W1328

Agriculture and the Circular Bioeconomy Across Sub-Saharan Africa

Tom Tabler, Professor and Extension Poultry Specialist, Department of Animal Science, University of Tennessee
Tanner Thornton, Graduate Research Assistant, Department of Animal Science, University of Tennessee
Logan Lewis, Extension Agent I, University of Tennessee Extension, Montgomery County
Pramir Maharjan, Assistant Professor and Extension Poultry Specialist, Department of Agricultural and Environmental Sciences, Tennessee State University
Joseph Felix Chibanga, Scientific Officer-Animal Nutrition, Animal Science Research Centre, National Institute for Scientific and Industrial Research, Lusaka, Zambia
Thomas Odiwuor Rewe, Associate Professor of Integrated Agro-Systems, Pwani University, Kilifi, Kenya

The bioeconomy uses renewable, nature-based resources like plants, microorganisms and certain types of waste to produce food, materials, energy and more. It aims to create a more sustainable ecosystem that can address some of our world's greatest challenges, including food security, sustainable development and how to best use natural resources. Its purpose is to reduce reliance on fossil fuels, improve public health, enhance agricultural practices and foster a more sustainable and circular economy. While the bioeconomy includes various industrial sectors, food systems play the largest role. A circular bioeconomy brings together two sustainability concepts: 1) it uses renewable biological resources to create biological products, and 2) it reuses, repurposes or recycles those resources and organic waste back into the economy. There is vast potential to create a more circular bioeconomy across supply chains where the agricultural sector is involved over much of the African continent.

Agriculture and the Circular Bioeconomy

Building a sustainable, circular bioeconomy is essential for advancing sustainable resource use. Agricultural systems are the backbone of human civilization, providing food, fiber and fuel to a growing world population expected to reach 9.7 billion in 2050 (United Nations, 2019). However, traditional farming practices often come under scrutiny due to their negative environmental impacts, including degeneration of soil, water quality and air through greenhouse gas (GHG) emissions. In discussions regarding sustainable agricultural development in Sub-Saharan Africa (SSA), much has been made of the need to apply regenerative principles to improve rural livelihoods. The notion of circularity, or the circular economy, is frequently combined with agro-ecological rhetoric, often overlooking examples of a long-standing tradition of circular resource use efficiency in traditional mixed crop and livestock farming in rural low-income settings (Duncan et al., 2023). Historic circular economy examples within the international agricultural research system as applied to smallholder agriculture include 1) studies focusing on the impact of crop residue retention, 2) work on residue incorporation and/or mulching and their effects on crop yields and soil fertility, 3) research on the effects of manure use on crop yields and soil fertility, 4) work on the feeding of crop residues to livestock, and 5) potential for small-scale bioenergy production (biogas) and biofertilizer from biodigester slurry.

In an agricultural and food systems context, circular economy tends to be termed circular bioeconomy to distinguish it from circularity in manufacturing, which tends to rely more on extracted non-renewable resources (Duncan et al., 2023). The integration of the bioeconomy into agriculture aims to optimize crop productivity in space and time through the implementation of advanced technologies and modernized production methods (Papadopoulou et al., 2024). From an agricultural standpoint, one of the greatest challenges facing humankind, both now and in the future, is feeding a constantly growing population (Pandey and Dwivedi, 2020; Circle Economy, 2021). FAO (2017) has estimated that we will need to increase food production by 5.1 billion tonnes (5.6 billion tons) before 2050. This will put huge pressure on agricultural ecosystems and could cause negative impacts on the natural environment as agricultural production consumes large amounts of water and energy (Aznar-Sánchez et al., 2018). In addition, more than 90 percent of environmental impacts due to land use are related to agriculture (Kusumastuti et al., 2016; Aznar-Sánchez et al., 2019).

While there is widespread belief in the potential benefits of the circular bioeconomy for achieving sustainable growth and competitiveness, some scientific publications have drawn attention to potential negative impacts associated with the bioeconomy (Papadopoulou et al., 2024). These include increased pressure on water resources and natural ecosystems as well as doubts regarding its effectiveness in reducing emissions (Priefer et al., 2017; Lago et al., 2019; Stegmann et al., 2020; Lazaridou et al., 2021). These publications also raise concerns about competition for land, agricultural intensification, eutrophication and the potential introduction of invasive species. All things considered however, the circular bioeconomy encourages sustainability in agricultural production by cutting down on wasteful and excessive resource use (Kalogiannidis et al., 2022a, b, c; Kalfas et al., 2023). Furthermore, it mitigates the environmental effects of agricultural practices and increases the adaptability of agricultural systems.

Circular bioeconomy in agriculture evolves from the broader concept of a circular economy, which refers to a recovering system of agriculture in which resource inputs and waste, as well as emissions and energy leaks, are curtailed by either slowing or closing and reducing material and energy loops (Selvan et al., 2023). Transforming the agricultural food system from the current linear production system, often referred to as a “take-make-waste” system, to a circular bioeconomy that reduces, recycles, recovers, reuses and regenerates wastes and transitions from fossil to biobased fuels and products is being hailed as critical for meeting the world’s growing population’s need for food, fiber and fuel in an environmentally sustainable manner (Khanna et al., 2024). The existing food production system is referred to as linear because it relies on a one-directional process of using extracted inputs, producing outputs and generating residues that become waste. Acknowledging the limitations of continued reliance on this approach to meet continuing and increasing demands for agricultural food products (Tilman et al., 2011; Basso et al., 2021) has led to a call for a paradigm shift towards a circular bioeconomy (Ellen MacArthur Foundation, 2015; Van Zanten et al., 2023).

