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Circular Bioeconomy in sub-Saharan Africa: Transforming African Food Systems

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Agricultural food systems currently face a wide range of complex challenges due to the decreasing availability of agricultural land, climate change (Hamam et al., 2023), the threat of dwindling water resources (Oonincx et al., 2012), and the increasing pollution of both aquatic and terrestrial ecosystems (Springmann et al., 2018). The agricultural food industry is increasingly aware of the environmental impact of the over-exploitation of natural resources and waste production, which has prompted a search for sustainable alternatives based on the recent concept of circular bioeconomy principles. Since the industrial revolution, the world has relied upon a **linear economic model** that can be summarized as take the resources you need, make what goods you can for sale and profit, and dispose of what you don't need (Sariatli, 2017; Ellen MacArthur Foundation, 2019). However, such thinking has created a situation that is no longer sustainably able to support future generations. Thus, the need to consider a circular, more sustainable food production model now exists.

Understanding how a circular bioeconomy can be established within the context of African food systems, especially at the smallholder level, is critical to realizing the circular food systems that would propel Africa towards more resilient and sustainable food systems (Sekabira et al., 2023) and strengthen the possibility of attaining the United Nations' Strategic Development Goals (UN SDGs) by 2030. Circular bioeconomy systems have the potential to 1) improve the availability of safe and nutritious food by increasing livestock, crop and fishery yields through resource-efficient technologies and production diversification, 2) strengthen local value chains by recycling food, feed, fiber, and fuel resources, 3) optimize the food-energy-water nexus by converting tradeoffs into synergies, 4) make marginal or overexploited and degraded lands useable for food production under unfavorable environmental conditions, and 5) create livelihood opportunities for disadvantaged communities and reduce climate-negative impacts of conventional food systems.

BACKGROUND INFORMATION

Bioeconomy represents the transition from fossil-based resources to renewable biological resources that uses these renewable biological resources to produce food, materials, and energy and aims to reduce greenhouse gas (GHG) emissions by replacing fossil carbon from nonrenewable resources (Ward et al., 2016). Bioeconomy is defined as "the production of renewable biological resources and converting these resources and waste streams into value-added products, such as food, feed, bio-based products, and bioenergy" (European Commission, 2012). A critical feature of the bioeconomy is extending biomass production and processing beyond food, feed, and fiber; converting biowaste and agricultural residues into useable products; improving the efficiency of the agro- and bio-processing industries in the region; and providing feedstock for novel biobased products (East African Science and Technology Commission, 2021). The **bioeconomy is not complete without the circular economy and vice versa**, and the two are not entirely a part of each other (Carus and Dammer, 2018). For example, Feleke et al. (2021) indicated that many new developments in the bioeconomy, such as technological advances like precision livestock farming, gene editing, etc. are not essential parts of the circular economy's framework. However, they offer a strong economic, social, and environmental justification for bringing together aspects of the two concepts into a single framework called the circular bioeconomy (Feleke et al., 2021).

Currently, according to the Global Footprint Network (2024), the world's population would need 1.7 Earths to support its demands on renewable natural resources. As the global population grows, the demands on natural resources and biomass production increases. To prevent exceeding Earth's biophysical limits, there is widespread acknowledgement of the need to transform our economy, including our food system in terms of production, consumption, and waste production (Rockström et al., 2023). Promoting a circular bioeconomy that fits within planetary boundaries is widely recognized as one of the primary strategies proposed by many countries to achieve this goal. A circular bioeconomy offers a conceptual framework for using renewable natural capital to transform and manage land, food, health, and industrial systems, with the goal of achieving sustainable wellbeing in harmony with nature (FAO, 2024).

With over 140 million children born each year, the global population is projected to reach 9.7 billion by 2050 and 11.2 billion by 2100 (FAO, 2017). The Food and Agriculture Organization of the United Nations (FAO) estimates that if current population growth trends continue, by 2050, the global caloric demand will increase by 70 percent and crop demand for human consumption and animal feeds will need to double in low-income countries (FAO, 2009). Africa's population is projected to increase significantly, reaching 2.5 billion by 2050, accounting for approximately 27 percent of the global population (United Nations, 2017). In 2022, more than 20 percent of Africa's population faced hunger (FAO et al., 2022), and one in every three Africans was affected by water scarcity (UN ECA, 2023). In addition, **seven of the 10 countries most vulnerable to the effects of climate change are located on the African continent**. As 95 percent of African agriculture is rain-fed (Muchure and Nhamo, 2019), changing climatic conditions threaten the productivity and economic viability of food production systems, with negative implications for livelihoods and food security, especially among rural smallholders (Mohammed et al., 2024).

CIRCULAR BIOECONOMY

A circular bioeconomy is the intersection of the bioeconomy with the circular economy, with an emphasis on the sustainable use of biological resources through closed-loop systems that rely on reducing, reusing, and recycling biomass. Therefore, a circular bioeconomy provides ecosystem services that allow the sustainable production, use, conservation and regeneration of biological resources and their transformation to food, feed, materials and energy within ecosystem boundaries. In other words, it aims to support sustainable wellbeing for society at large, based on healthy, biodiverse, and resilient ecosystems (Palahi et al., 2020). Generating a resource efficient circular bioeconomy alone is projected to reach a value of U.S. $7.7 trillion by 2030 (WBCSD, 2019).

The recent global shift toward sustainable development has brought increased attention to the concept of a circular bioeconomy, which represents a promising pathway for achieving a more sustainable and resilient future (Mpofu et al., 2021; Ncube et al., 2022). The term circular bioeconomy was introduced by the European Commission, which, as mentioned previously, defines it as: "the production of renewable biological resources and the conversion of these resources and waste streams into value-added products such as food, feed, bio-based products and bioenergy." **Sustainability and circularity** must be at the center of the bioeconomy if it is to be successful. These objectives will promote the renewal of the agricultural industry, the modernization of our primary production systems and the protection of the environment, and will help enhance biodiversity (European Commission, 2018). A circular bioeconomy encompasses numerous aspects, including sustainable agriculture, waste management, renewable energy generation, and the development of numerous bio-based products (Muscat et al., 2021; Klein et al., 2022; Ansari et al., 2023) and, by transitioning from a linear "take-make-dispose" model to a circular approach, focuses on reducing waste, optimizing resource use, and promoting sustainable agricultural practices (Tan and Lamers, 2021; Ansari et al., 2023; Holden et al., 2023). Whereas the linear model of modern food production is vulnerable to climate change effects.

