soluble nutrients.	Reduces moisture, which improves product stability.	N/A	N/A
Roasting		**Low temperature**		
	Extends shelf life by reducing moisture.	Preserves the integrity of starch.	Produces firmer semolina.	Produces a more attractive colour and flavour.
	High temperature			

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	Loss of certain nutrients (ex., carotenoids).	Reduces water absorption capacity.	Reduces maximum viscosity.	Risk of excessive browning and burnt flavour.
Stockage	**Stored incorrectly**		N/A	N/A
	Risk of oxidation and loss of nutrients	degrades functional properties		

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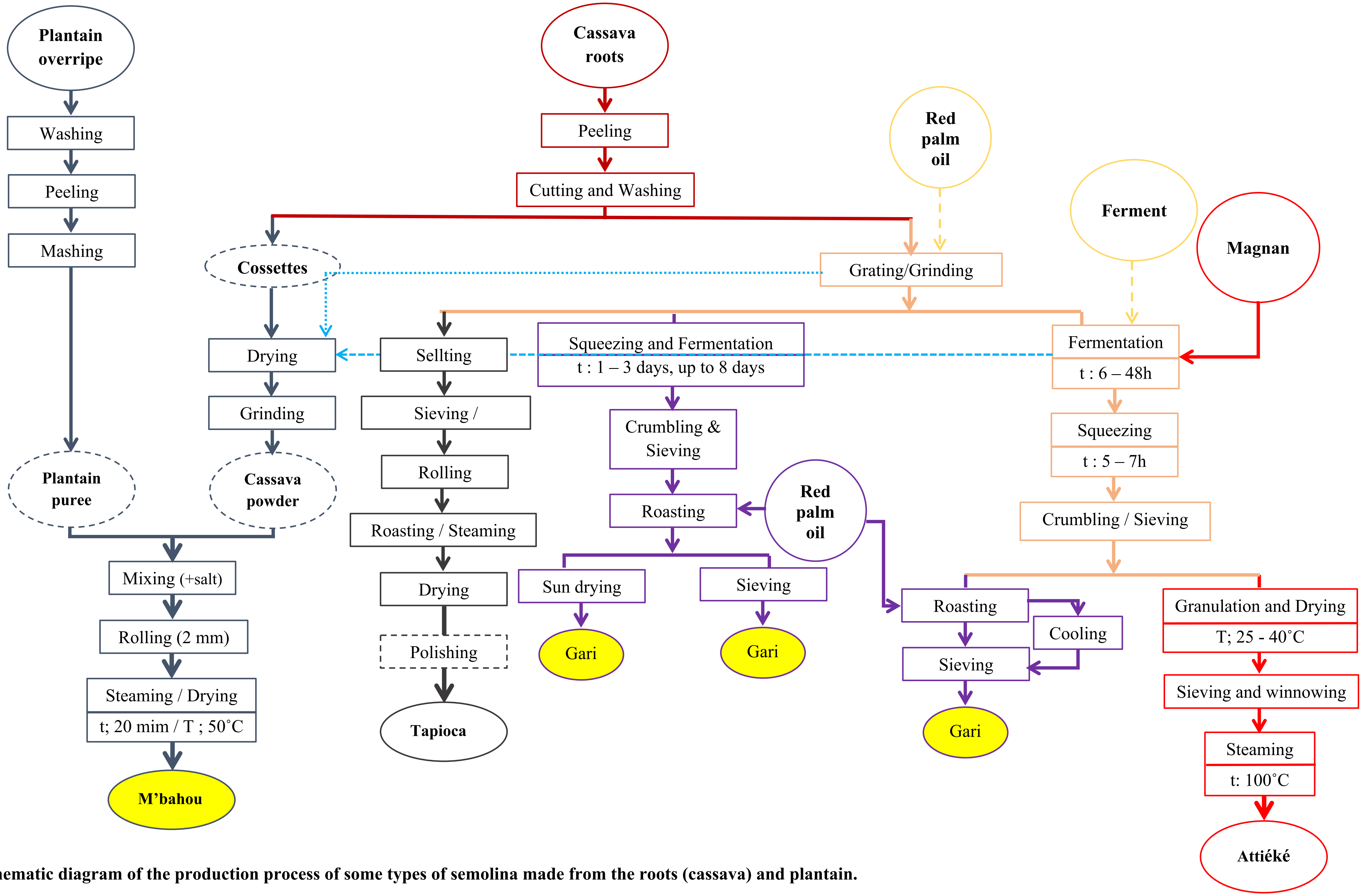

Figure 2. Schematic diagram of the production process of some types of semolina made from the roots (cassava) and plantain.

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3.1. *Attiéké*: Cassava couscous, a fermented product

Attiéké is a fermented cassava couscous, an iconic dish in Ivorian cuisine[79]. It is distinguished by its grainy texture and slightly sour taste, which are the direct result of its manufacturing process, particularly fermentation. Consumed initially in the south of Côte d'Ivoire, the product has grown in popularity and is now produced and consumed throughout the country and in other parts of West Africa [80,81]. Women have traditionally dominated the production process of *Attiéké* and require specific technical skills. However, the quality of *Attiéké* can vary considerably depending on the cassava variety used, processing techniques, and fermentation inoculants [81,82].

