Gender-Responsive Utilization of Agri-Food By-Products as Sources of Functional Food Ingredients in Sub-Saharan Africa

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Abstract
Agri-food by-products are abundant in sub-Saharan Africa (SSA) yet are frequently discarded or downgraded to low-value uses despite being concentrated sources of functional fractions, including polyphenols (flavonoids, phenolic acids), carotenoids/pigments, dietary fiber and pectins, proteins/peptides, oils, and enzymes (e.g., bromelain). This review aimed to synthesize evidence on how climate-smart utilization of smallholder-generated residues can advance African food systems while addressing gender equity, which mediates who controls by-products, adopts technologies, and captures returns. Using a narrative review design, peer-reviewed articles and authoritative institutional reports or institutional provenance were compiled from major scholarly databases and institutional repositories. The synthesis indicates that common SSA residues—cereal brans/husks, cassava peels, fruit peels/kernels, oilseed cakes, and brewery spent grains—often contain higher bioactive concentrations than edible fractions and can be upgraded via low-cost, decentralized pathways such as drying, milling, fermentation/biotransformation, detoxification, and simplified "green" extractions (ethanol/water, ultrasound-assisted extraction, microwave-assisted extraction), alongside basic stabilization steps and food-safety practices. A conceptual framework links contextual driver (climate variability, seasonality, norms, tenure, markets, policy) to gender-differentiated resource access, shaping CSA outcomes across adaptation (income diversification), mitigation (waste reduction), and productivity/value addition. Case evidence from Nigeria (cassava peel flour and fermentation to reduce cyanogenic glycosides), Ghana (mango peel powders/extracts and potential cooperative pectin supply), and Kenya/East Africa (brewer's spent grain and sorghum bran fortification) shows women lead post-harvest processing yet face credit, time poverty, equipment, extension, quality-certification, and market barriers, with gender-blind formalization risking elite capture. Gender-responsive technology design, inclusive/blended finance, cooperatives, tailored extension, and risk-based food-safety governance are therefore critical to enable safe market entry, equitable benefit sharing, and scalable climate-smart valorization in SSA.

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1. Introduction

Sub Saharan Africa characterized by smallholder agriculture and food systems generate a large amount of agricultural and food-processing by-products, many of which are either underutilized or discarded despite containing valuable nutritional and functional elements. This issue happens because there are significant post-harvest losses, limited agro-processing capabilities,

and weak connections between primary production and value-added activities (Michel *et al* 2024). By-products like cereal bran, fruit peels, oilseed cakes, cassava peels, and brewery residues are often considered waste or low-value animal feed (Shah *et al*. 2025), even though they are rich in bioactive compounds such as polyphenols, carotenoids, dietary fiber, proteins, and bioactive peptides (Faraoni & Laschi 2024). Utilizing these materials for food and nutrition purposes aligns with circular economy principles and offers a strategic opportunity to improve the sustainability of food systems in the region (Fernandes *et al*., 2024)[17]. In addition to their biochemical potential, agri-food by-products are a crucial yet underexplored means of enhancing rural livelihoods and food security.

Smallholder agriculture is predominant in SSA food systems, and most by-products are produced at the household or community level during primary processing activities like milling, peeling, drying, brewing, and oil extraction (Stathers *et al*., 2024) [44]. When effectively utilized, these materials can be converted into functional food ingredients, fortified foods, or intermediate inputs for local agro-industries, thereby reducing waste, improving resource-use efficiency, and creating additional income streams (Yadav *et al*., 2024). However, turning technical potential into meaningful development outcomes requires careful consideration of the socioeconomic and institutional contexts in which by-products are produced, handled, and transformed.

Gender relations are central to these contexts. Across SSA, women play a dominant role in post-harvest handling, small-scale processing, food preparation, and informal food marketing, positioning them as key custodians of agri-food by-products (Wekesah *et al*., 2019) [49]. Despite this centrality, women often face structural constraints that limit their ability to move beyond low-return processing activities to higher value uses. Limited access to land, credit, processing equipment, extension services, and formal markets frequently undermines women's capacity to scale by-product utilization or capture its economic benefits (Nordhagen, 2021) [37]. Consequently, interventions that overlook gender dynamics risk reinforcing existing inequalities, even when they are technically successful or environmentally beneficial.

This review addresses these interconnected challenges by synthesizing evidence on agri-food by-product utilization in SSA through a gender-responsive lens. It integrates insights from food science, post-harvest technology, and agrifood systems research to examine (i) the types and bioactive potential of major agri-food by-products produced in smallholder systems; (ii) low-cost and environmentally sustainable processing approaches suitable for decentralized contexts; (iii) gender-specific constraints and opportunities shaping utilization outcomes; and (iv) policy and programmatic strategies that can support the equitable and scalable implementation of these products. By combining technical and socio-institutional perspectives, this review aims to inform research, policy, and practice on how agri-food by-product utilization can contribute to more inclusive, resilient, and sustainable food systems in SSA.

2. Methodology

This review compiles peer-reviewed articles and authoritative institutional reports published between 2010 and 2025, capturing both essential research and the latest developments pertinent to our study's aims. A systematic search was conducted across major academic databases, including Scopus, Web of Science, PubMed/PMC, MDPI, SpringerLink, and Elsevier ScienceDirect, ensuring comprehensive coverage of agricultural sciences, climate change, environmental sustainability, and socioeconomic systems. To contextualize the empirical findings within development practice and policy environments, grey literature and technical reports were sourced from reputable institutions such as the Food and Agriculture Organization (FAO), CGIAR research centers, the Global Alliance for Improved Nutrition (GAIN), and the Natural Resources Institute (NRI). Search strings and Boolean operators were iteratively refined around key themes, including climate resilience, agricultural sustainability, livelihoods, environmental impacts, and food system transformation.

3. Results And Discussion

3.1. Conceptual framework for Gender-responsive Approaches to Climate Smart Agri-food By-product Utilization in Sub-Saharan Africa

Figure 1 presents a conceptual model that clarifies how gender dynamics affect the effectiveness and fairness of using climate-smart agri-food by-products in sub-Saharan Africa (SSA). This model places by-product utilization within the frameworks of climate-smart agriculture (CSA) and circular food systems, highlighting the interactions between environmental influences, gender-based resource access, technological and organizational pathways, and governance structures. It emphasizes that achieving sustainability, resilience, and equity is not automatically assured but depends on social and institutional conditions. At the top of the model, contextual drivers encompass the broader environmental and socio-institutional conditions under which byproducts are produced and used in the industry.

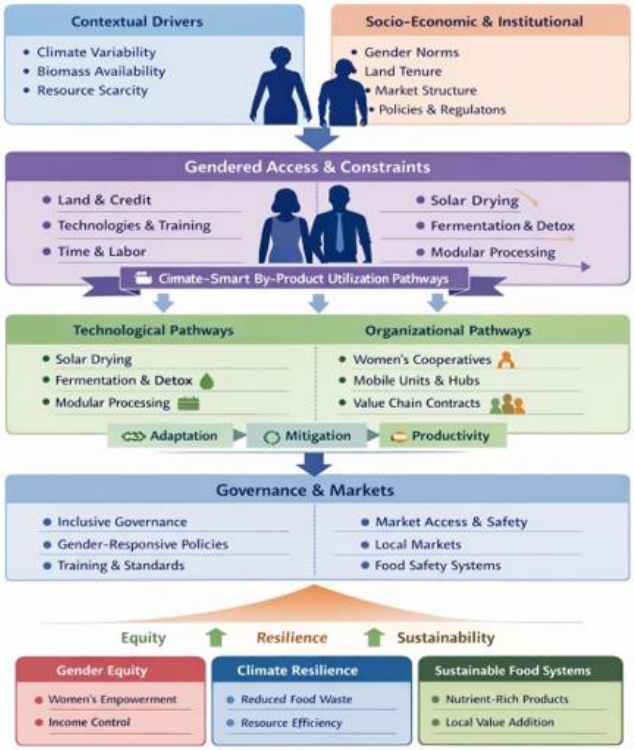

Fig 1: Conceptual framework for Gender-responsive Approaches to Climate Smart Agri-food By-product Utilization in Sub-Saharan Africa

Elements such as climate variability, resource scarcity, and biomass seasonality influence the quantity and type of by-products available, whereas gender norms, land tenure systems, market structures, and policy environments determine who controls these resources and the conditions under which control occurs (FAO, 2019). These drivers create a structural context within which both women and men participate in post-harvest handling and by-product utilization. The central layer of the model focuses on gender-differentiated access to resources and capabilities, serving as the primary analytical perspective of this study. Although women are predominantly involved in post-harvest handling and small-scale processing across SSA, they often face restricted access to land, credit, technologies, extension services, time, and decision-making power (Doss *et al*., 2018) [10]. These constraints shape women's ability to engage in and benefit from by-product utilization initiatives, often confining them to low-return processing roles unless deliberate gender-responsive measures are introduced. This layer underscores that gender inequality is not merely an outcome but also a structural determinant of the utilization pathways.