Climate change can negatively affect food availability, reduce access to food, and affect the quality and safety of food. For instance, increase in temperature, changes in patterns of precipitation, changes in extreme weather events, and reductions in water availability may result in decreases in water availability that may lead to reduced agricultural productivity (U.S. Environmental Protection Agency, 2016).

Some effects of climate change on livestock productivity include the following:

- **Increased heat waves**: Over time, heat stress can amplify susceptibility of livestock to disease, low fertility, and decreased milk production;
- **Drought**: Is a threat to pasture and feed availability through decreased quality of available forage to grazing animals. Furthermore, due to droughts, crop production and yields can be affected, and survival and productive performance of livestock that are dependent on grains are the most at risk;
- **Increased parasite and disease prevalence**: The changes in climate such as increased temperature and rainfall, has favored survivability of parasites, disease vectors and pathogens;
- **Increase in carbon dioxide (CO_2)**: Despite increasing the productivity of pastures on which livestock feed, excess availability of atmospheric CO2 pastureland can also reduce pasture quality. For this reason, more forage must be consumed to meet the same nutritional requirements.

Thus, climate change contributes to food insecurity, poverty, poor human health, soil degradation, and biodiversity loss – making the linear food production model, therefore, unsustainable (Kaza et al., 2018; Kershaw et al., 2021; Muscat et al., 2021). Alternatively, **a circular bioeconomy model that ensures more conservative use of resources** has become increasingly important to sustainable food production. Specifically, a more sustainable circular bioeconomy model that focuses on recycling and reusing organic waste is essential to close gaps in nutrient recycling within agricultural systems and establish more resilient rural-urban nexus food systems (Sekabira et al., 2022).

Without sustainable food production and consumption systems, achieving many of the UN SDGs, like poverty alleviation, food security, environmental health, and sustainable cities is in jeopardy (FAO, 2018; Kershaw et al., 2021; Muscat et al., 2021). The challenge to sustainably feed the world's ever-increasing human population amidst diminishing resources and increasing climate change impacts becomes greater each year. Humans are among the numerous causes of the worsening global food production and consumption systems' situation we face today. The linear model of resource use employed by modern food production/consumption systems is blamed for depletion of natural resources (Majumdar et al., 2016; Kershaw et al., 2021). Under this unsustainable linear model, **food production occurs in rural areas, while most food consumption occurs in urban areas,** where most recyclable organic waste accumulates in dumpsites, rudimentary sanitation facilities, or is released into the environment, particularly in lesser developed countries (Geissdoerfer et al., 2017; Kirchherr et al., 2018; Muscat et al., 2021). However, organic waste (any biological waste from farms and other green residues, food, household, processing plants, or waste from both livestock and humans that can easily be recycled naturally by microorganisms) contains valuable soil nutrients, and not taking advantage and reusing them in food systems where they were originally mined creates gaps in nutrient loops, resulting in long term soil nutrient depletion (van der Wiel et al., 2019). Therefore, a linear production system renders the rural-urban food system nexus non-resilient (Sekabira et al., 2022).

A key concept of the circular bioeconomy is the use of biomass materials in products that create the most value over multiple lifetimes (Philp and Winickoff, 2018; Paes et al., 2019; Stegmann et al., 2020). Sustainable organic waste management is a critical aspect in the development of a circular bioeconomy (Venkata-Mohan et al., 2016; Maina et al., 2017). A circular bioeconomy model reduces waste produced across a given supply chain and utilizes all food waste and organic waste within the chain to recycle nutrients (Jurgilrvich et al., 2016; Carus and Dammer, 2018). Stegmann et al. (2020) developed a bio-based value pyramid depicting the relative value associated with each manufacturing option (Figure 1), with the goal to provide guidance for optimizing the value of biomass over time in a circular economy. In many African food systems that are characterized by low farm inputs, there is potential to transform organic waste into useful farm inputs (Frankema, 2014). Even though moving down the value pyramid is associated with a decrease in the resource quality with fewer opportunities for further uses of the material, Stegmann et al. (2020) acknowledged that **"low value" application may be associated with greater environmental and socio-economic benefits** depending on the situation. As a result, researchers have explored the potential of bioeconomy to contribute to meeting the UN SDGs (Dietz et al., 2018; Heimann, 2019: Mak et al., 2020). However, from a sustainability perspective, the bioeconomy must prioritize sustainability to address these challenges. The current bioeconomy is still largely relying on non-renewable energy and fossil-based raw materials like nitrogen fertilizers, organic chemicals, and polymers that are predominantly derived from petroleum oil and gas (Tan and Lamers, 2021), products which are not sustainable long-term. Sustainable bioeconomy is not only about substituting fossil resources with renewable resources, but it will also require sustainable biomass feedstock production, biomass conversion processes, and products (Tan and Lamers, 2021).