Although quite successful at delivering agricultural outputs, this linear production model is highly dependent on external inputs (e.g., seeds, fertilizers, pesticides, energy) prone to degrading and depleting its resource base (e.g., soils, surface and ground water, nutrients), creating pressure on the environment (e.g., water pollution, GHG emissions, loss of biodiversity), driving increased farm size and specialization and diminishing rural livelihoods and opportunities for smaller, less specialized farming enterprises (Basso et al., 2021). Reversing these trends while simultaneously dealing with the complex challenges ahead will require a transformation of our current systems of food production and consumption (Herrero et al., 2020; Rosenzweig et al., 2020).

A sustainable agricultural food production system must be the central and primary sector of the economy for a circular bioeconomy to operate efficiently. This will require transformation from the traditional linear economic model that creates tremendous food waste and GHGs to a circular economic model that can reduce agricultural waste by reusing all products and byproducts to generate additional value in a closed system (Tinda et al., 2024). This is possible because circular agriculture is built around four main pillars, which are 1) a closed-loop waste-free agricultural production system, 2) maximal use of renewable resources, 3) optimal resource usage and 4) the preservation and enhancement of complexity and biodiversity. These pillars define the circularity principle in agriculture (Velasco-Muñoz et al., 2022).

The main objective of a circular economy system is to couple economic growth with sustainable resource use (Cullen, 2017; Pauliuk, 2018) through the implementation of three key principles (Ellen MacArthur Foundation, 2015): 1) regenerate natural systems through the control of finite stocks and balancing of renewable resource flows, 2) optimize resource yields by keeping materials within biological and technological cycles for as long as possible, and 3) design out waste and pollution from production and consumption. The circular economy seeks out a more efficient use of resources by establishing new business models that respect the environment while generating new job opportunities and improving well-being and equity in society (Ghisellini et al., 2016). In this regard, the transition from a linear economic model to a circular economy model represents a challenge that requires the development and application of new knowledge that will enable the creation of innovative, technological and sustainable processes, products and services (Greco et al., 2019). However, in the case of food production, scientific progress related to circularity is still in the early developmental stages. Although some countries have pioneered adoption of some tangible circular economy policies (Pauliuk, 2018), implementation still faces barriers that will require systemic change at the technological, cultural, regulatory and market levels (Kirchherr et al., 2017).

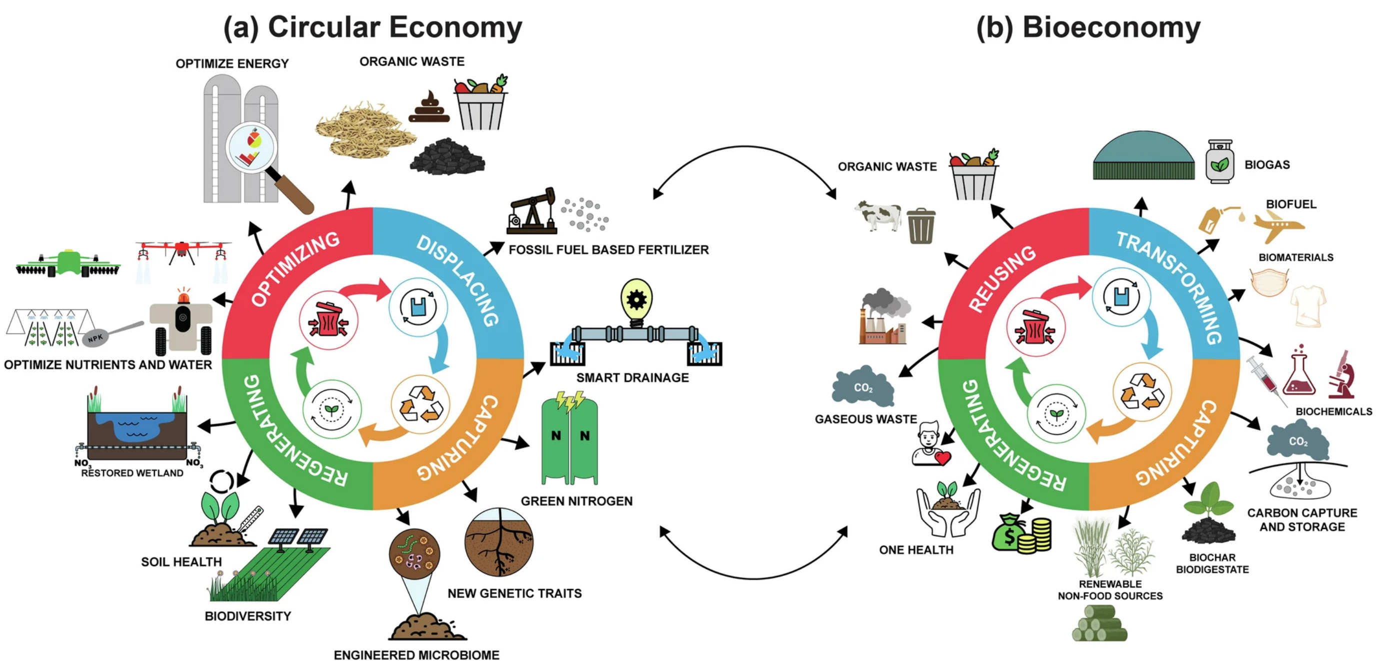

Figure 1: *Multiple pathways to a circular bioeconomy: a represents multiple pathways to reduce, reuse, and recycle waste in a circular economy; b represents multiple pathways to produce inputs, food and energy products. Together, the two panels show the interconnections among the pathways to reduce, reuse, and recycle waste and to convert unavoidable waste and other biological resources to bioproducts that displace fossil fuels. Source: Khanna et al. (2024).*