3.1.1. Nutritional value of *Attiéké*

Attiéké is an energy-rich food, but its caloric value is significantly lower than that of gari, ranging from 161.95 to 215.26 kcal per 100 g[83]. This lower energy density is attributed to its higher moisture content, which ranges from 50 to 55% of the product[83,84]. It is mainly composed of carbohydrates (36.6 g to 47.11 g per 100 g)[83], making it a sustainable source of energy. Like other cassava products, *Attiéké* is low in protein (0.77 to 1.74 g) and fat (0.15 to 3.60 g)[83,84]. It is a source of fiber (approximately 1.5 g), which aids digestion and promotes a feeling of satiety[84]. Minerals are present, with potassium (47.22 mg per 100 mg of ash) being the most abundant, followed by calcium (6.84 mg), phosphorus (6.20 mg), and magnesium (4.38 mg)[84]. This profile indicates that *Attiéké* is typically consumed as a complementary component of a meal, paired with protein-rich dishes to achieve a balanced diet. The final nutritional quality of the product is not solely a function of the raw cassava but is significantly influenced by the production processes.

3.1.2. Unit operations of *Attiéké* production and their impacts

The production of *Attiéké* is a complex process involving a series of distinct unit operations. Each of these steps plays a critical role, not only in transforming the raw cassava into the final semolina but also in shaping its fundamental properties. The following sections detail each unit operation and its specific, integrated impacts on the nutritional, functional, rheological, and sensory characteristics of the finished product.

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3.1.2.1.Peeling and Washing

This foundational step is the initial point of processing for cassava roots. It involves the physical removal of the outer skin and a subsequent cleaning with water. This operation is critical for food safety. It removes impurities and, most importantly, eliminates toxic compounds such as cyanogens that are present in the cassava skin[85,86]. This reduction of anti-nutrients and contaminants is a prerequisite for producing a safe food product [84,87]. Peeling and washing also serve a functional purpose by increasing the surface area of the cassava root that is exposed. This is a crucial preparation step for subsequent operations, as a larger surface area facilitates more effective grinding and fermentation.

3.1.2.2.Grinding

Following the initial preparation, the cassava roots are ground into a fine paste [80]. The fineness of this grinding process has a significant and direct influence on the properties of the semolina. Grinding is essential for breaking down the cellular structures of the cassava, a necessary action to improve starch availability for the subsequent fermentation process [88]. The particle size resulting from grinding is a primary determinant of the final product's texture. A fine grating process increases the cassava's water absorption capacity and swelling power, which in turn leads to a smoother, more dispersible texture in the final semolina[89]. Conversely, a coarser grating reduces the water absorption and swelling power, resulting in a more granular and slightly coarse texture[89]. This direct relationship between particle size and texture allows producers to control the final mouthfeel of the *Attiéké*.

3.1.2.3.Fermentation

This is a crucial, multi-hour process that typically lasts between 6 and 48 hours [81,85,88]. It is initiated by a traditional cassava-based starter known as "*magnan*," which contains a variety of microbial strains, notably yeast-like *Candida tropicalis* and lactic acid bacteria[90]. Fermentation is the principal detoxification mechanism, responsible for significantly reducing toxic cyanogenic glycosides and hydrocyanic acid[90–92]. It also improves the bioavailability of nutrients, such as vitamins and amino acids[93,94]. The duration and control of fermentation have a profound influence on the final product's quality. An optimally controlled fermentation results in a light, granular texture and the development of the characteristic, slightly acidic

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flavor and aroma[95,96]. However, fermentation that is too short poses a risk of incomplete dough formation and leaves high levels of residual cyanide[97,98]. Conversely, an excessively long fermentation period can lead to an overly acidic taste and a reduction in the maximum viscosity of the cooked product [99,100]. The variability often seen in traditional starters can lead to inconsistent product quality, highlighting the importance of standardized fermentation conditions to ensure uniform sensory and safety attributes in the final product.

3.1.2.4.Squeezing

The fermented cassava pulp is subjected to a pressing operation to remove excess water[88,101]. The removal of water during this stage concentrates the remaining nutrients in the pulp[101,102]. However, it is important to acknowledge that there can be a minor loss of soluble nutrients in the expelled water, which represents a trade-off inherent in the process. By reducing the moisture content, squeezing significantly improves the product's stability and facilitates subsequent processing steps such as sieving and drying[80,103]. This step is also fundamental in achieving the granular texture that is characteristic of *Attiéké*[88,102].

3.1.2.5.Sieving and Granulation

This operation involves passing the squeezed pulp through a sieve to separate fine particles and achieve a semolina with a uniform size[104]. The primary function of this step is to produce a semolina of uniform granulometry. This directly impacts the final texture of the *Attiéké*, which must be granular and light to be acceptable to consumers[86,104]. The sieving and granulation process ensures the consistency of this key textural property.

3.1.2.6.Drying

The semolina's moisture content is reduced to between 12% and 15% through drying, which is typically done in the sun or with mechanical dryers [105,106]. Drying is a crucial preservation step. The reduction in moisture is essential for prolonging the product's shelf life and inhibiting the growth of undesirable microorganisms, thereby ensuring its microbiological safety[90].