The framework subsequently delineates climate-smart by-product utilization pathways, integrating both technological and organizational dimensions within the industry. Technological pathways encompass low-energy drying, fermentation, detoxification, and modular processing approaches that align with the smallholder contexts and climate adaptation objectives. Organizational pathways include women-led cooperatives, shared or mobile processing units, and inclusive contractual arrangements that facilitate the aggregation and market access for women. When designed with gender responsiveness, these pathways concurrently contribute to the three CSA pillars: adaptation (income diversification and reduced vulnerability), mitigation (waste reduction and resource efficiency), and productivity (value addition from existing biomass) (Yadav *et al*. 2024).

Governance and market mechanisms are critical mediators in translating utilization into equitable outcomes. Gender-inclusive governance structures, supportive policies, food safety standards, and access to local and institutional markets determine whether benefits are equitably distributed or monopolized by better-resourced actors (Nordhagen 2021) [37]. In the absence of such safeguards, the commercialization and formalization of by-product value chains risk displacing women from resource and income control, despite their pivotal role in processing. At the foundation of the framework, outcomes and impacts are categorized into three interlinked domains: gender equity, climate resilience, and sustainable food systems. Gender-responsive utilization can enhance women's control over income, bolster their decision-making power, and alleviate their labor burdens.

Concurrently, climate-smart outcomes include reduced food loss and waste, improved resource-use efficiency and enhanced resilience to climate shocks. These outcomes support broader food system transformation through the increased availability of functional and bioactive food ingredients, local value addition, and inclusive agro-industrial development (Glazebrook *et al*., 2020; Lelea *et al*., 2022) [22]. Thus, the framework underscores positive feedback loops, whereby gender equity reinforces climate resilience and the sustainability.

3.2. Agri-food by-products in SSA: types and biochemical potential

Common agricultural by-products of SSA include cereal brans, cassava peels, fruit peels, oilseed cakes, and brewery spent grains. These materials are rich in phenolics, carotenoids, dietary fiber, proteins, and peptides, often at

higher concentrations than those found in edible crop fractions.

3.2.1. Typical by-products available to smallholders

Smallholder systems in SSA produce a wide array of by-products, including cereal brans and husks (maize, sorghum, millet, and rice), root crop residues (cassava peels and sweet potato peels), fruit peels and kernels (mango, citrus, banana, and pineapple), oilseed cakes and press residues (groundnut cake and sunflower meal), brewery and coffee residues, and vegetable processing pomaces (Shah *et al* 2025; Mutwedu *et al* 2022; Kebede *et al*., 2022; Mahgoub, *et al*. 2018; Lardy, *et al* 2018) [30, 32]. These residues are often underutilized or used as low-value animal feed, fuel, or disposed of. Studies on agrifood residue portfolios highlight this diversity and the presence of high-value fractions (polyphenols, fibers, pigments, and enzymes) (Heuzé, *et al* 2016-2024; Tufarelli, *et al* 2018; Ravindran, and Blair, 2017; Alemayehu, *et al* 2017; Belewu, and Babalola, 2009) [2, 7, 27, 41, 46].

3.2.2. Bioactive compounds and functional ingredients recoverable from agri-food residues

Residues from agri-food processing are increasingly recognized as rich sources of bioactive compounds that offer functional, nutritional, and therapeutic advantages. Notably, phenolic compounds, including flavonoids and phenolic acids, are well-documented for their potent antioxidant, anti-inflammatory, and antimicrobial properties. These compounds are predominantly found in peels, pomaces, seeds, and skins rather than the edible portions. For instance, olive pomace, grape pomace, and citrus peels often have significantly higher total polyphenol content than their fresh counterparts (Galanakis, 2021; Gullón *et al*., 2020) [20, 25]. Another important group of compounds includes carotenoids and natural pigments, such as lycopene from tomato peels and lutein from leafy and fruit residues, which serve as natural colorants and lipid-soluble antioxidants, playing a recognized role in reducing oxidative stress and enhancing human health (Rodríguez-Amaya, 2022) [42].

Dietary fibers and pectins derived from fruit and vegetable by-products act as texturizing agents in food systems and have prebiotic effects by selectively promoting beneficial gut microbiota and short-chain fatty acid production (Raczkowska *et al*., 2024). In addition to carbohydrate-based compounds, agri-food residues provide valuable proteins and peptides, particularly from oilseed cakes, legume hulls, and cereal by-products. These components can act as natural emulsifiers and, following enzymatic hydrolysis, yield bioactive peptides with antioxidant, antihypertensive, and antimicrobial properties (Liu *et al*., 2021). Oils and other lipophilic substances, including nutraceutical oils and plant sterols, can be extracted from seeds and press cakes, showing potential for lowering cholesterol and reducing inflammation (Galanakis *et al*., 2023) [21]. Moreover, enzymes, especially proteases like bromelain from pineapple peels, cores, and stems, are high-value products with applications in the food processing, pharmaceutical, and biotechnology industries (Fissore *et al*., 2023) [18].

The concentration and bioavailability of these compounds are highly dependent on the matrix and are influenced by the cultivar, processing intensity, and storage conditions. Emerging green extraction technologies, such as ultrasound-assisted, microwave-assisted, enzyme-assisted, and supercritical CO_2 extraction, along with controlled microbial fermentation, have been shown to enhance extraction efficiency and bioactivity by releasing bound compounds and generating new functional metabolites (Galanakis, 2021) [20]. These advancements position the valorization of agri-food by-products as a crucial component of circular bioeconomy strategies, particularly in resource-limited regions.

3.3. Value-adding technologies and approaches suited to smallholders

3.3.1. Low-cost and "green" extraction methods in smallholder systems

Although advanced industrial extraction technologies, such as supercritical fluid extraction (SFE) and pressurized liquid extraction (PLE), are generally out of reach for smallholder producers because of their high costs and energy demands, numerous affordable and eco-friendly extraction methods are increasingly considered suitable for community-level agro-processing in developing areas (Galanakis, 2021) [20]. One of the most scalable options is simple solvent extraction using ethanol–water mixtures, as ethanol can be food-grade, locally sourced, and reused with a minimal environmental impact. In countries such as Nigeria and Ghana, cooperatives linked to smallholders have effectively used aqueous ethanol extraction, along with sun or solar drying and milling, to produce polyphenol-rich powders from citrus, mango, and cashew residues for use in bakery products and nutraceutical blends (Gullón *et al*., 2020;) [25]. These methods fit well with existing artisanal processing practices and require minimal technical training while achieving acceptable extract yields and bioactivity.

Emerging techniques for process intensification, such as ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE), show potential for adaptation to simpler and low-energy formats. Pilot-scale studies in South Africa and Kenya have shown that batch-type UAE systems powered by small generators or solar-hybrid energy sources can significantly reduce extraction time and solvent use when extracting phenolics and pigments from grape pomace, rooibos residues, and vegetable trimmings (Raczkowska *et al*., 2024; Galanakis *et al*., 2023) [21]. Although MAE is more energy-intensive, low-power domestic microwave units have been tested in controlled environments for the rapid extraction of carotenoids from tomato peels, providing a viable option for cooperatives near grid electricity or agro-processing centers. Notably, both UAE and MAE improve the mass transfer efficiency, enabling small processors to achieve higher yields from limited biomass resources. Fermentation and enzymatic biotransformation offer strong opportunities for smallholder integration, as they utilize indigenous knowledge, require low external inputs, and use locally available microbial cultures.

Solid-state fermentation of cereal brans, fruit peels, and oilseed cakes using lactic acid bacteria or filamentous fungi has been shown to enhance flavonoid availability, release bound phenolics, produce bioactive peptides, and reduce anti-nutritional factors such as phytates and tannins (Fatima *et al* 2023). These fermentation-based strategies are highly compatible with rural conditions, as they require minimal water, can be conducted at ambient temperatures, and simultaneously improve the food safety, shelf life, and functional performance of byproduct-derived ingredients. At the most accessible end of the valorization spectrum, drying

and milling remain essential green technologies for stabilizing bioactive compounds in small-scale settings.

Fruit peel powders (e.g., mango, baobab, and pineapple) and cereal bran flours are increasingly produced through solar drying and hammer milling, creating shelf-stable functional ingredients for local markets and school feeding programs (Rodríguez-Amaya, 2022; Galanakis *et al*., 2023) [21, 42]. These powders retain significant levels of polyphenols, dietary fiber, and pigments while avoiding the use of solvents. Recent evaluations consistently highlight that the effectiveness of by-product valorization in smallholder systems hinges not on advanced technology but on adaptation to specific contexts. This involves aligning extraction techniques with local energy resources, water availability, labor expertise, and market needs, thereby promoting sustainability, inclusivity, and resilience in low-income agri-food systems (Galanakis, 2021; Raczkowska *et al*., 2024) [20].