However, there are currently existing and emerging technological pathways to enable the transition of the agricultural food sector to circularity for any product supply chain and across the multitude of products in an economy (Figure 1a). Similarly, there are multiple types of applications of synthetic biology, gene editing and biotechnology, and precision fermentation to convert and upcycle agricultural wastes and perennial energy crops to plant-based proteins, bioproducts and bioenergy that are substitutes for chemical and fossil energy-based products (Canadell and Schulze, 2014) (Figure 1b). Additional pathways include redesigning landscapes to include leguminous crops that necessitate fewer chemical treatments, pasture for grass-fed animals, converting organic waste generated at all stages ranging from crop residues to food scraps into compost and biochar for nutrient-rich soil amendments or into renewable natural gas can improve soil health and crop productivity and reduce the need for fossil fuels (Northrup et al., 2021; Schulte et al., 2022).

The principles of circular economy provide a guide to redesigning food and agricultural systems to capture and reuse resources and embedded byproducts within biological cycles to more closely mimic near zero-waste in ecological systems (Ellen MacArthur Foundation, 2019). In broad terms, circular bioeconomy envisions food and agricultural systems that are coupled with material and energy flows at various levels of the value chain (production, processing, distribution, consumption) so that they can be reused as agricultural inputs (e.g., manure, composts, or sludges as biofertilizer, treated municipal wastewater for irrigation, food waste as animal feed), used in producing other valuable products (e.g., bioplastics and advanced biomaterials) or serve as sinks for waste (e.g., sequestration of atmospheric CO2 in soils) (Basso et al., 2021).

Due to its biological complexity, agriculture offers some of the clearest examples of circular resource use, many of which have evolved out of necessity over centuries of practice and formal and informal knowledge transfer in transitional low input and extensive farming systems (Figure 2). Examples include the observance of seasonality in production to match crop calendars with peak growing conditions, the use of crop residues in animal feeds, soil nutrient augmentation from livestock and human waste and the optimized use of other animal bio products, including for renewable energy production (Duncan et al., 2023).

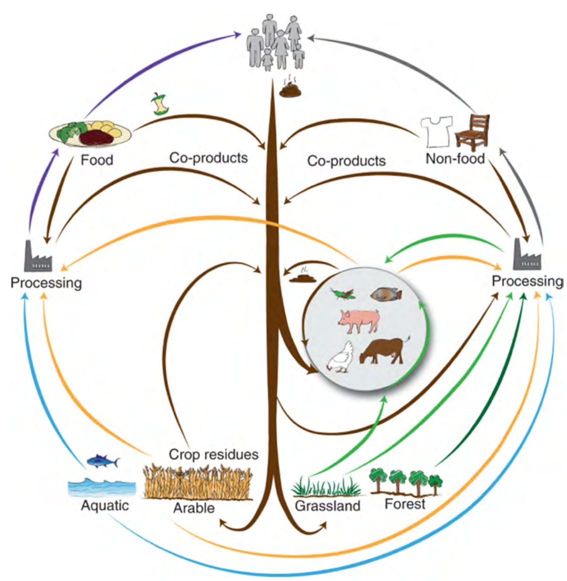

Figure 2: *Biomass flows in a circular bioeconomy. Source: Muscat et al. (2021).*

The most formal, although contested, definition of circular economy was previously provided in a review by Kirchherr et al. (2017) and states, "A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond) with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity to the benefit of current and future generations." However, arguments about the scope persist, particularly in relation to the inclusion of social equity criteria and social responsibility in supply chains (Duncan et al., 2023). This led Figge et al. (2023) to offer an alternative definition: "The circular economy is a multi-level resource use system that stipulates the complete closure of all resource loops. Recycling and other means that optimize the scale and direction of resource flows, contribute to the circular economy as supporting practices and activities. In its conceptual perfect form, all resource loops will be fully closed. In its realistic imperfect form, some use of virgin resources is inevitable."

Circular Bioeconomy in Africa

The African food crisis accompanied by poverty, dwindling production resources, increased urbanization, and rapid population growth requires development of an alternative, sustainable and innovative food solution adapted to the specific needs of the continent (United Nations, 2015; Dasgupta, 2021; Assan, 2023), specifically SSA. The persistent food crisis, strongly affected by gender inequality in agriculture and food production, is an existential threat to attaining the United Nations' Sustainable Development Goals (SDGs) (Assan, 2023). Such an alternative is the circular bioeconomy which, as defined previously, aims to maximize the use of biological resources, minimize waste generation, reduce environmental impact and make transition from a linear economy, where resources are extracted, used and discarded, to a circular economy, where resources are continuously cycled and reused (Ahmad and Ashraf, 2023).

Development of the circular bioeconomy could have a significant and positive impact on the attainment of SDGs 1, which concerns the global pledge to end poverty in all its forms by 2030. In addition, SDGs 2 focuses on the need to promote sustainable agriculture, which is essential for fighting hunger and thereby ensuring food security and enhancing nutrition (Kirchherr et al., 2018). To meet SDGs 1 and 2, it is necessary to capture holistically the association between circular bioeconomy practices such as composting, anaerobic digestion and using food waste for animal feed or bioenergy production and food security (Anand, 2016; Sekabira et al., 2022; Chitaka and Schenck, 2023). There is an urgent need for an empirical approach to circular bioeconomy practices that would apply consistently and practically to the different agricultural sectors used to achieve the SDGs in the context of developing countries (Sekabira et al., 2024).