3.1.2.7.Steaming

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Steaming is the final essential heating step in *Attiéké* production. It gives the semolina its final texture and is critical for both safety and digestibility[88]. This operation is vital for eliminating any remaining traces of cyanide residues that may have survived the fermentation process[107]. Steaming also improves the digestibility of the product and aids in the retention of key nutrients, such as carotenoids, in varieties of biofortified cassava[106]. The steaming process is fundamental to developing the final texture, which is a key sensory attribute that determines consumer acceptance.

3.2. *Gari*: A highly energetic cassava semolina

Gari, also known as "saviour" or tapioca in Cameroon, is a staple food in sub-Saharan Africa. It is a cassava semolina characterized by a fine or coarse texture, whose color can vary from white to yellow depending on the production methods[108]. It is obtained through a transformation process that includes grating, fermentation, pressing, and roasting the cassava pulp[78]. Each of these stages influences not only the food safety of the product but also its nutritional, functional, and rheological properties.

3.2.1. Nutritional value of *Gari*

Gari is a staple food in sub-Saharan Africa, and its nutritional properties, like those of other cassava-based foods, are primarily shaped by its production process. It is primarily a source of energy and carbohydrates. It has a high energy value, with data ranging from 330 to 370 kcal per 100 g. This calorie density comes mainly from its high carbohydrate/starch content, which makes up most of its composition, with values ranging from 62.6 g to 84.4 g per 100 g of product [108,109]. The proportion of sugars is very low, generally less than 0.5 g per 100 g. On the other hand, *Gari* is very low in protein and fat. Protein content is marginal, ranging from 1.96 g to 2.88 g, while fat is almost absent, with values ranging from 0.33 to 1.58 g [108,110]. It is also a source of dietary fiber, with an average value between 1.24 and 3.46 g per 100 g [108], as reported in one source. However, another source mentions an exceptionally high value of 48 g, which is likely a measurement error. Micronutrients such as vitamin A (13.2–732 IU/100 g) [108], calcium (31.41-49.86 mg), and iron (23.0-62.4 mg) are also listed [110]. The final nutritional composition is a direct consequence of a series of unit operations, most notably fermentation and roasting.

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3.2.2. Unit operations of Gari production and their impacts

3.2.2.1. Peeling and Washing

This initial step involves peeling the cassava roots and washing them to remove dirt, impurities, and the outer skin. This is a crucial preparatory stage that removes anti-nutrients and contaminants, thereby laying the groundwork for a safe final product [111,112].

3.2.2.2. Grating

The peeled cassava is grated into a fine pulp. The fineness of this grating, whether done manually or mechanically, is a critical variable. The particle size of the grated pulp directly impacts the final texture and functional properties of the gari [109,113]. A fine grating increases the contact surface area, which improves the product's water absorption capacity and swelling power. A coarser grating, on the other hand, results in a more granular and gritty texture [113,114].

3.2.2.3. Fermentation

This is a critical process that typically lasts for 2 to 3 days, during which the cassava pulp is detoxified by the action of microorganisms. Fermentation is the primary step for reducing toxic cyanogenic glycosides to safe levels. Optimal fermentation time not only ensures food safety but also improves the bioavailability of nutrients. The duration of fermentation has a direct effect on the cooked gari's texture and viscosity. An optimal fermentation period develops a desirable flavor and texture [115–117], whereas excessive fermentation can lead to an overly acidic product and cause significant starch degradation, which reduces the viscosity of the cooked gari [99,100].

3.2.2.4. Squeezing

The fermented cassava pulp is pressed to remove excess moisture. This dehydration step is essential for preventing product deterioration and improving its stability during storage [118]. It also prepares the pulp for the subsequent roasting stage and plays a role in shaping the final texture.

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3.2.2.5. Roasting (Garification)

This is the final stage of *Gari* production, where the dehydrated pulp is heated to high temperatures to form the characteristic crunchy granules. The high temperatures used during roasting can lead to a loss of certain nutrients, such as carotenoids, particularly in fortified cassava varieties [113,119]. The roasting temperature and duration are the most significant factors in determining the final gari's color, flavor, and texture. Well-controlled roasting produces gari with a slightly acidic flavor, an attractive color, and a uniform texture [115–117]. Insufficient roasting results in a poor texture, while excessive roasting can lead to a burnt flavor and excessive browning [113,119,120]. The temperature also affects the rheological properties; lower roasting temperatures tend to preserve the integrity of the starch, which results in a firmer final product [112,113].

3.2.3. Comparison of traditional and mechanized *Gari* production methods

The production of *Gari* can be broadly categorized into two methods: traditional and mechanized. Each approach presents distinct advantages and disadvantages that influence the final product's quality, safety, and efficiency (**Table 2**).

Traditional Methods (**Figure 3**): These methods, often manual, are characterized by high variability in product quality. A key feature of traditional production is the potential for prolonged fermentation times, which are highly effective at reducing cyanide content and enhancing the final flavor and texture. However, the roasting process in traditional methods is often less controlled, which can lead to a greater loss of nutrients, such as carotenoids [119,121].