3.3.2. Steps in Postharvest Processing that Enhance Value in Smallholder Systems

In African smallholder agricultural systems, postharvest processing is crucial for transforming low-value residues and excess produce into market-ready products with a longer shelf life and improved nutritional value (Ariyo *et al* 2025; Kaur and Watson, 2024. Bisheko and Rejikumar, 2023) [8,29]. Bekele, 2021) [6]. The process of adding value starts with sorting and grading, allowing farmers and community processors to distinguish between materials fit for consumption and by-products that can be used for further processing. For instance, in Morocco, smallholder olive and citrus growers regularly sort their fruits to channel peels and pomace into secondary value chains, which helps minimize waste and enhances traceability and food safety (Galanakis, 2021; FAO, 2019) [20]. In warm climates, where microbial growth is swift, hygienic practices such as washing, using clean surfaces, and maintaining basic personal hygiene are especially important to prevent foodborne diseases. Community training programs in Senegal and Cameroon have shown that simple sanitation measures can significantly lower contamination risks in dried fruit peels and cereal brans intended for human consumption or animal feed (Amoah *et al*., 2020; FAO, 2019) [3].

Drying is one of the most accessible and widely utilized postharvest technologies in smallholder settings, as it reduces moisture content, inhibits microbial proliferation, and stabilizes the bioactive compounds. Solar drying, employing raised racks or cabinet dryers, is prevalent among mango, pineapple, and tomato producers in Ghana and Nigeria, where peels and trimmings are dried and stored for subsequent processing (Hailu *et al*., 2021) [26]. This process is typically followed by comminution (milling) using hammer or plate mills, resulting in fine powders suitable for incorporation into porridges, bakery mixes, and composite flour. In Burkina Faso, women-led cooperatives process baobab pulp and cereal brans into functional powders that enhance dietary fiber intake and micronutrient density, illustrating how low-tech milling supports nutrition-sensitive and gender-inclusive value chains (Chadare *et al*., 2020) [9].

When technical capabilities permit, employing gentle extraction and concentration methods can increase the value of the product. Aqueous or ethanol–water extraction followed by low-temperature or vacuum evaporation has been assessed in cooperative processing centers in Tunisia, facilitating the concentration of polyphenols and natural pigments from date pits and pomegranate peels while maintaining their bioactivity (Gullón *et al*. 2020) [25]. Although more technically challenging, microencapsulation using carriers such as maltodextrin or gum arabic is gaining traction in semi-formal processing hubs associated with smallholder supply chains, particularly in Côte d'Ivoire, where encapsulated cocoa and fruit by-product extracts enhance oxidative stability, shelf life, and transportability (Ntiamoah *et al*. 2021). In the final stage, straightforward product formulation transforms these intermediate ingredients into market-ready products, including fortified porridge blends, bakery premixes, natural colorants, and feed supplements, which directly address local dietary needs and the demands of growing urban niche markets.

Maintaining food safety is vital at every step of processing. Each stage presents potential hazards, whether microbial, chemical, or physical, necessitating thorough hazard assessments, quality control measures, and phase-specific training. Studies on community agro-processing initiatives in Central and West Africa indicate that small, affordable improvements can greatly enhance safety, increase value, and raise household income without the need for full industrial compliance (FAO 2019; Galanakis 2021) [20]. When processing aligns with local infrastructure, energy availability, and skill levels, it becomes an effective means of inclusive value creation, enabling smallholder farmers to move beyond selling raw products and participate more equitably in the expanding bioeconomy and functional food markets.

3.4. Gender Dimensions in Smallholder Agri-Food Systems: Who Handles, Processes, and Benefits?

3.4.1. Women's Roles in Smallholder Postharvest Handling, Household Processing, and By-product Management

In sub-Saharan Africa (SSA), women are vital to post-harvest activities, household food processing, small-scale milling, drying, brewing, and informal food marketing within smallholder farming systems. Research and systematic reviews have consistently shown that women contribute a significant portion of labor to tasks such as cleaning, sorting, peeling, drying, and the initial transformation of agricultural products (Doss *et al*., 2018; Wekesah *et al*., 2019) [10, 49]. These labor-intensive stages are also key points where agri-food by-products, such as fruit peels, cereal bran, husks, and pulp residues are produced, separated, and managed. Consequently, women are strategically positioned at the intersection of food preparation, waste management, and by-product valorization, especially in rural and peri-urban areas, where formal processing infrastructure is scarce and household-based processing is prevalent.

Despite their central role, women's extensive involvement in post-harvest and processing activities does not automatically lead to equivalent control over productive resources, investment decisions, and income streams. A significant body of evidence from SSA indicates that women face systematic barriers in accessing land, secure tenure, credit, mechanization, extension services, and formal input and output markets (Quisumbing *et al*., 2015). These structural inequalities hinder women's ability to transition from low-capital, labor-intensive processing to higher-value activities, such as standardized drying, extraction, packaging, or

branded product development. Consequently, even when women manage key byproduct streams and contribute the majority of labor, they are often restricted to low-return segments of agri-food value chains, while men or external actors capture higher-value nodes such as bulk trading, large-scale processing, and formal marketing.

Recent gender-focused agri-food research emphasizes that addressing these constraints is crucial for unlocking the full economic, nutritional, and environmental potential of agri-food byproduct valorization in smallholder systems. Interventions that combine gender-responsive extension, collective action through women's cooperatives, access to appropriate technologies, and tailored financial services have shown promise in enhancing women's agency and returns from processing activities (Ragasa *et al*., 2019). Furthermore, because women typically prioritize household food security and nutrition, empowering them within byproduct value chains can lead to positive spillovers in terms of dietary diversity, child nutrition, and local food availability. Therefore, incorporating gender-intentional strategies into by-product valorization initiatives is not only a matter of equity but also essential for scaling sustainable, inclusive, and resilient agri-food systems across SSA.

3.3.2. Gendered barriers to technology adoption and scaling in climate-smart by-product utilization

Gender disparities in accessing essential resources and services continue to present significant structural obstacles to the adoption and growth of climate-smart agri-food by-product utilization technologies in sub-Saharan Africa (FAO 2019). Women who are small-scale farmers and processors frequently face limited access to capital, savings, and formal credit, which constrains their ability to invest in necessary post-harvest and processing equipment, such as solar dryers, mills, improved storage facilities, or small-scale extraction units (Ariyo *et al* 2025). These technologies are crucial for climate-smart value addition, as they contribute to reducing post-harvest losses, lowering emissions through energy efficiency, and preserving bioactive compounds in the face of increasingly unpredictable weather patterns. However, studies across SSA reveal that women's lower levels of financial inclusion and weaker collateral positions systematically hinder their ability to upgrade technology and comply with new food safety and quality standards (Quisumbing *et al*., 2015; Nordhagen, 2021) [37]. Insecure land tenure and limited control over processing sites further impede women's capacity to collect biomass feedstocks, establish permanent facilities, or participate in cooperative climate-smart processing hubs, particularly in peri-urban and irrigated areas vulnerable to climate stress.

Time poverty represents an additional and frequently overlooked obstacle to women's participation in technology adoption and enterprise scaling. Throughout sub-Saharan Africa (SSA), women disproportionately shoulder the burden of unpaid domestic labor, childcare, and the collection of fuelwood and water—tasks that climate change and environmental degradation exacerbate (Assan, 2022). This unequal distribution of labor significantly diminishes the time available for entrepreneurship, skills acquisition, technology training, and involvement in collective by-product valorization initiatives (Doss *et al*., 2018) [10]. Gender disparities persist in extension and training systems. Women are consistently less likely than men to receive information on climate-smart post-harvest technologies, quality assurance, digital marketing platforms, or regulatory requirements, particularly when extension delivery is facilitated through mobile phones, producer organizations, or male-dominated networks (Ragasa *et al*., 2019). These informational asymmetries restrict women's ability to adopt innovations that could enhance resilience, reduce losses, and improve adaptive capacity under climate variability.

Market-related constraints further exacerbate these challenges. Factors such as weaker bargaining power, limited mobility, and dependence on informal or localized markets often result in lower prices and diminished returns, even for processed or value-added byproducts (Van Touch *et al* 2024) [48]. As climate-smart agri-food value chains increasingly prioritize scale, standardization, and certification, women risk exclusion from higher-value segments unless deliberate corrective measures are implemented. Collectively, these constraints highlight the need for gender-responsive and climate-intentional design in interventions aimed at reducing post-harvest loss and utilizing the byproducts. Without targeted approaches, such as inclusive finance, labor-saving technologies, gender-responsive extension, and collective business models, new technologies and commercialization efforts may inadvertently benefit men or better-resourced actors, thereby reinforcing existing inequalities rather than fostering climate-resilient and socially inclusive food systems in SSA (Nordhagen 2021) [37]. In the context of escalating environmental, socioeconomic, and market uncertainties, it is crucial to understand the adaptive strategies of smallholder farmers to ensure sustainable agricultural productivity and effective environmental management.