Without sustainable production and consumption systems, the achievement of several SDGs, like poverty reduction, food security, environmental health and sustainable cities is in jeopardy (FAO, 2018: Kershaw et al., 2021; Muscat et al., 2021). The linear model of resource use employed by modern food production and consumption systems is blamed for depletion of resources (Majumdar et al., 2016; Kershaw et al., 2021). Such a linear production system renders the rural-urban food system nexus non-resilient (Sekabira et al., 2022), hence making it unsustainable (Kaza et al., 2018; Kershaw et al., 2021; Muscat et al., 2021). Circular bioeconomy is a combination of circular economy and bioeconomy (Kershaw et al., 2021). A circular economy attempts to rearrange the linear take-make-use-dispose resource model in production and consumption systems with a circular formation (Geissdoerfer et al., 2017), while bioeconomy aims to provide goods and services sustainably through use of biological resources, processes and products (Kershaw et al., 2021; Muscat et al., 2021). Reusing recycled waste in such a manner would close nutrient loops and replenish soil nutrients and organic matter, all of which would increase sustainable farm productivity (van der Wiel et al., 2019). This is especially true in African food systems that are characterized by low farm incomes where there is potential to transform organic waste into useful farm inputs (Frankema, 2014).

Mixed crop/livestock production is the dominant farming system in Sub-Saharan Africa with varying degrees of interaction between crop and livestock enterprises depending on climate and population density (McIntire et al., 1992). The smallholder mixed crop/livestock system is characterized by nutrient flows among the components of the system (soil, rangeland, crop and livestock). For example, crop residues are fed to livestock while livestock deposit manure on crop fields as shown in Figure 3. In line with circularity principles, a significant proportion of the nutrients are recycled within the systems, particularly animal manure and crop residues while grains are largely consumed by households (Stangel, 1995).

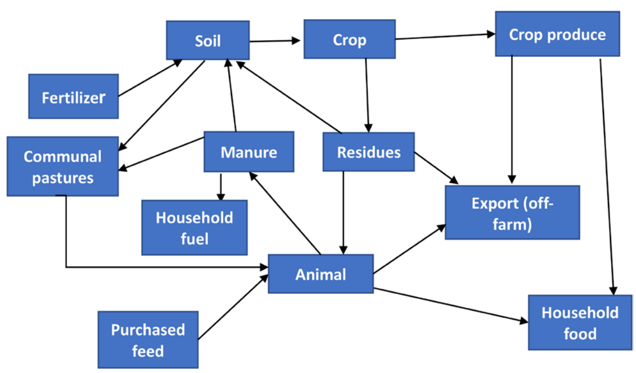

Figure 3: *Pathways of nutrient flows in mixed crop/livestock systems in sub-Saharan Africa. Source: Duncan et al. (2023).*

The cycling of biomass through livestock, and the use of manure and urine 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 in nutrient loss, primary productivity of rangeland, crops and livestock, and consequently, household food security (Duncan et al., 2023). 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 (Bationo 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.

Reusing and recycling materials (biomass and nutrients), which are key principles of the circular bioeconomy, has been an integral part of the smallholder mixed crop/livestock systems in SSA long before the recent popularity of the circular bioeconomy concept. Reusing and recycling materials is a necessity for smallholder farmers in SSA because external inputs are not readily available or affordable. Despite the inherent nutrient recycling in mixed crop/livestock farming in SSA, closing nutrient loops is a challenge since such systems are still characterized by waste and nutrient loss through animal grazing (deposition of manure on non-productive areas, such as around watering stations), nitrogen volatilization through manure and urine, harvesting of crop produce and residues for off-farm use, significant nutrient loss due to soil leaching and off-farm export of produce (grain, roots and tubers) and livestock products (Duncan et al., 2023).

Circular Bioeconomy Agricultural Practices in Africa: Opportunities, Challenges

Circular bioeconomy from an agricultural standpoint has three key principles, namely 1) preserving and enhancing natural resources, 2) the efficient use of resources and 3) multipurpose use and recovery of waste (Tindwa et al., 2024). Each of these areas offers unique opportunities for both farmers and communities to further the concept of circularity in agricultural production. Each of these key principles has been a part of agricultural production systems in SSA for generations. However, the region requires the coordinated harnessing of emerging technologies that offer more opportunities for agricultural production, manufacturing and waste management, to improve livelihoods and achieve poverty reduction in SSA (Tindwa et al., 2024). Sadly, current policies in most African countries do not prioritize organic waste recycling and reuse, and in some countries, circular bioeconomy policies are largely nonexistent (Kaza et al., 2018; Gatune et al., 2021). In addition, scientific evidence is currently insufficient to guide global food systems' policies on addressing gaps in the circular bioeconomy (Jurgilievich et al., 2016; Geissdoerfer et al., 2017; Gatune et al., 2021).

Moreover, Geissdoerfer et al. (2017) note that the principle focus of circular bioeconomy research has been on developed countries, perhaps because the severe consequences of the linear model have been most pronounced in highly industrialized countries. However, the rapidly increasing African urban population is just as well exposed to the severe consequences of food insecurity and poor sanitation in urban centers due to waste accumulation and excessive soil nutrient depletion in rural areas (Kaza et al., 2018; RUNRES, 2020). Without a reversal of this non-restorative use of resources, sustainable development in Africa grounded on efficient resource-use food production and consumption systems could be difficult to attain (Kirchherr et al., 2017; Kaza et al., 2018: Kirchherr et al., 2018; Gatune et al., 2021; Muscat et al., 2021).