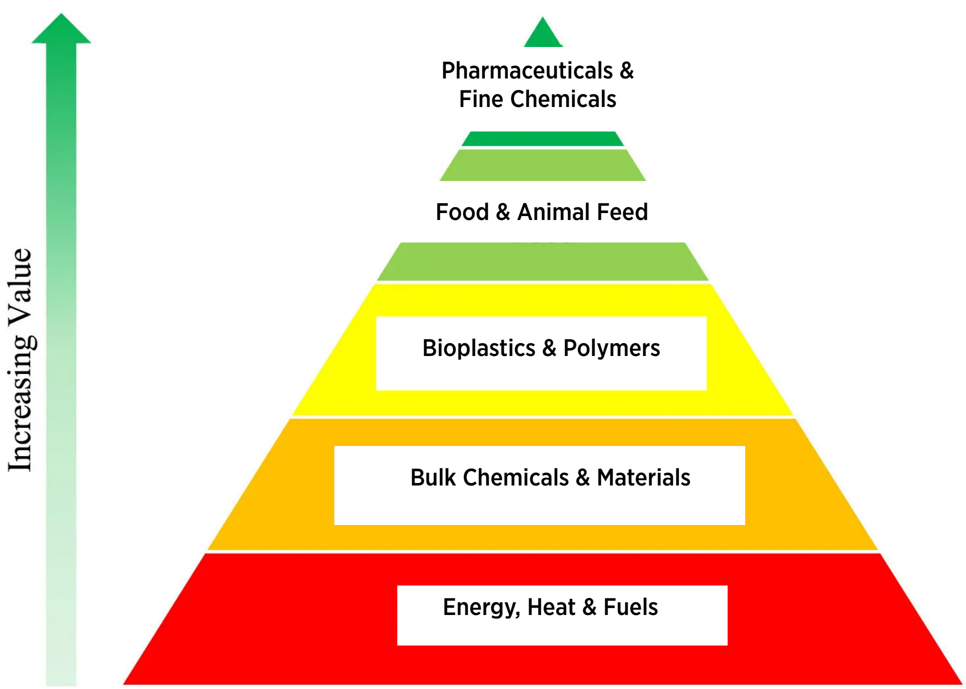

Figure 1. *Bio-based value pyramid. Source: Chitaka and Schenck, 2023 (adapted from Stegmann et al., 2020).*

There are **multiple themes to a circular bioeconomy**: technical and economic viability of biomass extraction and use; bioeconomy promises and challenges; sustainability of biobased products, processes and services; bioeconomy governance; biosecurity; bioremediation; and framework and tools (D'Amato et al., 2020). The most important factor influencing circular bioeconomy development is access to renewable resources, with natural capital being the most basic and vital element (Woźniak et al., 2021; Görtz et al., 2022). A circular bioeconomy is a potential solution to climate change, which poses a threat to human existence. Production of biological feedstocks like bioenergy and biomaterials creates a greener and low-carbon environment (Sharma and Malaviya, 2023). Bioprocessing and assimilation of waste to generate value-added products leads toward a sustainable circular bioeconomy (Leong et al., 2021). However, despite advancements in the circular bioeconomy, roadblocks like rigid policies and protocols; jurisdictional limitations; public perceptions; lack of Extension personnel to assist with information dissemination, outreach and transfer; and lack of funding make it difficult to implement circular bioeconomy strategies in specific locations (Kemp et al., 2015). Although, a circular bioeconomy does improve resource availability and environmental efficiency, lowers GHG emissions, reduces dependency on non-renewable resources, and helps address climate change (Mohan et al., 2016; Carus and Dammer, 2018). Potential pathways by which circular bioeconomy strategies can help in climate action are represented in Figure 2.

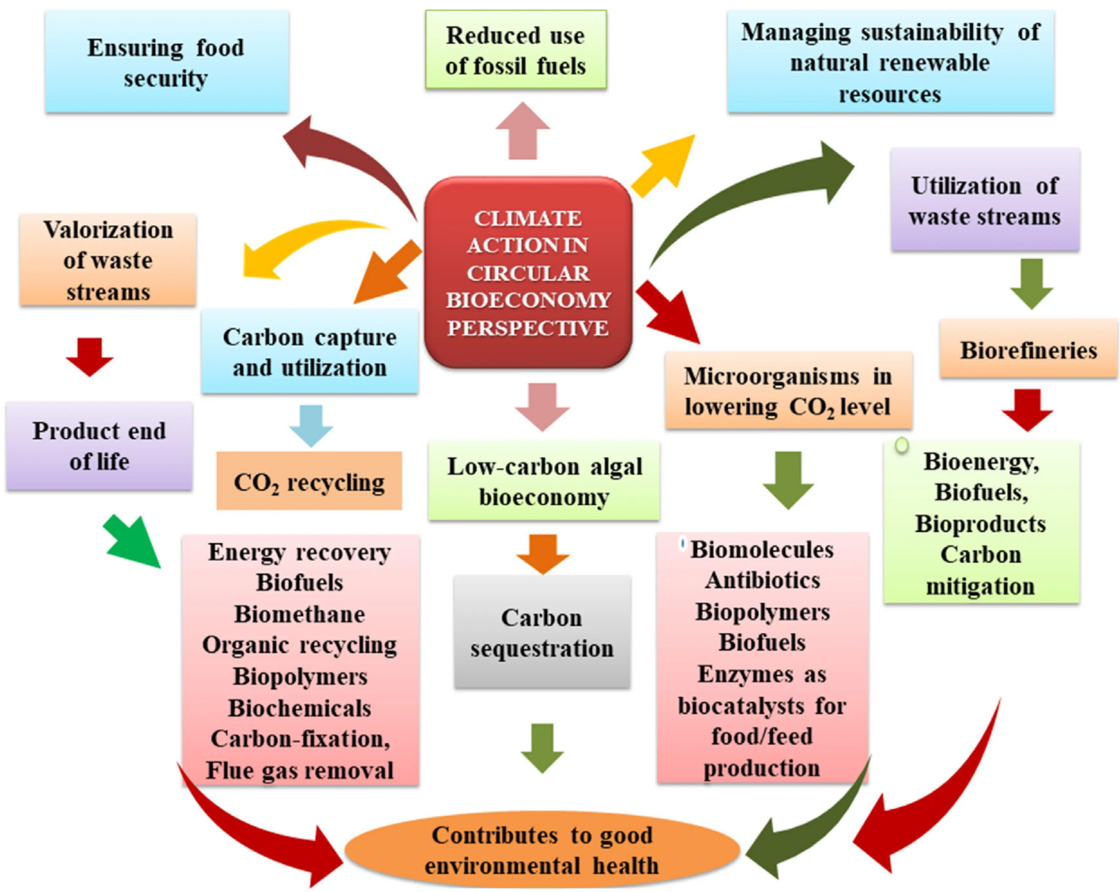

Figure 2. *Climate action through circular bioeconomy strategies. Source: Sharma and Malaviya, 2023.*