3.4. Risks of gender-blind by-product utilization interventions: Evidence from Sub-Saharan Africa

Research on agri-food value chain interventions in sub-Saharan Africa underscores the considerable risks associated with gender-neutral approaches to by-product utilization and post-harvest commercialization (Jimu *et al* 2026; Leavy and Poulton, 2007) [28]. In various countries, initiatives aimed at formalizing value chains through centralized processing centers, aggregation hubs, or mechanized facilities have established entry requirements, such as land ownership, minimum capital thresholds, registration, or formal supply contracts, which systematically disadvantage women (Assan, 2015). For instance, studies from Kenya and Tanzania indicate that women processors engaged in small-scale dairy, horticulture, and grain by-product handling were excluded following the introduction of centralized processing facilities, as land and equipment ownership was transferred to male household heads or cooperatives predominantly led by men (Lelea *et al*., 2022). Similarly, in Nigeria, cassava peel valorization and mechanized gari processing initiatives, which initially involved women, saw control shift to men as the enterprises became more profitable and capital-intensive, thereby marginalizing women's roles in decision-making and ownership (Doss *et al*., 2018) [10].

Similar dynamics have been observed in the West African shea and cocoa value chains, where women, who traditionally dominate post-harvest handling and by-product management, lose control as commercialization progresses (Turreira-García, 2025) [47]. In Ghana and Burkina Faso, the formalization of shea butter processing—bolstered by

advanced technologies and export-oriented standards—often results in men taking ownership of processing equipment and marketing channels, whereas women are relegated to wage labor or informal processing roles (Quisumbing *et al*., 2015; Lelea *et al*., 2022). In Côte d'Ivoire, comparable patterns emerge in cocoa by-product utilization, where women's participation diminishes as processing hubs implement certification requirements, bulk procurement systems, and mechanized operations that favor those with greater capital and institutional access (Ragasa *et al*., 2019). These transitions pose particular challenges in climate-smart by-product initiatives, where scaling and efficiency gains, if not carefully designed, can inadvertently reinforce existing gender inequality. Such exclusionary outcomes weaken both the equity and sustainability of by-product utilization interventions.

When women are displaced from ownership and leadership roles, interventions risk eroding local legitimacy, undermining collective action, and reducing the long-term adoption of sustainable practices (Assan 2015). Empirical evidence indicates that women's exclusion often leads to lower household-level reinvestment in nutrition, education, and climate adaptation, which are key co-benefits of climate-smart agri-food systems (Doss *et al*., 2018) [10]. Consequently, a growing body of literature advocates ex-ante gender analysis, gender-responsive technology assessment, and participatory design as prerequisites for scaling post-harvest loss reduction and by-product valorization initiatives in SSA (Lelea *et al*., 2022). Without such safeguards, efforts to commercialize by-products may inadvertently shift benefits toward men or better-resourced actors, undermining inclusive climate resilience and the transformative potential of circular bio-economy strategies.

3.4.1. Operational checklist for gender-responsive agric-by-product utilization

3.4.1.1. Initial assessment and design

Evidence from agricultural development programs in Sub-Saharan Africa suggests that neglecting to conduct such gender-disaggregated diagnostics often results in interventions that inadvertently exclude women or shift control over valuable by-products as commercialization progresses (Meinzen-Dick *et al*., 2014) [36]. To effectively implement gender-responsive initiatives for the utilization of by-products, it is imperative to commence with a comprehensive assessment that integrates technical mapping of by-product streams with thorough gender analysis. This process involves documenting the seasonality, quantity, quality, and current applications of by-products, such as fruit peels, cereal brans, and oilseed cakes, while also identifying the individuals responsible for collecting, transporting, processing, controlling, and benefiting from these materials within households and communities (Thompson *et al* 2009). Practical tools, such as volumetric supply maps, gender-disaggregated stakeholder matrices, and profiles of intra-household decision-making, are crucial in ensuring that project design considers existing labor roles, power dynamics, and constraints before the introduction of new technologies or business models.

3.4.1.2. Technology and business model selection

In developing technology choices and business models, it is imperative to prioritize inclusivity, affordability, and local maintainability to facilitate the effective participation of women in climate-smart byproduct utilization. Technologies requiring low capital investment, such as solar dryers, small hammer mills, manual presses, and mobile or modular processing units, are more accessible to women than fixed, capital-intensive infrastructure and are better suited to decentralized smallholder contexts (Kimario *et al* 2021). Similarly, inclusive business models, such as women's cooperatives, producer groups, and rotating shared assets, have been effective in reducing entry barriers and distributing risks more equitably (Nordhagen, 2021) [37]. Conducting technology usability trials that explicitly involve female users is essential, as design features related to labor intensity, safety, time requirements, and maintenance significantly influence their adoption. Indicators such as the proportion of female users, frequency of technology use by women, and user-reported constraints provide early signals of whether the selected technologies and models are genuinely gender-responsive.

3.4.1.3. Finance and governance

Securing appropriate financial resources and establishing inclusive governance frameworks are vital for the growth of women-led byproduct-utilization projects (OECD 2021). Therefore, gender-responsive initiatives should integrate blended finance tools, group lending, savings and credit associations, and alternative collateral options that match women's asset profiles (Quisumbing *et al*., 2015). At the organizational level, transparent governance structures, such as cooperative bylaws mandating female participation in leadership and decision-making roles, are crucial for avoiding elite capture as businesses grow. Monitoring metrics, such as the rates of loan uptake and repayment among women and the percentage of women in executive and oversight positions, are essential for assessing whether financial and governance systems are perpetuating or reducing gender disparities.

3.4.1.4. Capacity building and extension

According to the guidance provided by the FAO, women's participation in standard extension activities is frequently constrained by time limitations, domestic responsibilities, and restricted mobility (FAO, 2026). The guidance recommends that these gender-specific barriers be considered in extension planning to enhance access and effectiveness. Capacity building and extension services must be explicitly designed to address gender-based constraints related to access, time availability, and information flow (Gemechu, 2023). Gender-sensitive training should encompass food safety and quality assurance, including basic Hazard Analysis and HACCP principles, detoxification and safe handling of by-products, processing operations, equipment maintenance, and enterprise management.

Crucially, the delivery of training should be scheduled at times and locations that are compatible with women's domestic responsibilities and mobility constraints, and should be facilitated using participatory and practical approaches (Ragasa *et al*., 2019). Evidence from Sub-Saharan Africa indicates that when women receive targeted training, the adoption rates of post-harvest and processing technologies increase significantly, with positive effects on household nutrition and income stability. Key indicators include the number and proportion of women trained,

completion rates, and pre- and post-training competency assessments to monitor learning outcomes. These sources provide evidence-based support for developing training and extension programs that explicitly address gender-based constraints related to access, time availability, and information dissemination within smallholder agricultural systems.

3.4.1.5. Food safety, markets, and monitoring

Food safety significantly impacts women's livelihoods, especially in the context of utilizing agricultural by-products within smallholder systems. In regions such as sub-Saharan Africa and other low- and middle-income areas, women often occupy a central and sometimes dominant position in informal and semi-formal food value chains. This includes activities such as the processing, handling, and marketing of crop residues and agro-industrial by-products (Food and Agriculture Organization of the United Nations [FAO], 2011; World Bank, 2019) [50]. Initiatives aimed at modernizing, regulating, and formalizing agri-food value chains through the enforcement of stricter standards, certification requirements, and traceability systems are frequently motivated by concerns over food safety.

While these reforms are intended to improve public health outcomes and enhance market competitiveness, evidence suggests that they may inadvertently marginalize women. Women often face structural challenges in accessing capital, training, infrastructure, and compliance information (Grace 2015; Food and Agriculture Organization of the United Nations 2018) [23]. Without incorporating gender-responsive strategies, the process of formalization risks perpetuating existing inequalities by displacing women from lucrative segments of value chains rather than fostering their involvement in safer and more sustainable agri-food systems. Ensuring food safety, market access, and continuous monitoring is essential for sustaining gender-responsive byproduct utilization initiatives (Grace, 2015) [23]. Low-cost quality assurance protocols, such as standardized drying times, moisture testing, hygienic packaging, and basic record keeping, help smallholder processors meet minimum safety standards without imposing excessive compliance costs. Early engagement with accessible markets, including school feeding programs, local bakeries, community retailers, and fortification initiatives, improves demand certainty and reduces market risks for women-led enterprises. Continuous monitoring of gender-disaggregated income, labor allocation, time use, and environmental outcomes is necessary to detect unintended consequences, such as increased unpaid labor burdens or benefit capture by better-resourced actors (Lelea *et al*. 2022). Indicators such as women's income shares, changes in time use, and volumes of by-products safely diverted from waste streams provide an evidence base for adaptive management and long-term impact assessments.