Waste generation in SSA is expected to triple by the year 2050 (Kaza et al., 2018). Because SSA is characterized by middle- to low-income countries, the proportion of organic waste in the overall amount of municipal waste is relatively higher than in more developed regions of the world. Sub-Saharan Africa currently produces around 54 and 56 percent of all food and green waste, respectively, compared to only about 32 percent of the total waste produced in high-income countries and cities (Kaza et al., 2018; Khan et al., 2022). This highlights the potential of the third principle of agricultural circularity—multipurpose use and recovery from waste. Most of the organic fraction of waste can be converted to fertilizer using affordable technology. Instead of burying such waste in landfills or subjecting it to open burning or dumping, the opportunity is there to seize the potential for its conversion into organic fertilizer using simple technologies such as composting (Tindwa et al., 2024).

One of the greatest challenges facing most SSA countries is the prevailing practice of generating and accumulating heterogeneous waste and disposing of it in designated areas without prior segregation according to the type of waste (Abbasi et al., 2021; Tahiru et al., 2024). Another challenge in the use of biomass to develop sustainable bioenergy is the absence of a clearly documented or traceable biomass value chain that would ensure a constant supply of biomass feedstock to fuel energy production machinery in most SSA countries (Tindwa et al., 2024). Other challenges impeding the waste-to-energy approach in most of SSA include ineffective waste collection methods, a lack of suitable waste-to-energy generation technology in place, a lack of financial support and policies related to waste-to-energy projects and the absence of coordination between different governmental institutions (Khan et al., 2022). However, waste-to-energy investments still present the best opportunities for developing nations. This is because, in addition to reducing GHG emissions, such investments are anticipated to create employment opportunities for the surrounding communities (Kurniawan et al., 2022).

As the global population has continued to increase, agriculture has undergone radical transformations to keep pace and continue to provide an adequate food supply (Ramankutty et al., 2018). These transformations have had a major impact on land use patterns and on the natural environment. Agricultural transitions vary greatly depending on the situation but can be roughly characterized as moving from livestock herding to smallholder/subsistence agriculture, through to more market-oriented/semi-commercial production, before moving on to more industrial-type models of production and finally evolving into a phase where the majority of production is incorporated into a more conservation-oriented form of agriculture where farmers become land stewards responsible for delivering environmental objectives (Duncan et al., 2023). The degree to which circular bioeconomy principles are adhered to during this transition is partly a function of the extent of coupling between livestock and crop enterprises. The "sweet spot" for livestock-crop interactions appears to be a mixed livestock/crop production system (Figure 4) (Steinfeld, 1998; Powell et al., 2004).

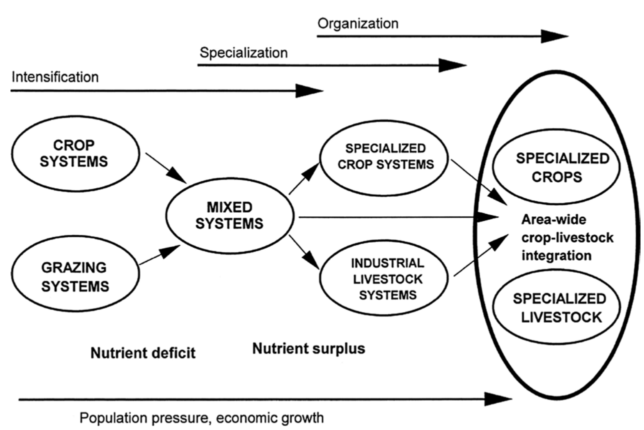

Figure 4: Evolution of crop-livestock interactions as systems evolve in response to population and economic growth. Source: Steinfeld (1998).

Soil health is critical for these agricultural transformations to take place. The soil is known to provide multiple ecosystem services, leading to the sustainable functioning of the ecosystem, which directly affects human health and agricultural productivity (Lambers and Cong, 2022). As a substrate for plant growth, the soil is essential in sustaining plant vigor and growth and in the regulation of water dynamics and carbon sequestration (Smith et al., 2020), all of which contribute to a healthy soil ecosystem. Therefore, healthy soil is the result of an interconnected web of activities involving soil organisms and organic matter as they are modified by agronomic practices. Healthy soil must have the capacity to provide an environment for the optimum growth and development of plants and thus support the health of animals and humans (Tindwa et al., 2024). Accordingly, the circular regenerative agricultural practices summarized in Figure 5 can invariably be used to positively moderate and modify the soil content and its potential for the emission of GHGs into the atmosphere (Gerke, 2022).

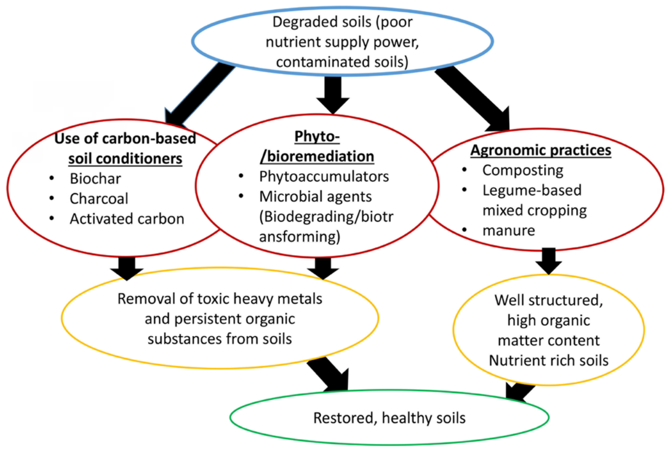

Figure 5: Summary of circular regenerative agricultural practices used to restore soil health in degraded soils in African agriculture. Red cycles show the alternative regenerative agricultural practices that can be applied on degraded soils, yellow cycles show the possible results of the practices leading to restoration of soil health-green cycle. Source: Tindwa et al. (2024).