CLIMATE CHANGE

Climate change is a serious threat to smallholder farmers across sub-Saharan Africa (SSA). Already, it is unlikely that the UN Sustainable Development Goal 2 (SDG2) on food security can be reached amid the new normal of frequent and recurring droughts, floods, cyclones and rising temperatures and sea levels. **One third of global droughts now occur in SSA**, and one single such weather event can significantly increase food insecurity, especially in countries where agricultural productivity is already less than half the global average (Fuglie et al., 2020; Ritchie, 2022). Higher temperatures, rising sea levels, floods, droughts, storms and acidification weigh on agricultural yields and weaken the nutritional value of food (Baptista et al., 2022). Industrial use of fossil fuels threatens the long-term habitability of the planet (i.e., fresh air, clean water, sustainable food supply, biodiversity, and a stable climate) and results in serious concerns including climate change, growing pressure on ecosystems, modified land-use patterns, agricultural intensification, biodiversity loss, and energy crises (Pfau et al., 2014).

Climate change is a ubiquitous and escalating threat to the world's rich biodiversity, ecosystems, and human civilization, particularly to vulnerable communities, tribes and indigenous peoples (Diaz et al., 2019). As a result of pressure from politicians and society to address these threats, **the industrial world is transitioning towards a circular bioeconomy** that is more resource-efficient and less harmful to the environment (Leong et al., 2021).

Complicating the issue are findings indicating that climatic conditions and economic challenges work together to encourage conflict, particularly in areas that strongly rely on agriculture (Koubi, 2019; Scheffran et al., 2019). Conflicts undermine Africa's economic foundations and have a significant impact on socioeconomic development (Bedasa and Deksisa, 2024). In addition, because of soil erosion, soil nutrient depletion, a drop in soil organic matter and the loss of soil biodiversity, **40 percent of Africa's soils are deteriorating**, putting the continent's soils in danger (Bedasa and Deksisa, 2024). Climate change affects crop yields since SSA already has a water shortage and more than **97 percent of its agricultural land is rain-fed** (Lamptey, 2022). Drought-prone regions that are dependent on rain-fed agriculture are more exposed to conflict and social upheaval (Tekalign et al., 2023). Wars in East Africa have had a negative impact on food shortages and food security while more variable and unpredictable climate conditions negatively affect the region's food security and rural livelihoods (Bedasa and Deksisa, 2024) (Figure 3).