3. 5. Sub-Saharan Africa on Specific By-products and Value Chains

3.5.1. Nigeria: Cassava-peel utilization and women processors

Nigeria ranks among the leading global producers of cassava, with its processing predominantly conducted by smallholder and household operations (FAO, 2011). These operations generate substantial quantities of cassava peels as byproducts. Empirical estimates suggest that peels constitute approximately 10–30% of the fresh root mass, with most small-scale processing systems reporting values in the 10–20% range, contingent upon the cultivar and processing methods (FAO, 2019). This represents a significant yet underutilized biomass resource with potential applications in feed, food, and bio-based value chains. Despite their potential, cassava peels are frequently discarded or underexploited because of safety concerns, particularly the presence of cyanogenic glycosides, and the limited local processing capacity to transform them into safe, value-added products (CGIAR, 2022).

Women play a pivotal role in cassava processing in Nigeria, undertaking the majority of household-level activities, including peeling, fermenting, pressing, frying gari, and drying (World Bank,2019) [50]. This gender-specific division of labor positions women as the principal custodians and decision-makers regarding cassava peels and other processing residues. Research indicates that women predominate in the processing and small-scale marketing segments of the cassava value chain, where decisions regarding byproduct handling are made (FAO, 2011; Forsythe *et al*., 2016) [16]. Given that peels are produced during manual processing, predominantly performed by women, decisions to discard, feed, compost, or commercialize them are significantly influenced by women's knowledge, time availability, and access to resources. Consequently, interventions aimed at enhancing by-product utilization must explicitly incorporate gender-responsive approaches that acknowledge women's technical expertise and the structural constraints they face.

Initiatives piloted in Nigeria and nearby West African nations illustrate that affordable climate-smart technologies can significantly improve the valorization of cassava peels when combined with gender-sensitive support and technical innovation (Nweke, 2004). Techniques such as sun or solar drying to create long-lasting peel flour, controlled fermentation to decrease cyanogenic compounds, and the development of peel-based livestock feed blends have yielded encouraging results (Aro *et al*., 2010; Montagnac *et al*., 2009). Furthermore, evidence indicates that community-based processing centers, especially those co-owned by women's groups and backed by microfinance, training, and enhanced market access, can enhance safe utilization pathways (CGIAR, 2022). Nonetheless, for effective scaling, it is essential to incorporate detoxification, hygienic handling, infrastructure support, and financial inclusion while assessing outcomes related to women's control over income, market involvement, and time constraints to ensure a fair and sustainable impact on the project.

3.5.2. Ghana: Mango-peel extracts and women's processing groups

Ghana has a growing mango sector supplying both fresh markets and processing industries producing juices, purées, and dried products, which collectively generate substantial volumes of by-products, particularly peels and seeds. Empirical studies indicate that mango peels and seeds together may account for 35–60% of total fruit mass during industrial processing, while peels alone typically constitute approximately 5–20%, depending on cultivar, maturity, and processing method (Pacheco-Jiménez *et al*., 2018; Wongkaew *et al*., 2020). Mango peels are especially rich in bioactive compounds, including phenolic compounds such as

mangiferin, carotenoids, and dietary fiber, which makes them suitable feedstocks for antioxidant extracts, natural colorants, pectin, and powdered functional ingredients with applications in food fortification and nutraceuticals (Gullón *et al*., 2020) [25].

Within Ghana's rural and peri-urban mango value chains, women play a central role in small-scale processing, fruit drying, and informal marketing, particularly during peak harvest seasons. However, evidence shows that as mango processing becomes centralized into medium-scale or industrial facilities, control over by-product streams often shifts toward male entrepreneurs and investors who can meet capital, certification, and compliance requirements (Quisumbing *et al*., 2015; Lelea *et al*., 2022). Women processors frequently face barriers in accessing finance, standardized equipment, and quality certification, limiting their participation in higher-value urban and export markets despite their dominance in upstream handling and drying activities. These dynamic risks excluding women from emerging by-product valorization opportunities unless gender-responsive institutional arrangements are deliberately incorporated.

At the community level, simple ethanol–water extraction, combined with solar or cabinet drying and milling, has been demonstrated as a feasible, low-cost pathway for producing mango peel powders that can function as natural antioxidants or colorants in local foods. While small-scale pectin extraction is technically feasible, it requires higher levels of process control, water, and energy inputs. Pilot initiatives in Ghana and comparable West African contexts suggest that women's cooperatives pooling mango peels to supply semi-centralized pectin or extractors represent a viable hybrid model—maintaining women's involvement in collection, drying, and initial processing while leveraging partnerships with private processors for capital-intensive extraction (Galanakis, 2021) [20]. Such cooperative aggregation models have shown promise when linked to local bakeries, juice processors, and artisanal food manufacturers, offering realistic business pathways that balance climate-smart waste reduction, value addition, and gender inclusion.

From a gender and sustainability perspective, several lessons emerge. Aggregation through women's groups helps overcome seasonality and minimum lot-size constraints associated with extraction technologies, while training in hygienic handling, basic quality control, and market negotiation strengthens women's bargaining power and market positioning. Where higher-value extraction (e.g., pectin or concentrated phenolic extracts) is targeted, blended finance and public–private partnerships can offset capital costs while preserving women's roles in upstream supply and primary processing. Together, these approaches illustrate how mango by-product valorization in Ghana can contribute simultaneously to climate-smart resource use, rural income diversification, and more equitable participation of women in agri-food value chains.

3.5.3. Kenya (and regional East Africa): Brewer's spent grain and sorghum bran in women-led micro-enterprises

The rapid expansion of micro-, craft-, and sorghum-based breweries across East Africa has resulted in the generation of substantial volumes of brewer's spent grain (BSG), a by-product that is often underutilized or disposed of as waste. Typical production estimates indicate approximately 20–25 kg of BSG per 100 L of beer, equivalent to 0.20–0.25 kg per liter, consistent across barley- and sorghum-based brewing systems (Mussatto *et al*., 2022; Lynch *et al*., 2016) [33]. On a dry matter basis, BSG is characterized by high dietary fiber content (often >40–50%), moderate protein levels (15–30%), and appreciable quantities of minerals and residual bioactives, making it a promising ingredient for bakery fortification, extrusion snacks, and composite flours following drying and milling. In parallel, sorghum bran, generated during dehulling and milling, is rich in phenolic compounds—particularly 3-deoxyanthocyanidins—which exhibit antioxidant activity and are increasingly recognized for their functional food potential (Dykes & Rooney, 2006; Gullón *et al*., 2020) [25].

In Kenya and neighboring East African countries, women are prominent actors in urban and peri-urban micro-enterprises, including small bakeries, snack production units, and cooperative food processors that are well positioned to utilize BSG and sorghum bran as functional ingredients. However, several constraints limit uptake. Fresh BSG has a high moisture content (>70%), making it highly perishable and prone to microbial spoilage and mycotoxin contamination if not dried promptly. Additional barriers include transport costs from breweries, irregular supply volumes, and limited access to drying and milling infrastructure. Evidence from pilot initiatives indicates that women-led groups that negotiate stable supply agreements with breweries, combined with investment in low-cost solar or tunnel drying and small hammer mills, can successfully convert wet BSG into shelf-stable flour for bakery fortification, improving both nutritional quality and enterprise profitability (Galanakis, 2021; Mussatto *et al*., 2022) [20]. Tailored extension and business development services—delivered at times compatible with women's schedules—have been shown to significantly enhance adoption and sustained use.

Technologically, solar tunnel dryers and cabinet dryers provide climate-smart solutions for reducing moisture content rapidly while minimizing energy costs and emissions. Once dried, simple milling produces BSG flour that can be incorporated into bread, biscuits, and porridge blends, while sorghum bran can be fermented or otherwise treated to reduce tannin content and improve sensory acceptability before food use (Dykes & Rooney, 2006). Successful models in Kenya demonstrate that partnerships between breweries and women's micro-enterprises, supported by clear off-taker arrangements with local bakeries, schools, and institutional feeding programs, create reliable demand and reduce market risk. From a gender perspective, several lessons emerge: addressing logistics and timely drying is essential to prevent spoilage; formal agreements that secure supply and fair pricing are necessary to prevent capture by better-capitalized actors; and technical assistance on food safety, particularly mycotoxin management, is critical to ensure that by-product-based foods meet safety standards. Collectively, these approaches illustrate how climate-smart valorization of BSG and sorghum bran can simultaneously reduce waste, enhance urban food nutrition, and expand women's economic participation in East African agri-food systems.