As agricultural systems intensify, farms specialize into crop or livestock production, and the nutrient transfers between livestock and crops become more challenging as intensification puts more pressure on maintaining circular bioeconomy principles (Oosting et al., 2022). In extreme cases, this can lead to examples such as beef feedlots that require total import of feed nutrients in some areas with wide-scale crop monocultures in others. This decoupling of crop and livestock production comes with significant environmental issues. For example, through spatial concentration of livestock and the resulting difficulties with locally disposing of large quantities of manure (Van Der Peet-Schwering et al., 1999; Gesing, 2023) as well as biodiversity loss through the use of monocrops (Robinson and Sutherland, 2002; Stoate and Wilson, 2020).

This type of transition is well underway in regions such as Southeast Asia and China (Lam et al., 2017). However, in SSA, farming is still predominantly based on mixed crop-livestock production on small farms. The growing demand for food has been met mainly by the expansion of land use for cropping and for livestock at the expense of previous natural habitat (Ramankutty et al., 2018). As a result, environmental issues associated with intensification have yet to fully materialize in SSA, but with population growth and rising incomes leading to an increased demand for livestock products, a similar trajectory is eventually likely in SSA (Duncan et al., 2023). To avoid the potential decoupling of livestock and crop production that could result from system intensification, there is a need for circular bioeconomy innovations that fit the context of SSA. This could include a range of innovations such as those centered on improved manure management and, particularly, reuse and recycling of existing biomass as livestock feed which might otherwise enter the waste stream using such technologies as:

- breeding of dual-purpose crops in the crop-livestock circular bioeconomy
- conversion of cereal straw residues into high-quality feed
- use of cassava waste as livestock feed
- conversion of food waste to livestock feed through insect production

Other possible technological solutions that would allow intensification but maintain circular bioeconomy benefits include increased use of legumes in mixed crop-livestock production (Muoni et al., 2019). Legumes fix atmospheric nitrogen reducing requirements for inorganic nitrogen fertilizer and improving nutrient use efficiency at the system level. Improved manure management methodologies that reduce nitrogen volatilization also are an important research area for enhancing nutrient use efficiency in smallholder systems (Diogo et al., 2013). Small-scale mechanization has strong potential to increase the feasibility of manure application to crop plots by reducing the labor constraint to manure use (Van Loon et al., 2020). Enhanced use of cultivated forage to reduce the need to import nitrogen through purchased feed also is a strong potential pathway to enhancing the smallholder circular bioeconomy during their system's evolution (Paul et al., 2020).

Rationale for Circular Bioeconomy in East Africa

The development of a circular bioeconomy in East Africa represents a transformative opportunity to improve rural livelihoods by improving sustainable economic growth, enhancing food security and promoting environmental stewardship. The BioInnovate Africa network, supported by the Swedish International Development Agency, has had as a core activity the development and commercialization of bio-based innovations (Rosa and Martius, 2021). Most of these projects have so far concerned agricultural bioeconomy. The BioInnovate Africa-funded project "Developing an Innovation-led Bioeconomy Strategy for Eastern Africa" is comprised of partners that include South Sudan, Ethiopia, Burundi, Kenya, Rwanda, Tanzania and Uganda. Additional bioeconomy initiatives and strategies are developing within other African nations (Figure 6). A circular bioeconomy offers a promising path for sustainable economic growth and development, leading to improved rural livelihoods across the region. The region's abundant natural resources, including agricultural products, forestry and marine ecosystems, offer a rich foundation for bio-based industries to tap into.

Figure 6: *Bioeconomy landscape in Sub-Saharan Africa. Source: Rosa and Martius (2021).*

Despite the potential, however, the region has only to a limited degree been able to apply technologies and know-how that could modernize agricultural production, bioprocessing and value addition. The low degree of bioprocessing and value addition makes it difficult for the region to take advantage of its bioresources as an engine for economic growth. Several significant challenges impede the growth of a circular bioeconomy in East Africa. Addressing these challenges is crucial to unlocking the region's bioeconomy potential and achieving sustainable economic and environmental outcomes (Virgin et al, 2024). These gaps and challenges include:

- Limitation in infrastructure (transport, energy supply, storage facilities)
- Lack of technology and facilities for processing and value addition
- Lack of skilled workforce
- Low agricultural productivity
- Inadequate and in many cases stifling policy and regulatory frameworks
- Lack of access to finance and venture capital
- Low level of private sector engagement
- Inadequate market awareness and weak demand/bioeconomy promotion

Eastern Africa is home to vast agricultural lands, rich biodiversity and a youthful population— all factors that position the region to become a leader in circular bioeconomy innovation. By capitalizing on these assets, it should be possible to transform agricultural practices, increase the value of bio-based products and develop new industries that are both sustainable and economically viable. A circular bioeconomy holds the promise of improving food security, enhancing environmental sustainability and creating resilient communities in the face of global challenges. For example, the positive association between using organic waste as livestock feed and food security, as well as its strong negative association with severe food insecurity, illustrates the potential of using organic waste as livestock feed towards enhancing household food security, while ensuring circular food systems (Sekabira et al., 2024). This is because the circular bioeconomy practice can easily impact household food security through livestock farming via multiple fronts (Sheldrick et al., 2003; Klammsteiner et al., 2020).