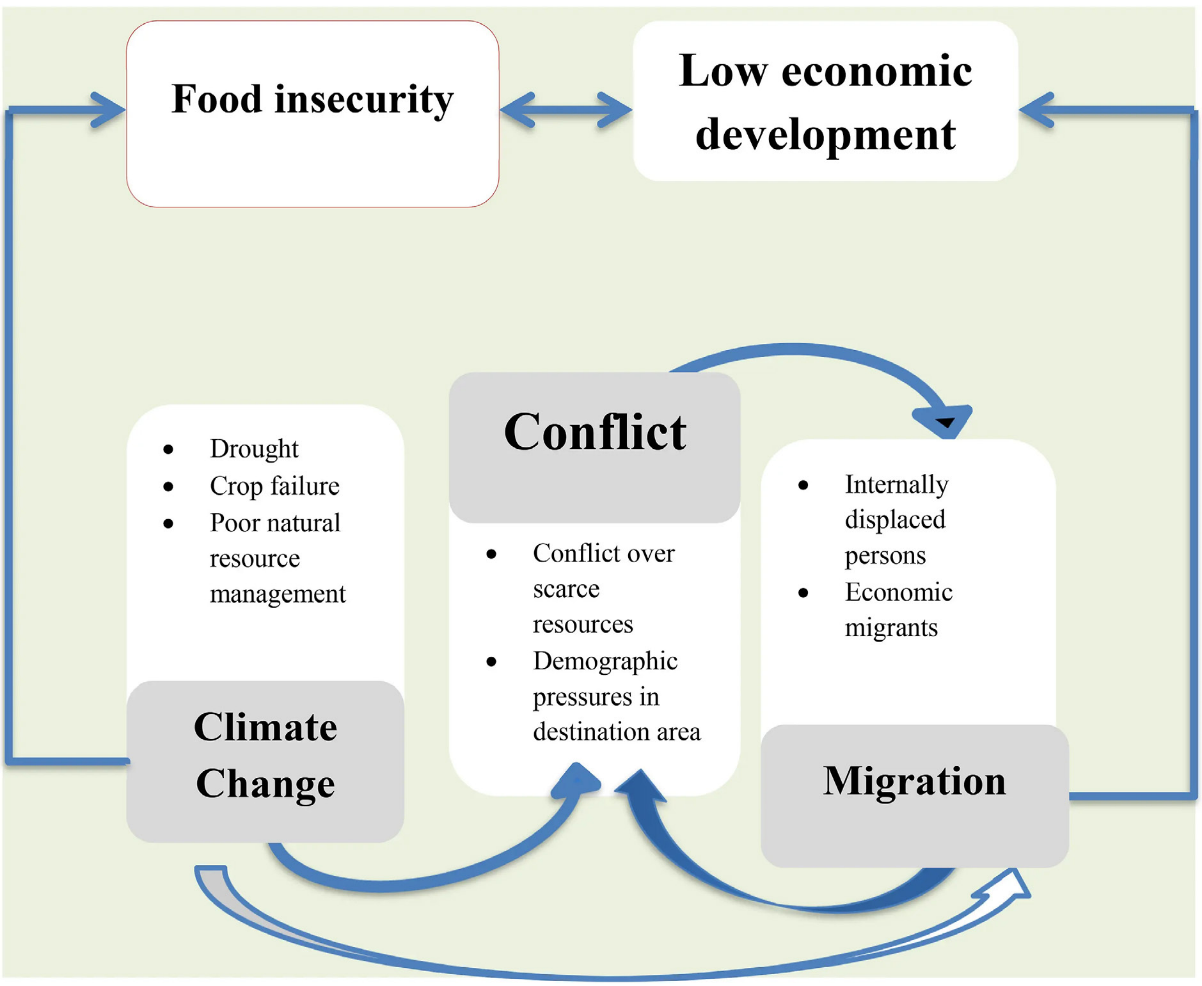

Figure 3. *Conceptual model of climate, conflict and migration. Source: Bedasa and Deksisa, 2024.*

For humanity to survive in the future, it is critical to recognize that **climate change mitigation, circular economy, improved nutrition, and technological innovation** must all play a role in food security, particularly in regions like sub-Saharan Africa (Brenya et al., 2024). Food security is possible based on the alignment of a country's food resources channeled to innovational activities such as improving soil fertility, precision livestock farming practices, technological farming innovations, gene modification of plants and livestock, etc. (Figure 4). Innovative tactics aimed at eradicating agricultural and food waste via recycling, processing, packaging, etc. enables households to obtain extra nutrients which may have otherwise been lost if food waste had not been reduced, reused, recycled, regenerated, etc. (De Pee et al., 2017; Mok et al., 2020; Roversi et al., 2020; Brenya and Zhu, 2023; Brenya et al., 2023).

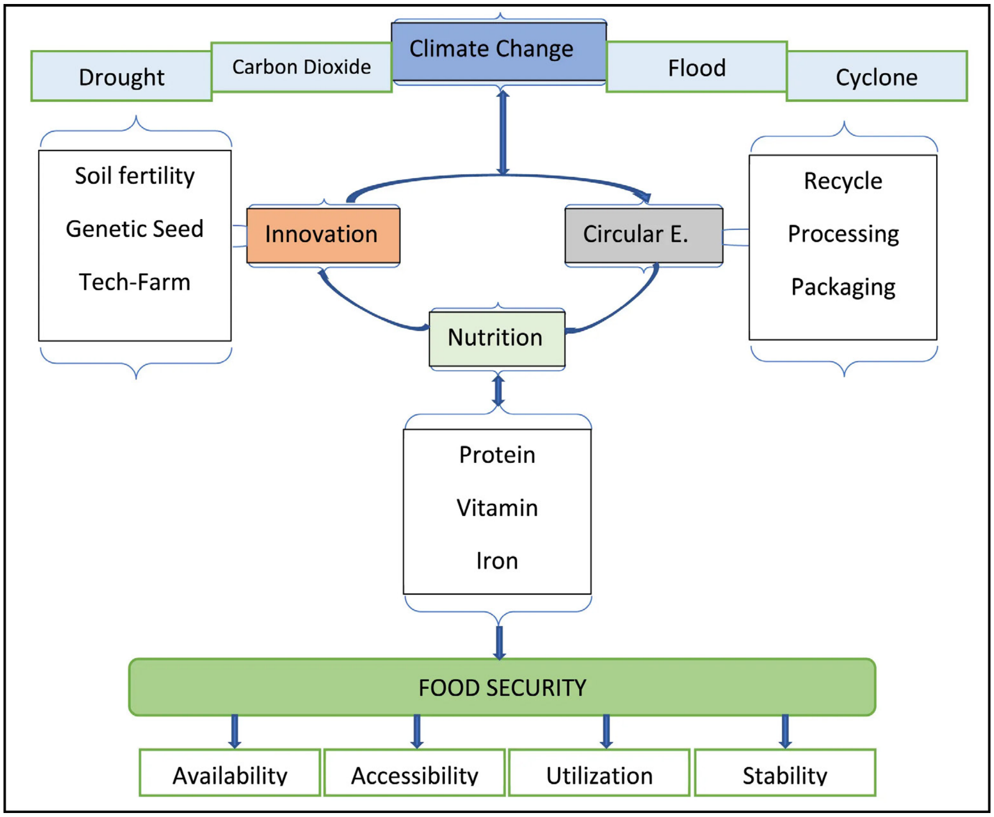

Figure 4. *Construct mechanism impact on food security. Source: Brenya et al., 2024.*

ROLE OF LIVESTOCK

Reusing and recycling of materials (biomass and nutrients), which are key principles to the circular bioeconomy, has been an integral part of the smallholder mixed crop-livestock systems in SSA long before the recent popularity of a circular bioeconomy model. Reusing and recycling of materials is **a necessity for smallholder farmers in SSA** because external inputs are not easily available or affordable (Duncan et al., 2023). The cycling of biomass through livestock, and the use of manure to fertilize the soil, has long been an important linkage between livestock and soil productivity in semi-arid Africa (Powell et al., 1996). Efficient cycling of nutrients in mixed crop-livestock systems is important for soil fertility management, elimination or reduction of nutrient loss, primary productivity of rangelands, crops, and livestock, and consequently, household food security. Although efficient nutrient cycling in the smallholder mixed crop-livestock system is inadequate to sustain the productivity of the system to meet today's growing food needs without external inputs (Bartiono et al., 2007), nutrient cycling is an important element of mixed crop-livestock farming, substantially reducing the need for importation of external inputs in the form of inorganic fertilizer and concentrate feed for livestock.