3.5.4. Malawi, Zambia and Zimbabwe: Cereal brans, oilseed cakes, and women-led climate-smart processing

Across Malawi, Zambia, and Zimbabwe, maize-based food systems dominate both rural and urban diets, and smallholder milling and oilseed processing generate substantial quantities of cereal brans (maize, sorghum, millet) and oilseed cakes (groundnut, sunflower, soybean). Maize bran alone typically constitutes 10–20% of milled grain weight, while oilseed cakes may account for 55–70% of the original seed mass following oil extraction, representing a large but underutilized biomass stream (FAO, 2019; Galanakis, 2021) [20]. These by-products are rich in dietary fiber, residual protein, minerals, and phytochemicals, making them suitable for fortified porridge blends, bakery products, and livestock feed when appropriately processed. Climate variability, recurrent droughts, and rising food prices in Southern Africa have intensified interest in valorizing these residues as part of climate-smart strategies to reduce waste, stabilize food supplies, and diversify rural incomes.

Women play a central role in small-scale milling, oil pressing, porridge preparation, and informal food marketing in all three countries, positioning them as key managers of cereal brans and oilseed cakes at household and community levels. In Malawi, women dominate community hammer-mill operations and the preparation of maize-based porridge blends, while in Zambia and Zimbabwe, women are heavily involved in groundnut and sunflower processing, drying, and local trading. However, similar to patterns observed elsewhere in SSA, women face persistent barriers to upgrading by-product utilization, including limited access to credit, storage infrastructure, improved drying technologies, and formal markets (Doss *et al*., 2018; Ragasa *et al*., 2019) [10]. As milling and oil extraction become more mechanized or centralized—often through donor-supported hubs or private investment—control over by-products and equipment frequently shifts to men or better-capitalized actors, reducing women's participation in higher-value segments of the chain.

Pilot initiatives and NGO-supported programs in Southern Africa demonstrate that low-cost, climate-smart processing pathways can enhance women's value capture when gender considerations are integrated from the outset. Solar or fuel-efficient drying of maize bran and oilseed cakes, followed by milling and blending with legumes or biofortified crops, has enabled the production of fortified porridge mixes for local markets and school feeding programs in Malawi and Zambia. In Zimbabwe, women's groups engaged in sunflower and groundnut processing have successfully used simple roasting, fermentation, and blending techniques to improve shelf-life, reduce anti-nutritional factors, and enhance sensory quality of by-product-based foods (Galanakis, 2021; Nordhagen, 2021) [20, 37]. Where community-owned processing units are combined with microfinance, cooperative governance, and targeted training on food safety and quality assurance, women are better able to retain control over by-product streams and income flows.

From a gender and climate-smart perspective, several lessons emerge across Malawi, Zambia, and Zimbabwe. Decentralized processing and aggregation through women's groups help overcome scale and seasonality constraints, while reducing transport costs and postharvest losses. Blended finance and group-based lending are critical for enabling women to invest in dryers, storage, and small mills without relinquishing ownership to external actors. Finally, monitoring systems must track not only volumes of bran or oilseed cake processed, but also women's control over proceeds, changes in time use, and nutritional outcomes, to ensure that by-product valorization contributes to equitable, resilient, and sustainable agri-food systems under increasing climate stress.

3.6. Nutritional Composition, Bioactive Profiles, and Yield Potential of Selected Agri-Food By-Products

Tables 1 and 2 provide a comprehensive overview of the compositional characteristics, functional bioactive fractions, and yield potential of selected agri-food by-products, which present significant valorization opportunities within smallholder and agro-industrial systems. Table 1 details the proximate composition and key functional compounds of cassava peels, mango peels, sorghum bran, and brewer's spent grain, illustrating that these residues are rich in dietary fiber, proteins, and bioactive phytochemicals, including phenolic compounds, carotenoids, and antioxidant compounds. Although certain by-products contain anti-nutritional factors, such as cyanogenic glycosides in cassava peels, the application of appropriate processing methods (e.g., detoxification, fermentation, drying, or extraction) can enhance their safety and functional applicability. The presence of concentrated bioactive compounds further highlights their potential for value-added applications, such as functional foods, feed formulations, natural extracts, and industrial ingredients.

Table 1: Composition and key bioactives of selected agri-food by-products (typical ranges)

By-product	Proximate Analysis	Functional Fractions (Bio actives)	Key uses	Sources
Cassava peels	DM 75–90%; CP 6–12%; Fiber 20–35%	Cyanogenic glycosides (require removal); fiber; phenolics	Detoxified flour, fermentations, fiber ingredients	Mukhtar *et al*. (2023); FAO (2019)
Mango peels	DM 20–70%; Fiber 40–80%	Mangiferin, carotenoids, polyphenols, and pectin	Antioxidant extracts, pectin, functional powders	Kučuk *et al*. (2024); Wongkaew *et al*. (2021)
Sorghum bran	DM >90%; Protein 8–15%; Fiber 30–60%	3-deoxyanthocyanidins, phenolic acids	Functional flour, antioxidant ingredients	Awika (2004); Li *et al*. (2021)
Brewer's spent grain	DM (dried) ~90%. Protein 20–30%. Fiber 40–60%	Dietary fiber, proteins, phenolics	Bakery fortification, extruded foods	Steiner *et al*. (2015); Lynch *et al*. (2016)

Table 2: Primary product and yields of selected by-products

Primary product	Agric-by-product	Yield/ton	Source
Cassava roots (gari/starch)	Cassava peels	0.10–0.30 t (10–30%)	Household peeling often 20–30% (FAO, 2019)
Mango fruit (pulp/juice)	Peel + seed	0.35–0.60 t	Peel proportion varies by cultivar (Wongkaew *et al*., 2021)
Brewery (beer production)	Brewer's spent grain	~200–250 kg per 1,000 L beer	Moisture 70–80% when fresh (Steiner *et al*., 2015)
Cereals (milling/dehulling)	Bran/husk	0.05–0.20 t (5–20%)	Bioactive concentrated in bran (Awika, 2004)

3.7. Policy Environment for Gender-responsive Agri-food By-product Utilization

3.7.1. Gender sensitive policies

Creating a supportive policy framework is vital for advancing the gender-responsive utilization of agri-food by-products in sub-Saharan Africa (SSA). Governments and development partners can play a pivotal role in facilitating decentralized processing infrastructure through mechanisms such as grants, blended finance, and targeted subsidies for small-scale equipment, including solar dryers, hammer mills, storage facilities, and modular processing units. Research on postharvest and value chain interventions demonstrates that infrastructure tailored to decentralized and smallholder needs can lower transaction costs, improve quality control, and boost women's involvement, especially in environments where women face systemic challenges related to land ownership, collateral requirements, and restricted access to capital (Affognon *et al*., 2015; Stathers *et al*., 2024) [1, 44]. Additionally, investments in rural energy access and digital services can significantly enhance the practicality of localized byproduct processing and value addition in the region.

Moreover, policies that specifically incorporate gender-responsive value chain development into national agricultural plans are more likely to increase women's participation in the more lucrative areas of agri-food systems. Customized technical support, enhanced extension services, and backing for women-led cooperatives improve access to skills, markets, and collective bargaining power (Meinzen-Dick *et al*., 2014; Doss *et al*., 2018) [10, 36]. Governments should also modify food safety standards, certification systems, and regulatory frameworks to include informal and semi-formal processors while ensuring public health is protected. Streamlined compliance processes, phased certification models, and cost-effective inspection methods can prevent regulatory demands from inadvertently excluding women-led microenterprises and small-scale processors (FAO, 2019), thus fostering inclusive and sustainable byproduct valorization.

3.7.2. Financing mechanisms

Women continue to encounter significant obstacles in maximizing the utilization of byproducts due to a lack of financial resources. Research from Sub-Saharan Africa (SSA) indicates that microcredit and blended finance approaches, which combine grants with repayable funds, are particularly effective when tailored to fit women's asset bases, collateral constraints, and risk profiles (Quisumbing *et al*., 2015; Nordhagen, 2021) [37]. These financial solutions facilitate investments in processing equipment, quality assurance, and working capital, which are typically out of reach through conventional lending channels. Crucially, financial assistance is most beneficial when paired with business development services such as training in financial literacy, product innovation, food safety, and market engagement. Studies have shown that finance alone is inadequate; integrated finance-plus-training models lead to higher adoption rates, business sustainability, and income growth among female entrepreneurs (Ragasa *et al*., 2019; Nordhagen, 2021) [37].

Beyond financial access, structural barriers such as limited property rights, inadequate collateral recognition, and restricted involvement in formal financial systems further impede women's ability to grow byproduct-based businesses in the study area. Consequently, financial inclusion strategies should be integrated into broader institutional reforms that enhance women's economic empowerment and secure their tenure on productive assets. Evidence indicates that gender-responsive financial systems—supported by digital financial services, group-based lending models, and value-chain finance—reduce transaction costs and improve repayment performance while increasing women's investment capacity (World Bank, 2022; FAO, 2023). When financial access is paired with institutional support mechanisms that strengthen legal recognition, market connections, and risk-sharing tools, female entrepreneurs are better positioned to expand safe and profitable agro-processing and byproduct valorization activities in the study area.