Mechanized Methods (**Figure 4**): Mechanized production is more uniform and efficient, allowing for more precise control over process parameters [122]. This precision, particularly in the roasting stage, can improve nutrient retention and lead to a more consistent overall product quality [111,123]. However, mechanized methods may not always guarantee the same level of optimal cyanide reduction as the longer, traditional fermentation processes.

This comparison reveals a fundamental trade-off: traditional methods, while less uniform, may offer superior benefits in terms of detoxification and flavor development due to extended fermentation, whereas mechanized methods provide greater consistency, efficiency, and better

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control over parameters like roasting, which can enhance nutrient retention. An integrated approach that combines the best practices of both methods, such as using a standardized mechanical process with an optimized, biologically driven fermentation step, could represent a path toward producing a consistently high-quality and safe gari [99,100].

Particular attention should be paid to the fermentation and roasting stages, which are crucial for reducing anti-nutrients and improving gari's functional and sensory properties. Finally, promoting improved production techniques could increase food security and strengthen the economic empowerment of local communities, especially women, who play a central role in artisanal gari production [124].

Table 2. Comparison of Traditional and Mechanized Gari Production Methods.

Feature	**Traditional Gari Production**	**Mechanized Gari Production**
Product Uniformity	High variability	High uniformity
Efficiency	Lower (manual)	Higher (automated)
Cyanide Reduction	Highly effective due to long fermentation	It may not always be optimal
Nutrient Retention	Potential loss of nutrients from prolonged roasting	Improved retention with precise roasting control
Final Flavor & Texture	Superior flavor from long fermentation	More consistent, but flavor may differ

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Figure 3. The artisanal gari production process.[125]

(1) Cassava tubers after harvesting, (2) tubers are peeled and washed, (3) mechanical grinding of the tubers, (4) collection of the ground tubers, (5) palm oil and soy bean added, (6) placed in buckets, sealed with lids, and left to ferment for 48 h, (7) and (8) mixture is placed in a large bag, (9) the dewatering process, (10) sieving to remove large particles, (11) area where mixture is fried/garified, (12) frying/garification, (13) fine sieving (14) comparison between traditional gari (left) and gari fortified with soybean and palm oil.

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Figure 4. Mechanised gari production process diagram.[126]

3.3. *Tapioca*: A pure and versatile cassava starch

Tapioca, also known as sago in India, is a product distinct from *Gari* and *Attiéké*. It is an almost pure starch extracted from cassava root and sold in the form of flour, flakes, or pearls. As a starch, its nutritional composition is heavily focused on carbohydrates and has a limited nutritional profile.

3.3.1. Nutritional profile

The energy value of dry *Tapioca* is similar to that of *Gari*, with values of around 342-358 kcal per 100 g [127]. It is almost exclusively composed of carbohydrates (80.9 g to 89 g per 100 g) [127,128]. This concentration of carbohydrates is its main characteristic. In contrast, *Tapioca* contains very little protein (1.03 g to 1.1 g), fat (0.24 g to 1.6 g), and dietary fiber (1.8 g to 2.7 g) [127,128]. Its micronutrient density is also low, although some sources mention the presence of iron, potassium, and magnesium [128]. *Tapioca* contains no vitamins A, C, E, or B12. Its production involves complex processes directly influencing its final characteristics, such as texture, viscosity, and nutritional properties.

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3.3.2. Unit operations of *Tapioca* production and their impacts

3.3.2.1. Starch Extraction

This multi-stage process is the initial and most critical set of operations for *Tapioca* production. It involves the preparation of the cassava roots and the physical separation of the starch from other components.

This process begins with washing and peeling the cassava roots to remove impurities and the toxic, cyanogenic skin [85]. The peeled roots are then grated to facilitate starch extraction. The resulting mixture is then washed and filtered, and the starch is separated by sedimentation [129]. The quality of the raw cassava and the fineness of the grating directly influence the starch yield and the quality of the final product [130]. Modern mechanical grating methods are capable of producing a higher-quality starch with less fibrous residue [129]. This initial phase is also essential for safety, as the washing and peeling steps remove the majority of the toxic compounds. The quality of the water used during sedimentation can also affect the physicochemical properties of the starch, demonstrating that seemingly minor details can have a significant impact on the final product.

3.3.2.2. Heat Treatment (Gelatinization)

Once the starch has been extracted, it undergoes a heat treatment process that alters its functional and sensory properties. Starch pearls are immersed in boiling water, causing the granules to absorb water, swell, and become translucent. This gelatinization process is critical for achieving the desired soft, elastic texture of finished products like tapioca pearls [131,132]. It also significantly affects the viscosity of the tapioca, which is crucial for its use as a thickening agent in sauces, soups, and desserts [134]. Moisture heat treatment can be used to modify the starch structure, which lowers the gelatinization temperature, demonstrating how process parameters can be adjusted to achieve specific functional outcomes.[132] However, there is a limit to this process; excessive heat treatment can reduce the starch's swelling capacity, which would negatively impact the final texture [133]. This underscores the need for precise process control to achieve the desired result.