In a circular bioeconomy, arable land is used primarily to produce foods and other materials that fulfill human nutritional requirements and needs (De Boer and Van Ittersum, 2018; Van Zanten et al., 2019). Throughout the production and consumption of food products, residuals and co-products are generated from agricultural activities, industrial food processing, food losses and waste, and animal and human waste products. A primary goal of a circular bioeconomy is **to prevent human edible co-products from becoming food waste**. Under this paradigm, livestock can play a crucial role in the circular bioeconomy by recycling resources that are not part of the primary food supply, through diverse contributions in areas such as food production, utilization of plant-based products, residual management, nutrient recycling, soil health and renewable energy generation. Livestock enables **the upcycling of agricultural products** that cannot be consumed by humans into valuable and nutritional food, produce manure as an organic fertilizer rich in macro and micronutrients and organic matter, and deliver other ecosystem services and cultural value (FAO, 2024). Coupling crop and animal production at the proper density, together with appropriate management of animal manure as a nutrient source for crops, can contribute to sustainable agricultural practices and reduce the need for synthetic fertilizers (Soussana and Lemaire, 2014). This sustainable closed-loop approach can help maintain soil fertility, promote soil health, enhance long-term crop productivity and reduce production costs (Rufino et al., 2006).

Animal-based food provides a significant portion of the world's food supply, accounting for 34 to 40 percent of global protein consumption (FAO, 2023; Smith et al., 2024). By utilizing non-edible biomass such as forage and grasslands, crop residues and co-products from other industries (e.g. food waste and biofuel), **animals can convert low-value resources into high-quality nutrient sources** (meat, milk, and eggs) for human consumption.

This can promote circularity, if grasslands are managed sustainably and it does not occupy land that society may need to use for other purposes such as provision of biomaterials or conservation of biodiversity (FAO, 2024). Of the feed consumed by livestock, 86 percent is estimated to be unsuitable as food for humans, with the remaining 14 percent corresponding to one-third of global cereal crop production (Mottet et al., 2017). Within a circular bioeconomy, food-feed competition dynamics are reduced, while livestock systems based on recycling residual waste streams from food, feed production, and biobased industries are promoted. Unfortunately, because of the current linear nature of industrial livestock and agricultural systems, not all system inputs contribute to products consumable by humans and can generate residuals with the potential to pollute (FAO, 2023). It is estimated that between U.S. $1 to $2 trillion annually are lost through inefficiencies in the global food economy, and as much as 31 percent of the food produced for human consumption is wasted (UNEP, 2024). Redesigning the livestock sector based on circularity principles offers the opportunity to reduce food-feed competition, lower environmental impacts, improve the efficiency of water and energy use while contributing to global food security.

ROLE OF AGRICULTURAL EXTENSION SERVICES

Agricultural Extension Services (AES) refer to collaborative organized efforts to provide farmers, rural communities and other stakeholders with the necessary knowledge, skills and information to enhance agricultural productivity, sustainability and overall well-being. Extension agents serve as facilitators for communication and knowledge transfer to empower farmers for adopting innovative and sustainable practices, improve crop yields and address challenges related to agriculture and rural development (Anderson and Feder, 2007; Ali et al., 2012; Altalb et al., 2015). The primary purpose of AES is to bridge the gap between scientific research, government, technological advancements and practical applications on the farm (Anderson and Feder, 2007; Altalb et al., 2015). Unfortunately, a shortage of Extension personnel across much of SSA hinders progress on several fronts (Tabler et al., 2020a) even though AES have a vast potential to fast track the transformation of household moderate and severe chronic hunger to the level of food stability via knowledge dissemination and skills training (Brenya and Zhu, 2023).

However, the flow mechanism from AES knowledge transfer to achieving food security is complex and multi-faceted. The main mechanism flow depicted in Figure 5 indicates the direct causal process starts from Extension agents' knowledge and skill impartation that increases farmers' crop and animal production capabilities upon application. As a result, farmers have the option to consume some of their own production and sell the rest. Income generated from the sale of goods can be used for purchasing dietary diverse foods and/or non-food purchases such as school requirements, dowry payments, homestead improvements, etc. Therefore, an **increase in production resulting from AES training positively correlates with food securit**y (Brenya and Zhu, 2023).