3.7.3. Research and public–private partnerships

Public investment in research and development is crucial for advancing cost-effective climate-smart processing technologies tailored to smallholder contexts, including green extraction methods, fermentation-based biotransformation, and straightforward detoxification protocols. Research institutions and universities are instrumental in transforming laboratory-scale innovations into field-ready technologies that comply with food safety and affordability standards (Panzella *et al*., 2020; Fernandes *et al*., 2024) [17, 39]. Public–private partnerships (PPPs) can further expedite inclusive scaling by connecting women-led producer groups and small processors with downstream markets, processors, and service providers. Well-structured PPPs mitigate market uncertainty, facilitate technology transfer, and establish stable demand for byproduct-derived ingredients, whereas public oversight ensures equitable distribution of benefits (FAO, 2013; Meinzen-Dick *et al*., 2014) [36].

In addition to funding innovation, public investment plays a critical role in strengthening extension systems, capacity building, and regulatory support to ensure that climate-smart processing technologies are effectively adopted by smallholder processors. Technology transfer mechanisms must go beyond research outputs to include practical demonstrations, farmer field schools, digital advisory platforms, and hands-on training tailored to women-led enterprises and informal processors. Evidence shows that innovations generate sustainable impact only when embedded within local institutions that provide technical guidance, quality assurance support, and market linkages

(World Bank, 2021; FAO, 2023). Strengthening institutional coordination among research agencies, agricultural extension services, and private sector actors enhances scalability while safeguarding inclusivity and equitable benefit sharing in emerging byproduct-based value chains.

3.7.4. Food safety, regulation, and ethics

The extraction of bioactive compounds and functional ingredients for food applications must align with food safety and regulatory standards regarding contaminants, mycotoxins, pesticide residues, and microbial hazards. In Sub-Saharan Africa (SSA), disparities in regulatory capacity and a scarcity of laboratory infrastructure necessitate the adoption of practical, risk-based food safety strategies (Grace, 2025). These strategies encompass simplified hazard identification, implementation of good hygiene practices, and creation of cost-effective testing methods specifically designed for small-scale processors (Lelea *et al*., 2022). Ethical considerations are equally significant for gender-responsive byproduct utilization in the food industry. These considerations include equitable benefit-sharing arrangements, transparent contracting, and safeguards against exploitative business models that could shift the control of resources and income away from women as value chains become formalized. Research on post-harvest and value chains emphasizes the necessity of integrating ethical and gender safeguards early in program design to prevent elite capture and ensure long-term sustainability (Doss *et al*. 2018) [10].

Regulatory compliance should be conceptualized as a facilitative governance mechanism that augments market access, consumer trust, and product safety rather than being perceived solely as a technical impediment for small-scale processors. The establishment of clear guidelines regarding contaminant thresholds, permissible processing methods, labeling requirements, and traceability systems is essential for integrating byproduct-based innovations into formal food and feed markets. Nevertheless, regulatory instruments must be proportionate to local capacities to prevent the exclusion of smallholder enterprises that lack access to certification infrastructure or accredited laboratories. Recent evidence indicates that risk-based regulatory approaches and simplified compliance systems enhance inclusion while upholding food safety standards in low- and middle-income countries (Macheka *et al*., 2021; Grace *et al*., 2022) [24, 35]. Strengthening decentralized testing services, digital traceability tools, and extension-linked food safety training can mitigate compliance gaps and support equitable participation in formal value chains (Kumar *et al*., 2023; FAO, 2023).

3.8. Knowledge gaps and research priorities

While there is increasing interest in the utilization of agri-food by-products to develop sustainable and climate-smart food systems, substantial knowledge gaps persist, particularly concerning smallholder agriculture and gender equity in sub-Saharan Africa (SSA). Addressing these gaps is crucial for transforming promising pilot initiatives into scalable, inclusive, and safe food system interventions.

Initially, context-specific techno-economic evaluations of cost-effective extraction and processing methodologies appropriate for smallholder environments must be conducted. Most existing research on the recovery of bioactive compounds predominantly addresses laboratory-scale or industrial technologies, which are neither economically nor technically viable in Sub-Saharan Africa (SSA). There is a paucity of comparative assessments that incorporate capital costs, operating expenses, energy consumption, labor demands, and environmental performance under authentic smallholder conditions (Panzella *et al*., 2020; Fernandes *et al*., 2024) [17,39]. Such analyses are essential for identifying processing alternatives that are both climate-smart and economically sustainable for women-led, community-based enterprises.

Second, there is a paucity of gender-disaggregated analyses in value chain studies. Although the roles of women in post-harvest handling and small-scale processing are well documented, there is a dearth of quantitative studies examining the distribution of value and returns at each node of by-product value chains as commercialization advances. Evidence indicates that, in the absence of intentional safeguards, women may lose control over lucrative activities as value chains become formalized (Meinzen-Dick *et al*., 2014; Lelea *et al*., 2022) [36]. Consequently, future research should integrate gender analysis with value chain mapping to assess changes in income control, decision-making authority, and labor allocation across the various stages of byproduct utilization.

Third, research on food safety and stabilization is of paramount importance, particularly concerning residues containing anti-nutritional or toxic compounds. For instance, cassava peels contain cyanogenic glycosides, necessitating reliable detoxification protocols prior to their use as food or feed. Similarly, cereal and brewery residues are susceptible to mycotoxin contamination under suboptimal storage conditions (FAO 2019; Mukhtar *et al*. 2023). Applied research is essential for developing and validating cost-effective detoxification, drying, and stabilization techniques that can be safely implemented at decentralized levels, alongside practical risk assessment and monitoring tools for their application.

Fourth, market development and consumer research on byproduct-derived functional ingredients in SSA are limited in scope. While technical studies have demonstrated the bioactive potential of these products, fewer studies have examined the demand, consumer acceptance, willingness to pay, and cultural perceptions of foods derived from byproducts (Yadav *et al*., 2024). Market-oriented research, including sensory evaluation, branding strategies, and mapping of institutional markets, such as school feeding and health-oriented food programs, would strengthen the commercial viability of local byproduct utilization initiatives.

There is a notable deficiency in rigorous impact evaluations that assess the outcomes of gender-sensitive byproduct-utilization interventions. Most existing evidence is either descriptive or derived from short-term project monitoring data. To comprehensively evaluate the impact on women's income, nutritional outcomes, workload distribution, and empowerment, as well as broader environmental and climate resilience indicators, longitudinal and mixed-method evaluations are required (Doss *et al*., 2018; Nordhagen, 2021) [10, 37]. Such evidence is crucial for informing policy design, guiding donor investments, and developing scaling strategies.

4. Conclusion And Recommendations

In sub-Saharan Africa, agri-food by-products are a largely untapped source of bioactive and functional ingredients with the potential to significantly enhance sustainable food systems, thereby supporting nutrition and food security. These by-products, derived from widely grown crops like cassava, cereals, fruits, and oilseeds, as well as from agro-industrial activities such as brewing, are rich in dietary fiber, polyphenols, proteins, and other functional compounds. These can be extracted through cost-effective and climate-smart processing methods. When utilized effectively, valorizing these by-products can reduce food loss and waste, improve resource-use efficiency, and create additional income streams for both smallholders and processors. However, the distribution of these benefits is uneven. The gendered structure of agri-food systems in SSA—where women predominantly handle post-harvest processing and informal activities, yet face ongoing inequalities in access to land, finance, technology, and markets—significantly influences who can participate in, scale, and benefit from valorization initiatives. To ensure that by-product utilization leads to equitable and lasting outcomes, interventions must be explicitly gender-intentional rather than gender-neutral. This involves participatory technology design that considers women's labor constraints and expertise, inclusive financing mechanisms tailored to women entrepreneurs, and cooperative or collective business models that enhance women's bargaining power and market access. Gender-sensitive extension services and food safety standards, adapted to small-scale and informal processing contexts, are also crucial for enabling compliance without discrimination. On a broader scale, policy and donor support for decentralized processing infrastructure, applied research and development, and gender-responsive value-chain governance are vital to creating an enabling environment. Prioritizing women's agency and control over value-adding processes is not only a matter of social equity but also a strategic approach to maximizing the environmental, nutritional, and economic sustainability of agri-food systems in sub-Saharan Africa (SSA).

Ethics Statement

This study is based on secondary literature and did not involve human or animal subject.