3.3.2.3. Drying

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The gelatinized starch is then dried to form the *Tapioca* granules. Drying is a key step that improves both the texture and the shelf life of the *Tapioca* granules [136].[1] Advanced techniques, such as microwave drying, can offer further benefits by also inducing a form of pre-gelatinization, which increases the starch's binding capacity and results in more uniform granules [137]. This shows how technological innovation can combine multiple process benefits into a single, efficient operation.

3.4.*M'bahou*: A traditional dish made from overripe plantains

M'bahou differs fundamentally from the other foods studied, as it is made from plantains rather than cassava. It is a traditional dish eaten in eastern and central Côte d'Ivoire (culinary heritage of the Agni and Baoulé ethnic groups [3,6]), and its production is notably focused on utilizing "senescent" plantains, a product that is often rejected in the market due to its perishability [6].

3.4.1. Specific nutritional composition: a different profile from cassava products

The nutritional profile of *M'bahou* is exceptionally rich, particularly in micronutrients. A study[6] on dried *M'bahou* reveals that it has a low moisture content (7.13%) and is an excellent source of carbohydrates (87.64%) and starch (61.15%).4 Its energy value is approximately 364.87 kcal per 100 g. What sets it apart from cassava products is its richness in micronutrients. *M'bahou* contains significant amounts of vitamins, including vitamin A (134.67 µg), vitamin B1 (49.57 µg), and vitamin B2 (564.87 µg) per 100 g. Its mineral composition is also remarkable, with high levels of potassium (120.32 mg), calcium (85.50 mg), sodium (55.71 mg), and magnesium (46.23 mg). The dish is also a source of phytochemicals, such as polyphenols, phytates, tannins, and flavonoids. The most significant aspect of its nutritional profile, however, lies in its potential for enhancement through fortification. The replacement of a portion of the cassava powder with legume powders, such as soya or cowpea, can substantially increase the protein and lipid content, thereby improving the overall nutritional balance and reducing the glycemic index of the food [3,6].

3.4.2. Unit operations of *M'bahou* production and their impacts

3.4.2.1. Preparation of ingredients

The production of *M'bahou* begins with the preparation of its two primary ingredients: senescent plantain and cassava. The plantains are washed, peeled, and mashed [6], while the cassava roots are peeled, grated, dried, and ground into a powder. A key process variable in this stage is the optional pre-fermentation of the cassava flour for 2 to 10 hours [3].

3.4.2.2. Mixing, Granulation, and Drying

The plantain puree is mixed with the cassava flour (fermented or not) and salt to form a paste. This paste is then sieved and rolled into granules, which are pre-cooked (20 min) via steaming and finally dried at 50°C to reduce moisture [6]. The fermentation of the cassava, mentioned in the previous step, plays a significant role in limiting the agglomeration of the granules after cooking by reducing the cohesiveness and stickiness of the final product [3]. This is a desirable outcome for texture. However, this same fermentation process also reduces the elasticity and chewability of the food, which represents a processing trade-off [3]. The drying process, which reduces the moisture content to a low 7.13%, is critical for the long-term preservation of m'bahou. The low lipid content (0.24%) and acidic pH (5.55) of the food also contribute to its stability and resistance to rancidity and microbial growth [6].

3.4.2.3. Fortification

To improve the nutritional quality of the dish, 10% to 20% of the cassava powder can be replaced with protein-rich legume powders like soya or cowpea [3]. The addition of these legumes significantly increases the protein and lipid content of the *M'bahou*, thereby improving its nutritional balance. Fortification does alter the sensory attributes, such as color and flavor, but these fortified formulations remain generally acceptable to consumers [3]. The addition of the legumes can also partially counteract the reduction in elasticity caused by cassava fermentation, thereby increasing the hardness and elasticity of the final product while maintaining its low stickiness [3]. This demonstrates a sophisticated interplay of ingredients and processing that can be used to achieve a desired textural profile.

3.4.3. Role of *M'bahou* in food waste reduction and food security

The production of *M'bahou* is unique in its direct contribution to food waste reduction and food security. The dish makes use of senescent plantains, a product that is often rejected by the market due to its high perishability and advanced stage of ripeness [3]. By transforming this otherwise unmarketable crop into a valuable food product, the *M'bahou* production process not only reduces post-harvest losses but also plays a crucial role in the local economy. This practice provides a low-cost source of nutrition for communities, thereby contributing to food security and income diversification in both rural and urban areas. The optimization of the production process, particularly through fortification and improved techniques, makes the food more attractive to consumers, further strengthening its positive socio-economic impact.

3.5.Comparative Analysis and Broader Implications

3.5.1. Nutritional profiles

To facilitate comparison, the table below summarizes the nutritional profiles of the semolina foods studied, presenting average values or ranges per 100 g of product (**Table 3**). Analysis of the profiles reveals significant commonalities and important specificities. All of these foods are primarily sources of energy and carbohydrates, with low protein and fat content, confirming their role as staple foods in many diets. *Gari*, *Tapioca*, and *Attiéké*, all derived from cassava, are also naturally gluten-free, making them suitable for people with intolerances.

Table 3. summarizes the nutritional profiles of the semolina of cassava and plantain-based.