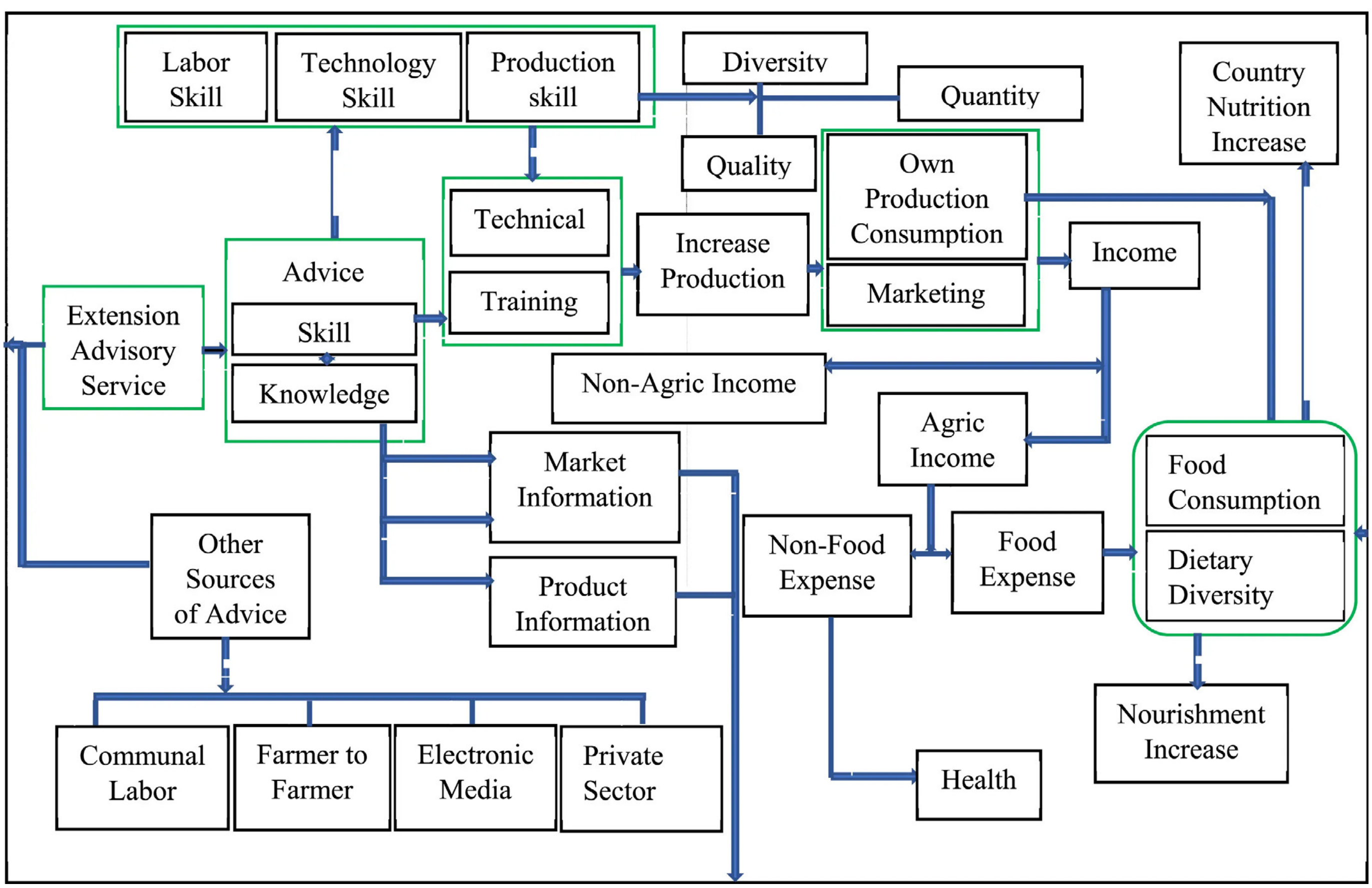

Figure 5. *Mechanism flow from agricultural Extension services to food security. Source: Brenya and Zhu, 2023.*

The need for increased numbers of knowledgeable Extension agents across SSA cannot be overstated. In relation to a circular bioeconomy, knowledgeable agents and the services they provide at the local level can contribute to circular bioeconomy adoption by disseminating knowledge concerning its principles and benefits, organizing training programs to enhance farmers' skills, facilitating the transfer of innovative technologies (i.e., precision livestock and crop farming practices) related to circular bioeconomy, advocating for supportive policies and actively participating in the monitoring and evaluation of the impact of circular bioeconomy practices (Yanfika et al., 2024). By disseminating the principles and benefits of a circular bioeconomy, Extension agents **empower farmers and other stakeholders with the necessary insights** to incorporate sustainable and regenerative practices into their agricultural activities while AES play a pivotal role in training farmers and stakeholders on sustainable agriculture and waste management practices. Extension agents also contribute to the agriculture sector's modernization and adherence to sustainable practices by staying current on the latest advancements and promoting the adoption of innovative technologies and precision farming practices related to a circular bioeconomy such as efficient resource utilization, biomass valorization (preserving or enhancing the value of an item) and circular supply chain management (Yanfika et al., 2024).

CHALLENGES

Numerous challenges and gaps exist for successful bioeconomy adoption across SSA. Understanding current gaps in the African food system must be a priority in efforts toward successful bioeconomy adoption and practice. Where are the bottlenecks and what should be done to address them? A typical example is the **current deficit in investment in academic learning facilities**, limiting practical experiences and appreciation of essential theories for real-world problem solving (Daniel and Bisaso, 2023; Nwosu et al., 2023). Another critical concern is the relatively low participation of public and private institutions in food system knowledge extension and capacity building. Outreach efforts, Extension programs and vocational and informal training are comparatively low, leaving most smallholder farmers, small and medium enterprises and other bottom-level bioeconomy players with little or no knowledge about the potential of bioeconomy and limiting their interest and active participation in a circular bioeconomy (Greenberg, 2017).

Production gaps exist at the farm level. Despite having the highest share of global arable land area and broad potential to expand production, Africa still faces extreme production inefficiencies, exacerbating food and nutritional insecurity and an unstable food supply chain (Giwa and Choga, 2020; Armstrong, 2022). Other challenges include unfavorable farm inputs, poor farm management practices, insufficient infrastructures, limitations in innovative production technologies, changing climate and land topographical dynamics, limited smallholder farmer access to Extension services and support systems especially among women smallholders (Tabler et al., 2020b) and knowledge gaps among farmers (Aidoo et al., 2023). There may likely be criticism towards a circular bioeconomy from various stakeholders who may consider this new paradigm too challenging to implement. The development of a circular bioeconomy may be severely hampered by organizational, scientific, financial, social and geopolitical obstacles, regardless of the scale (Leela et al., 2024). Therefore, it is essential to accurately identify and comprehend the key variables, presumptions, and limitations that may impact how circular bioeconomy techniques are implemented. This will require focus on topics like generating employment, marginalized people's empowerment, poverty alleviation and climate change, all which are especially relevant in the current African environment (Leela et al., 2024).

Presently, the poultry and livestock sectors are struggling to maintain pace with the growing demand for animal-based products against a backdrop of inadequate feed production, poor market structure, inadequate investment and support systems, climate change and herder-farmer frictions (Nkukwana, 2019; Amole et al., 2022; Erdaw and Beyene, 2022). An example of the detrimental effects of climate change is the recent situation in East Africa where approximately two million livestock were lost in a year due to recurring drought and marginal regional climate adaptation strategies (Dessalegn and Eziakonwa, 2023). Transforming food waste into livestock feed provides a sustainable alternative to traditional feed sources, offering several environmental and economic benefits (Pal et al, 2024). Incorporating such food waste-derived feeds can significantly improve animal health and growth rates, making them a viable alternative to conventional feed ingredients (Rahmani et al., 2022). By converting food waste into animal feed, the overall cost of production is reduced, benefiting farmers and livestock producers. By closing the loop on food waste and transforming it into a resource that supports agricultural sustainability and reduces waste, this aligns with the principles of a circular bioeconomy.