Author Contributions

The authors conceived the study, conducted a literature review, and prepared the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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References

1. Affognon H, Mutungi C, Sanginga P, Borgemeister C. Unpacking postharvest losses in Sub-Saharan Africa: a meta-analysis. World Dev. 2015;66:49-68. doi:10.1016/j.worlddev.2014.08.002
2. Alemayehu G, Urge M, Animut G. Feed resources, feeding practices and coping strategies to feed scarcity among smallholder livestock producers in Ethiopia. Agric Food Secur. 2017;6:35. doi:10.1186/s40066-017-0115-7
3. Amoah P, Drechsel P, Henseler M, Abaidoo RC. Irrigated urban vegetable production in Ghana: microbiological contamination in relation to farm practices. Int J Food Microbiol. 2020;330:108804. doi:10.1016/j.ijfoodmicro.2020.108804
4. Aro SO, Aletor VA, Tewe OO, Fajemisin AN. Nutritional potential of cassava tuber wastes: a case study of a cassava starch factory in Nigeria. Livest Res Rural Dev. 2010;22(11):212.
5. Awika JM. Properties of 3-deoxyanthocyanidins from sorghum. J Agric Food Chem. 2004;52(23):6907-14. doi:10.1021/jf049653f
6. Bekele D. Roles of postharvest management for food security: a review. Adv Crop Sci Technol. 2021;9(7):475. doi:10.4172/2329-8863.1000475
7. Belewu MA, Babalola FT. Nutrient enrichment of cassava peels using fungi for livestock feeding. Afr J Biotechnol. 2009;8(22):6358-62.
8. Bisheko MJ, Rejikumar G. Major barriers to adoption of improved postharvest technologies among smallholder farmers in sub-Saharan Africa and South Asia: a systematic review. Sustainability. 2023;15:70. doi:10.3390/su15010070
9. Chadare FJ, Linnemann AR, Hounhouigan JD, Nout MJR, van Boekel MAJS. Baobab food products: composition, nutritional value and processing. Crit Rev Food Sci Nutr. 2020;60(1):1-14. doi:10.1080/10408398.2018.1488796
10. Doss C, Meinzen-Dick R, Quisumbing AR, Theis S. Women in agriculture: four myths. Glob Food Secur. 2018;16:69-74. doi:10.1016/j.gfs.2017.10.001
11. Food and Agriculture Organization of the United Nations. The state of food and agriculture 2010-2011: women in agriculture – closing the gender gap for development. Rome: FAO; 2011. Available from: https://www.fao.org/3/i2050e/i2050e.pdf
12. Food and Agriculture Organization of the United Nations. Public-private partnerships for agribusiness development: a review of international experiences. Rome: FAO; 2013.
13. Food and Agriculture Organization of the United Nations. Developing gender-sensitive value chains: a guiding framework. Rome: FAO; 2018.
14. Food and Agriculture Organization of the United Nations. The state of food and agriculture 2019: moving forward on food loss and waste reduction. Rome: FAO; 2019. doi:10.4060/ca6030en
15. Food and Agriculture Organization of the United Nations. Digital agriculture and innovation for sustainable food systems. Rome: FAO; 2023.
16. Food and Agriculture Organization of the United Nations. The status of women in agrifood systems. Rome: FAO; 2023. doi:10.4060/cc5343en
17. Fernandes IP, Freire MTA, Pires JRA. Affordable and sustainable food processing technologies for small-scale producers. Food Control. 2024;155:110097. doi:10.1016/j.foodcont.2023.110097
18. Fissore EN, Ponce NMA, Gerschenson LN. Recovery of bromelain from pineapple waste: advances and applications. Biochem Eng J. 2023;198:108987. doi:10.1016/j.bej.2023.108987

19. Forsythe L, Posthumus H, Martin A. A crop of one's own? Women's experiences of cassava commercialization. J Gend Agric Food Secur. 2016;1(2):110-28.
20. Galanakis CM. Recovery of high added-value components from food wastes. Trends Food Sci Technol. 2021;116:257-69. doi:10.1016/j.tifs.2021.07.029
21. Galanakis CM, Rizou M, Aldawoud TMS, Ucak I, Rowan NJ. Innovations within the circular bioeconomy. Foods. 2023;12(2):352. doi:10.3390/foods12020352
22. Glazebrook T, Noll S, Opoku E. Gender, climate change, and farming in West Africa. Sustainability. 2020;12:10483. doi:10.3390/su122410483
23. Grace D. Food safety in low- and middle-income countries. Int J Environ Res Public Health. 2015;12(9):10490-507. doi:10.3390/ijerph120910490
24. Grace D, Lindahl J, Wanyoike F. One Health approaches to food safety. One Health. 2022;15:100402. doi:10.1016/j.onehlt.2022.100402
25. Gullón B, Pintado ME, Pérez-Álvarez JA, Viuda-Martos M. Polyphenols and antioxidant activity of food by-products. J Food Compos Anal. 2020;92:103535. doi:10.1016/j.jfca.2020.103535
26. Hailu G, Workneh TS, Belew D. Postharvest technology review. Cogent Food Agric. 2021;7:1862691. doi:10.1080/23311932.2020.1862691
27. Heuzé V, Tran G, Edouard N, Lebas F, Lessire M. Cassava peels. Feedipedia. Rome: FAO/INRAE/CIRAD/AFZ; 2016-2024. Available from: https://www.feedipedia.org
28. Jimu T, Chidoko C, Ndhlovu E. Informal markets and agri-food value chains in Sub-Saharan Africa. In: Ndhlovu E, editor. Agriculture and sustainable development in Sub-Saharan Africa. Cham: Springer; 2026. doi:10.1007/978-3-032-09881-8_7
29. Kaur R, Watson JA. Postharvest losses and supply chain management: a scoping review. Trans ASABE. 2024.
30. Kebede G, Asmare B, Mekuriaw Y. Brewery spent grain as livestock feed. Heliyon. 2022;8:e09412. doi:10.1016/j.heliyon.2022.e09412
31. Kučuk N, *et al*. Mango peels as industrial by-products: extraction and bioactive characterization. Foods. 2024;13(4):553. doi:10.3390/foods13040553
32. Lardy G, Anderson V, Caton J. Oilseed by-products in ruminant nutrition. J Anim Sci. 2018;96(7):2871-84. doi:10.1093/jas/sky180
33. Lynch KM, Steffen EJ, Arendt EK. Brewers' spent grain: a review. J Inst Brew. 2016;122(4):553-68. doi:10.1002/jib.363
34. Mahgoub O, Kadim I, Al-Marzooqi W. Fruit and vegetable by-products as feed. Anim Feed Sci Technol. 2018;236:1-12. doi:10.1016/j.anifeedsci.2017.12.012
35. Macheka L, Ngadze RT, Mubaiwa J. Risk-based food safety systems. Food Control. 2021;123:107734. doi:10.1016/j.foodcont.2020.107734
36. Meinzen-Dick R, Johnson N, Quisumbing AR, Njuki J, Behrman JA, Rubin D, *et al*. Gender asset gap. In: Quisumbing AR, *et al*., editors. Gender in agriculture. Dordrecht: Springer; 2014. doi:10.1007/978-94-017-8616-4_5
37. Nordhagen S. Finance for women entrepreneurs in agrifood systems. Washington, DC: IFPRI; 2021. Discussion Paper.
38. Organisation for Economic Co-operation and Development. Making blended finance work for agri-SMEs. Paris: OECD Publishing; 2021.
39. Panzella L, Moccia F, Nasti R, Marzorati S, Verotta L, Napolitano A. Bioactive phenolics from agri-food wastes. Front Nutr. 2020;7:60. doi:10.3389/fnut.2020.00060
40. Ragasa C, Aberman NL, Alvarez Mingote C. Gender differences in access to extension services. J Agric Econ.
41. Ravindran V, Blair R. Feed resources for poultry production. Worlds Poult Sci J. 2017;73(2):289-306. doi:10.1017/S004393391700002X
42. Rodríguez-Amaya DB. Natural food pigments. Food Res Int. 2022;157:111211. doi:10.1016/j.foodres.2022.111211
43. Shah AM, Zhang H, Shahid M, *et al*. Agricultural crop residues and agro-industrial by-products for livestock productivity. Animals (Basel). 2025;15(8):1184. doi:10.3390/ani15081184
44. Stathers T, Lamboll R, Mvumi BM, Baoua I. Postharvest innovations for resilience. Food Secur. 2024;16:1-18. doi:10.1007/s12571-023-01431-2
45. Steiner J, Procopio S, Becker T. Brewer's spent grain polysaccharides. J Inst Brew. 2015;121(3):415-22. doi:10.1002/jib.229
46. Tufarelli V, Ragni M, Laudadio V. Fruit and vegetable waste in livestock nutrition. Ital J Anim Sci. 2018;17(2):247-60. doi:10.1080/1828051X.2017.1340092
47. Turreira-García N. West African shea processors and market integration. Econ Bot. 2025;79:287-309. doi:10.1007/s12231-025-09646-0
48. Van Touch A, Tan DKY, Tran TA, *et al*. Smallholder challenges and opportunities. J Environ Manage. 2024;370:122536. doi:10.1016/j.jenvman.2024.122536
49. Wekesah FM, Mutua MK, Izugbara CO, Ezeh AC. Gendered patterns of time use in SSA. World Dev. 2019;117:95-109. doi:10.1016/j.worlddev.2018.12.008
50. World Bank. Profiting from parity: unlocking women's business potential in Africa. Washington, DC: World Bank; 2019. doi:10.1596/978-1-4648-1394-9

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