Product category	Raw material	Energy value (kcal)	Total carbohydrates (g)	Protein (g)	Fat (g)	Dietary fibers (g)
Attiéké	Cassava	161.5 - 215	36.6 – 47.11	0.77 – 1.74	0.15 – 3.60	2
Gari	Cassava	330 - 370	62.6 – 84.4	1.96 – 2.88	0.33 – 1.58	1.24 – 3.46
Tapioca	Cassava	342 - 358	80.9 - 89	1.03 – 1.1	0.24 – 1.6	1.8 – 2.7
M'bahou	Plantain	365	87.6	3.07	0.24	2.87

However, there are notable differences. *Tapioca* stands out as the purest food, being an almost exclusive source of starch, with the most limited nutritional profile in terms of micronutrients.

Gari, with its lower moisture content, is the most calorie-dense of the three cassava products. *Attiéké*, due to its fermentation process and higher water content, is the least energy-dense and provides fiber and minerals.

The most striking exception is *M'bahou*. Its raw material, plantain, gives it a micronutrient (vitamins A, B1, B2) and mineral (potassium, calcium) profile that is significantly richer than that of cassava products. These characteristic highlights that the raw material, beyond the processing methods, is the determining factor in the final nutritional richness.

3.5.2. Synthesis of Unit Operations and Their Critical Impacts Across Products

The analysis of *Attiéké*, *Gari*, *Tapioca*, and *M'bahou* production reveals several shared principles while highlighting unique differences. The initial steps of peeling and washing are universally critical for food safety, as they remove toxic cyanogenic compounds and other contaminants across all products. The fineness of grating is a consistent determinant of final product texture and functional properties, influencing attributes like water absorption and dispersion in *Attiéké* and *Gari*, and starch yield in *Tapioca*.

However, the most critical unit operations differ between the products. For *Attiéké* and *Gari*, fermentation is arguably the single most important step. It is a dual-purpose process that is vital for both food safety (detoxifying the cassava) and for defining key quality attributes (flavor, aroma, and texture). In *Tapioca* production, the transformative step is the heat treatment of gelatinization, which modifies the starch's structure to create the desired functional properties of swelling capacity and viscosity. *M'bahou* unique character is shaped by a combination of the use of a traditional, perishable ingredient (senescent plantain) and the innovative application of fortification to enhance its nutritional and textural properties. The final heating step also differs significantly; *Attiéké* is steamed, *Gari* is roasted (garified), and *Tapioca* is gelatinized and then dried, with each method imparting distinct characteristics to the final product.

3.5.3. An Overview of Food Safety and Quality Management

The reports repeatedly emphasize that food safety is critically important in producing all cassava-based semolinas. The presence of cyanogenic compounds in raw cassava requires a series of processing steps to ensure the final product is safe. The analysis indicates that peeling and washing are the initial defenses, followed by more advanced detoxification methods like fermentation and final heating (steaming for *Attiéké*, roasting for *Gari*). Nonetheless, microbiological risks still exist, especially due to the use of traditional inoculums and potentially contaminated water. To reduce these risks and maintain consistent quality, implementing comprehensive food safety management systems such as HACCP is crucial. These systems offer a structured approach to monitor and control critical points throughout the entire production process[85,145,146].

3.5.4. Socio-economic significance and future outlook of cassava semolinas

The production of these cassava-based foods holds significant socio-economic importance in West Africa. *Attiéké*, *Gari*, and *M'bahou* production not only provides a source of nutrition but also serves as a source of income, thereby contributing to poverty reduction and food security. The unique role of *M'bahou* in adding value to otherwise unmarketable plantains is a particularly strong example of how these traditional processes can reduce food waste and strengthen the local economy.

However, the artisanal production of these foods faces several challenges, including a lack of technical training for producers and a significant variability in quality, which is often a result of using different cassava varieties and inconsistent processing methods [81,92,146]. The future of these products lies in a strategic combination of traditional knowledge and technological innovation. By optimizing fermentation techniques and using improved cassava varieties, the organoleptic and nutritional quality of the products can be significantly enhanced. Furthermore, the professionalization of the production process through training and the implementation of food safety standards can lead to a more consistent, higher-quality product, which would ultimately meet consumer preferences and strengthen the economic empowerment of the local communities that produce them.

4.0. Potential of semolina processing as a sustainable solution to post-harvest losses of roots, tubers, and plantains in sub-Saharan Africa.

In the wake of artisanal processes for producing semolina from RTPs, it is essential to explore the potential of this processing as a sustainable solution to post-harvest losses in sub-Saharan

Africa. Although nutritious and an essential part of the staple diet, RTPs are highly perishable products that suffer significant post-harvest losses due to rapid deterioration and inadequate storage conditions. Processing these products into semolina using artisanal and semi-industrial techniques offers a unique opportunity to reduce these losses while providing economic, social, and environmental benefits. Analyzing these aspects shows how semolina processing can contribute to the region's food security and sustainable development.