Postproduction challenges exist in addition to production gaps. Postharvest losses are huge due to inadequate infrastructure to handle the harvest such as transport, storage, cooling and processing facilities. Approximately 30 to 50 percent of all foods produced in Africa south of the Sahara do not reach consumers' tables, primarily due to poor postharvest storage (Aidoo et al., 2023). Reducing these losses could contribute greatly to addressing food insecurity in Africa as well as providing farmers opportunities to engage in price negotiation and increase incomes. While most African countries are in the early stages of developing the bioeconomy, the accelerating trend at the global level toward advancing the bioeconomy for sustainable development suggests the critical need to expedite actions across Africa (Ronzon et al., 2020). Even though Africa is making progress in the practice of a circular bioeconomy, its regional distribution is skewed to only a few countries making significant gains, demonstrating enormous untapped potential in many regions and encouraging the need to strengthen sustainable economic and social development.

Food waste is a monumental challenge, not only in Africa but also around the world. The **environmental, economic and social impacts of food waste are profound**. When food is wasted, all the resources that went into its production are also wasted, including water (already scarce in much of the world), land, energy and labor (Pal et al., 2024).

In addition, food waste in landfills decomposes anaerobically, producing methane, a GHG with a global warming potential significantly higher (27-30 times greater over 100 years (U.S. Environmental Protection Agency, 2024)) than carbon dioxide. The carbon footprint of food waste is substantial with estimates suggesting that if food waste were a country, it would be the third largest emitter of GHG after the U.S. and China. The water footprint of food waste is perhaps even more alarming. The water used to produce wasted food is equivalent to three times the volume of Lake Geneva (the volume of water in Lake Geneva is 21.35 cubic miles, a single cubic mile of water is 1.1 trillion gallons), highlighting the inefficiencies of our current food production systems (McDowall et al., 2017).

Economically, the cost of food waste is enormous. Not only is the direct cost of the wasted food involved but also the cost of the resources involved in its production, the expenses associated with its transportation and storage and the cost of the eventual waste disposal (Pal et al., 2024). Particularly for businesses in the food retail and hospitality sectors, food waste represents a loss of potential revenue and increased operational costs. Globally, the economic impact of food waste is estimated at over $1 trillion annually, underscoring the scale of the issue and the potential benefits of food waste reduction (Kag et al., 2023). In addition, from a social standpoint, **while vast quantities of food are wasted, millions of people worldwide suffer from hunger and malnutrition**. The redistribution of surplus food to those in need is critical to addressing this paradox. Food banks and community kitchens play a vital role in channeling and distributing excess food to vulnerable populations (Mohanty et al., 2022).

However, logistical challenges, food safety regulations and a lack of awareness among potential donors can limit the effectiveness of such essential programs. Enhancing the capacity and efficiency of food redistribution efforts is vital for mitigating food waste's societal impact (Pal et al., 2024). While the sheer scale of the food waste problem poses challenges, it also offers immense opportunities for innovation and positive change. In both the short and long term, however, public awareness and engagement will be critical for the successful implementation of circular bioeconomy practices. There is an immediate need for effective strategies to raise awareness concerning the benefits of reducing and repurposing food waste and creating incentives for behavioral change related to the transformation of food waste into renewable food resources among businesses and consumers. **Behavioral change will be a prerequisite** to realizing the potential of a circular bioeconomy and a more sustainable agricultural production system in the future.

SUMMARY

The exploration of circular bioeconomy principles applied to food waste management has demonstrated significant potential for transforming food wastes into renewable food resources. Integration of food waste into the circular bioeconomy framework offers numerous environmental, economic and social benefits (Pal et al., 2024). Environmentally, it helps mitigate climate change by reducing GHG emissions associated with food waste decomposition in landfills. Economically, it creates new value chains and market opportunities, particularly for local communities and industries. Socially, it contributes to food security by enabling the recovery of nutrients and other valuable components from food waste, which can be reintegrated into the food supply chain. However, several challenges stand in the way of fully realizing the benefits of transforming food wastes into renewable food resources. Scalability to optimize large-scale application is a primary challenge. Development of innovative technologies and processes that can enhance the conversion of food waste into high-value products is another critical area. Additional research should focus on the potential of using food waste in precision agriculture practices, where nutrients recovered from food waste can be utilized to improve soil health and crop yields. The diversity of food waste types and a lack of tailored approaches for different food waste streams is also a challenge. Effective strategies for raising public awareness and engagement, essential for the successful implementation of circular bioeconomy practices, must also be developed.

Despite the challenges, circularity in agriculture and food production holds much promise for recovering lost resources, addressing the unintended negative consequences of a linear production system and transforming African food systems. The challenge to African agriculture, made more difficult by worsening climate change, is to adapt the circularity observed in natural ecosystems into practical applications for smallholder farmers and their current value chains, thereby shifting intensive linear systems away from the single goal of optimizing monoculture productivity toward circles of life capable of producing multiple benefits concurrently (Morton and Shea, 2022). Multiple benefits, including increased productivity, improved water quality, better pest and disease control, economic profitability, and improved soil health are potentially available from mixed multi-plant and animal agricultural systems that leverage integrated land management and biodiversity. Innovative technologies and precision crop and livestock farming practices that focus on and expand whole-farm management, builds on local conditions/situations and indigenous knowledge, and delivers multiple benefits will be necessary for circular bioeconomy systems to succeed. This will require that individual producers and entire African countries determine the circular system that best suits their unique situation and location. Solving the food insecurity problem is vital to the environmental, economic, and social sustainability of worldwide regional systems facing food security threats from climate change, environmental degradation, resource scarcity, regional poverty, and economic depression.

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