Role of Agricultural Extension Services

A circular bioeconomy encompasses various aspects, including sustainable agriculture, waste management, renewable energy generation and the development of bio-based products (Muscat et al., 2021; Klien et al., 2022; Ansari et al., 2023). Within this context, the role of agricultural Extension services (AES) in supporting circular bioeconomy practices has gained significant importance (Yanfika et al., 2024a). Agricultural Extension Services (AES) serve as crucial intermediaries between researchers, policymakers and farmers, bridging the gap between scientific knowledge and boots-on-the-ground implementation (Anderson and Feder, 2004; Klerkx, 2022). They are critical to information dissemination, providing training and technical assistance, and fostering innovation in the agricultural sector (Altalb et al., 2015; Msuya et al., 2017).

A circular bioeconomy blends the principles of circular economy with sustainable practices in the utilization of biological resources (Carus and Dammer, 2018; Stegmann et al., 2020; Tan and Lamers, 2021; Ansari et al., 2023). It aims to establish a closed-loop system that minimizes waste, optimizes resource utilization and emphasizes the restoration of natural ecosystems (MacArthur, 2013; Del Borghi et al., 2020; Ansari et al., 2023). Its foundational principles encompass resource use efficiency, valorization (enhancing value) of biomass, establishment of circular supply chains, regeneration of ecosystems and the cultivation of innovation and collaboration (Carus and Dammer, 2018; Schöggl et al., 2020; Tan and Lamers, 2021; Ncube et al., 2022). Such a holistic approach offers great promise for SSA across multiple fronts. In other words, the adoption of circular bioeconomy principles presents SSA with a unique opportunity to achieve synergistic outcomes across economic, environmental and social dimensions, ultimately leading toward a more sustainable and prosperous future for the continent and its people. However, someone must disseminate knowledge, skills and information to the people.

In that context, across SSA, AES are designed around organized efforts aimed at providing farmers, rural communities and other stakeholders with the necessary knowledge, skills and information to enhance agricultural productivity, sustainability and overall well-being (Anderson and Feder, 2007; Maiangwa et al., 2010; Rusliyadi et al., 2018; Yanfika et al., 2024b). Extension educators serve as facilitators for communication and knowledge transfer to empower farmers for adopting innovative and sustainable practices, improving crop yields, and addressing challenges related to agriculture and rural development (Anderson and Feder, 2007; Ali et al., 2012; Altalb et al., 2015). Unfortunately, a shortage of Extension workers across much of SSA hinders information dissemination, especially in isolated rural areas with little or no improved infrastructure (Tabler et al., 2020).

This highlights the critical need for the hiring and training of additional Extension personnel across SSA, as AES contribute to circular bioeconomy by disseminating knowledge about its principles and benefits, organizing training programs to enhance farmers' skills, facilitating the transfer of innovative technologies related to circular bioeconomy, advocating for supportive policies and actively participating in the monitoring and evaluation of the impact of circular bioeconomy practices. The implementation of circular bioeconomy practices in SSA will depend significantly on the multifaceted role of AES. Extension personnel and the services they provide are vital links for providing information and facilitating knowledge transfer on circular bioeconomy practices. Extension officers empower farmers and stakeholders with insights to incorporate sustainable and regenerative practices into their agricultural activities. In addition, AES play a pivotal role in training farmers and stakeholders on sustainable agriculture and waste management techniques. Through workshops, training programs and advisory services, AES personnel enhance the skills of the agricultural community, enabling them to adopt environmentally friendly practices that align with circular bioeconomy principles.

However, there are bumps in the road. Realizing the full potential of a circular bioeconomy in SSA is not without challenges. Limited awareness, technological barriers, inadequate policy support and a shortage of Extension personnel pose significant hurdles that must be addressed through strategic interventions and collaborative endeavors. Fostering greater adoption of circular bioeconomy principles aligns agriculture with sustainability principles which have traditionally been embedded by default in many farming systems across SSA. Although an important question concerns the respective roles of the market and governments in delivering circular innovations into agricultural systems in low-income countries (Duncan et al., 2023). If circular bioeconomy innovations are technically proven and profitable, we should see private sector adoption. However, non-adoption is often observed due to economic and behavioral barriers that are difficult to measure. Or there may simply be insufficient knowledge or financial support to incentivize innovations that are socially beneficial but unattractive from the private producer's perspective.

Extension personnel at the local grassroots level are a window to the private sector and what they are thinking and why. Through training additional Extension personnel, strengthening collaboration, enhancing capacity-building efforts, advocating for supportive practices, mobilizing financial resources and fostering public awareness, AES can overcome the challenges and effectively support the integration of circular bioeconomy practices throughout SSA. The successful implementation of circular bioeconomy principles in SSA hinges upon the involvement of AES at the local level across various key areas. By embracing circular bioeconomy principles and leveraging the potential of AES and their boots-on-the-ground connections with local small-holder clientele, SSA can chart a course toward sustainable development, fostering a greener, more resilient and prosperous future going forward. Extension personnel are a vital piece in educating farmers, stakeholders and consumers about the ecosystem services provided by circular bioeconomy products, which can lead to a change in preferences and a high willingness to develop and create a market for circular products and generate political support, making circularity more sustainable in the long run.

Projects that offer opportunities for up- and out-scaling potential in Sub-Saharan Africa include: 1) BioInnovate Africa initiatives (which fosters collaboration between scientists, industry and government to develop sustainable solutions for eastern Africa development priorities and supports development of a sustainable bioeconomy across Africa), 2) industrial-scale biofertilizer production, 3) bioenergy production from agro-industrial processing waste, 4) biofuels production and 5) bio-composites. Unfortunately, sustaining food security in SSA faces several major hurdles including gender inequality, weak economic growth, high inflation, low investment in irrigated agriculture and research, low crop productivity, high population growth, weak infrastructural development, corruption, etc. (Wudil et al., 2022). Promoting investments in agricultural infrastructure and Extension services together with implementing policies targeted at enhancing households purchasing power, especially those in rural regions, appear to be essential drivers for improving both food availability and food access. Moreover, adopting circularity within agrifood value chains to combat food waste and loss is of paramount importance. Nkansah-Dwamena (2023) indicated that the adoption of circular practices enhances household food security, diminishes external input dependency and fosters a self-sustaining and productive farming approach. In addition, collaboration and partnership among smallholder farmers, agrifood value chain participants, non-governmental organizations and policymakers is essential for creating a conducive environment that reduces food loss and waste, enhances food security and promotes circular agriculture adoption.