4.1.Better preservation

Processing RTPs into semolina significantly extends their shelf life, thereby reducing post-harvest losses, which can be as high as 30% in some regions [18,147]. RTPs are particularly susceptible to postharvest spoilage. Cassava, for example, begins to decompose within 24 to 48 hours of harvest, resulting in significant losses if no preservation measures are taken [148]. Processing into semolina, especially using drying techniques, significantly extends the shelf life of these products [49]. This preservation method is essential to improve the availability of products in local and regional markets while reducing losses due to physical and biological deterioration. Complementary preservation techniques, such as vacuum packaging or natural preservatives, could be explored to optimize semolina preservation.

4.2.Diversification of food and feed uses

Semolina made from RTPs offers excellent versatility, allowing for diversifying food products for human and animal consumption. Cassava semolina is a staple food in many African cultures, providing a nutritious and affordable alternative [40]. It can also produce functional foods and animal feeds, contributing to food security and dietary diversification [149,150]. Semolina could also be fortified with nutrients (such as vitamins and minerals) to address nutritional deficiencies prevalent in the region, while being used in animal feed to reduce costs for livestock farmers. This diversification opens up new economic and nutritional opportunities while meeting the needs of local communities.

4.3.Reducing food waste

Processing into semolina reduces food waste using products that would otherwise be lost after harvest. By extending shelf life and creating new products from surplus or damaged produce,

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this approach minimizes losses and adds value to available resources [151,152]. For example, food waste recovery initiatives turn losses into valuable products, thereby reducing waste and contributing to more sustainable management of agricultural resources. Awareness campaigns and training could be provided to encourage farmers to adopt these processing techniques, while partnerships with local businesses could facilitate the collection and processing of surpluses.

4.4. Recovery of by-products

Processing RTPs into semolina generates by-products that can be used in other sectors, such as animal feed, composting, or even the production of bioplastics [74,153]. Processing residues can be used to feed livestock or to enrich soil, promoting a circular economy and sustainable agricultural practices [154]. By-products could also produce energy (biogas) or biodegradable materials, contributing to a greener, more sustainable economy. Further research could explore these opportunities to maximize by-product recovery. In addition, the recovery of agricultural by-products could lead to new business models focused on sustainability and resource efficiency [155]. By-product recovery reduces waste and maximizes resource use while creating new economic opportunities.

4.5. Creating jobs and improving incomes for farmers

Processing into semolina creates significant economic opportunities, mainly by creating jobs in the processing, marketing, and distribution sectors [8,50]. This activity is particularly beneficial for women and youth, who find this sector a stable source of income and an opportunity for empowerment [156]. In rural areas with limited employment opportunities, these activities improve farmers' incomes and contribute to community development and economic resilience [157]. By selling processed rather than raw products, farmers can increase their incomes and access broader markets, contributing to the economic development of rural communities. In addition, ongoing education and training programs could be introduced to help farmers and local workers master new farming practices, technologies, and techniques for processing and marketing semolina, helping them adapt to market demands and improve their livelihoods [19]. In addition, agricultural cooperatives could be promoted to facilitate access to markets and increase the incomes of small producers.

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5.0.Challenges in processing roots, tubers, and plantains into semolina

The processing of RTPs into semolina is critical to sub-Saharan Africa's agricultural and economic development. However, this process faces several challenges that hinder its widespread adoption, including access to technology, training of local actors, access to markets, and competitiveness, as well as obstacles to the widespread adoption of these practices on an industrial scale. Each aspect deserves special attention to promote the processing and add value to local products.

5.1.Access to processing technologies

Access to processing technologies is challenging when producing semolina from RTPs in SSA. Modern technologies are essential to improving the productivity and quality of processed products. However, their adoption remains limited due to insufficient infrastructure and adequate finance, especially in remote areas. Agbe and Atake[158] note that agricultural credit could enable farmers to acquire modern equipment, but the majority of smallholder farmers often suffer from a lack of adequate finance [159]. This lack of technology prevents local processors from adopting modern techniques that could improve yields and product consistency. In addition, Forsythe et al. [160] note that plant breeding programs (RTBs) do not always consider the needs of processors and consumers, which hinders the adoption of improved varieties. Similarly, Jideani et al.[161], explain that the rise of industrialization has marginalized traditional food processing methods, reflecting the impact of inadequate technology on local practices. To overcome these barriers, it is crucial to increase investment in infrastructure and promote public policies that encourage technological innovation in the agricultural sector.

5.2.Training local stakeholders

Training local stakeholders is key to efficiently processing RTPs in Semolina. Many farmers and processors lack the knowledge to use available technologies and adopt optimal practices. Temple and Bon suggest that appropriate training programs could improve the productivity and quality of processed products [162]. Forsythe et al. also emphasize the importance of understanding community contexts when implementing new practices, as local knowledge contributes significantly to the successful adoption of innovations [160]. By integrating traditional

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knowledge with modern techniques, as Kouakou et al. suggest, communities could increase the efficiency of processing [163]. The ability to process RTP into semolina requires not only technical skills but also an understanding of market preferences and nutritional implications, as Adeyeye's review of food processing shows [164]. However, the lack of educational infrastructure and financial support for agricultural training remains a significant constraint, requiring increased investment in education and local capacity building.

5.3.Market Access and Competitiveness

Access to markets is a major challenge hampering the competitiveness of semolinas that process RTPs. Processed products must meet strict quality standards to compete with imports, but systemic problems such as inadequate transport infrastructure, logistical challenges, lack of financial capital to efficiently scale up production, and regulatory barriers limit access to national and international markets [165]. Nzossié and Temple[41], show that local producers struggle to compete with imported wheat flour, which is often subsidized, putting pressure on local prices. Economic Partnership Agreements (EPAs), with their tariff exemptions, put local products at a disadvantage compared to imported products that meet strict international food standards [161]. Furthermore, Royen et al.[166] points out that economic and logistical constraints in SSA limit opportunities for local producers. Developing appropriate market strategies, strengthening transport infrastructure, and supporting local producers with favorable trade policies are essential to improving competitiveness.

5.4.Large-scale adoption barriers

Socio-economic and cultural barriers hamper the adoption of large-scale RTP processing technologies. The high costs associated with modernization often deter smallholder farmers from investing in improved technologies [160]. These barriers are closely linked to cultural perceptions and historical practices, as illustrated by the gender dynamics in food processing identified by Okoye et al. [167]. Gender disparities in agricultural roles and decision-making can complicate the path to broader adoption of advanced processing methods. [168], also point out that climate instability and food security issues discourage long-term investment. Given the socio-economic and cultural contexts, it is clear that a multifaceted approach is needed to address the challenges associated with processing RTP. Adeyeye argues that innovative food processing technologies are key to improving food security in Africa; their success is highly dependent on local engagement and investment strategies tailored to farmers' needs [164].

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Overcoming these barriers requires targeted studies of community needs and public policies that support adopting innovative technologies while integrating local realities and traditional practices.

6.0.Prospective

Developing integrated traceability systems accessible to local stakeholders is crucial to enable the adoption of technological solutions (IoT, blockchain) for transparent product tracking across the value chain. Standardizing traceability standards, aligned with existing certifications, would enhance access to international markets for traditional sub-Saharan African food crops while raising awareness among local actors (producers, distributors, processors, traders) about traceability's role in reducing losses and boosting consumer trust. A practical example would be the use of devices connected (tablets, smartphones, etc.) to smart sensors via predictive algorithms to monitor real-time weather conditions (temperature, humidity, rainfall), soil irrigation, and the presence of any contaminants during cultivation, harvesting, storage, and transport. Partnerships with entities possessing advanced technologies, such as Central Africa's Rader Group, could support implementation. Additionally, assessing the technical and economic feasibility of predictive algorithms would help anticipate spoilage risks and optimize post-harvest logistics in rural and peri-urban settings, accounting for energy and financial constraints.

To maximize the impact of this approach, the following measures are essential. Strengthen public policies to support local value chains. Governments should promote regulatory frameworks and financial incentives that favor local processing and encourage investment in this sector. They should also promote affordable and sustainable technologies like solar cookers or semi-automatic dryers. These innovations would help reduce the environmental footprint while improving the efficiency of artisanal processing. Strengthen the technical skills of producers and processors through training and extension programs tailored to the specific needs of rural communities, thereby making a significant contribution to optimizing the quality and profitability of finished products. Encourage public-private partnerships to facilitate access to finance and appropriate infrastructure. Such collaborations could help mobilize the resources needed to modernize processing facilities while preserving artisanal and cultural aspects. Existing studies highlight these products' cultural significance and the challenges of modernizing traditional methods. Future research should refine mechanical processing,

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fermentation control, and optimization techniques to enhance safety without compromising traditional qualities. Further opportunities include expanding geographical research coverage, standardizing quality metrics, and developing safety innovations that align with indigenous practices.

7.0.Conclusion

In conclusion, the artisanal processing of RTP into semolina is an essential strategy for addressing the challenges of post-harvest losses, food security, and socio-economic development in SSA. The scientific data collected and analyzed in this review show that this practice can significantly reduce post-harvest losses by improving product preservation and economic value. It is also a viable alternative for strengthening food systems' resilience, improving rural communities' livelihoods, and responding to climatic and economic challenges. It represents a holistic approach that transforms a persistent problem into an opportunity for sustainable and inclusive development.

The associated socio-economic benefits are manifold: this activity could generate additional income, particularly for rural women, strengthen local food security, and help reduce dependence on food imports. What is more, small-scale semolina production is based on technologies that are accessible and adapted to local resources, making it easier to adopt in rural areas.

However, several challenges remain: limited access to modern equipment and adequate infrastructure, and the actors' low level of technical training continues to hamper the widespread adoption of these practices. Regional disparities are also observable, with tremendous success in areas benefiting from institutional support programs and proven technology transfer initiatives. The analysis revealed limited research coverage outside West Africa, inconsistent measurement methods across studies, and minimal data on m'bahou production.

Finally, the local semolina agro-industry represents an important opportunity to transform food systems in sub-Saharan Africa. More research is needed to explore further the collaborations between artisanal practices and modern industrial solutions and to assess their long-term impact on community food resilience. While challenges remain, this approach offers immense potential to ensure future generations' food security and economic prosperity.

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Data availability

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The data that support the findings of this study are available from the authors upon reasonable request.