Summary

Agricultural systems are the backbone of human civilization, providing food, fiber and fuel to an ever-growing population. There is huge potential to create a more circular bioeconomy across supply chains where the agriculture sector is concerned across much of Sub-Saharan Africa. A circular bioeconomy brings together two sustainability concepts; 1) it uses renewable biological resources to create biological products (i.e. the bioeconomy), and 2) it reuses, repurposes or recycles those resources and organic waste back into the economy. Circular bioeconomy may be a new concept to many individuals. However, for many smallholder farmers across SSA, the circular bioeconomy, by necessity, has been a way of life for generations. The current increased interest in the circular bioeconomy concept offers opportunities to refine and expand the model to the benefit of smallholder farmers across SSA as well as the environment.

There will be challenges to overcome, but the opportunities should not be overlooked. Training of additional Extension personnel to disseminate information and assist smallholders should be a high priority and undertaken immediately. Their connections at the local village and community level will be critical to successful transition to and implementation of the circular bioeconomy model. The current linear food production model is no longer sustainable going forward. The future of African circular agricultural production systems is, however, dependent on the development and placement of supportive infrastructure, including government programs aimed at equipping the agriculture sector with tools and innovative means of applying circular regenerative principles in production. Information dissemination and educating the smallholder and large-scale farming community across SSA about the circular bioeconomy agricultural practices that represent the best approach to migrating to a circular bioeconomy could lead to the creation of an increased sustainable and regenerative food security program and a more inclusive economy.

References

Abbasi, S. A., K. Harijan, M. W. A. Kahn, et al. 2021. Long-term optimal power generation pathways for Pakistan. Energy Science and Engineering 9:2252-2267.

Ahmad, A., and S. S. Ashraf. 2023. Sustainable food and feed sources from microalgae: Food security and the circular bioeconomy. Algal Research 74:103185.

Ali, A. S., M. Altarawneh, and E. Altahat. 2012. Effectiveness of agricultural extension activities. American Journal of Agricultural and Biological Sciences 7:194-200.

Altalb, A. A. T., T. Filipek, and P. Skowron. 2015. The role of agricultural extension in the transfer and adoption of agricultural technologies. Asian Journal of Agriculture and Food Sciences 3:500-507.

Anand, M. 2016. Innovation and sustainable development: A bioeconomic perspective. Brief for global sustainable report, GSDR. New Delhi.

Anderson, J. R., and G. Feder. 2004. Agricultural extension: good intentions and hard realities. World Bank Research Observer 19(1):41-60.

Anderson, J. R., and G. Feder. 2007. Chapter 44 – Agricultural Extension – in Gardner, B. L., G. C. Rausser, R. E. Evenson, and P. Pingali (eds) Agricultural Development: Farmers, Farm Production and Farm Markets. Vol 3. Elsevier.

Ansari, A., A. Pranesti, M. Telaumbanua, et al. 2023. Optimizing water-energy-food nexus: achieving economic prosperity and environmental sustainability in agriculture. Frontiers in Sustainable Food Systems 7:7

Assan, N. 2023. Socio-cultural, economic, and environmental implications for innovation in sustainable food in Africa. Frontiers in Sustainable Food Systems 7:1192422.

References (Continued)

Aznar-Sánchez, J. A., L. J. Belmonte-Ureña, J. F. Velasco-Muñoz, and F. Manzano-Agugliaro. 2018. Economic analysis of sustainable water use: a review of worldwide research. Journal of Cleaner Production 198:1120-1132.

Aznar-Sánchez, J. A., M. Piquer-Rodríguez, J. F. Velasco-Muñoz, F. Manzano-Agugliaro. 2019. Worldwide research trends on sustainable land use in agriculture. Land Use Policy 87: 104069.

Basso, B., J. W. Jones, J. Antle, R. A. Martinez-Feria, and B. Verma. 2021. Enabling circularity in grain production systems with novel technologies and policy. Agricultural Systems 193:103244.

Bationo, A., J. Kihara, B. Vanlauwe, et al. 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agricultural Systems 94:13–25.

Canadell, J. G., and E. D. Schulze. 2014. Global potential of biospheric carbon management for climate mitigation. Nature Communications 5:5282.

Carus, M., and L. Dammer. 2018. The circular bioeconomy – concepts, opportunities, and limitations. Industrial Biotechnology 14:83-91.

Chitaka, T. Y., and C. Schenck. 2023. Developing country imperatives in the circular bioeconomy: A review of the South African case. Environmental Development 45:100812.

Circle Economy. 2021. The Circularity Gap Report 2021. Available at: circularity-gap.world/2021#downloads. Accessed: March 27, 2025.

Cullen, J. M. 2017. Circular economy: Theoretical benchmark or perpetual motion machine? Journal of Industrial Ecology 21(3):483-486.

Dasgupta, P. 2021. The economics of biodiversity: the Dasgupta review: full report. Updated: 18 February 2021. London: HM Treasury. 610 pages. Available at: assets.publishing.service.gov.uk/media/602e92b2e90e07660f807b47/The_Economics_of_Biodiversity_The_Dasgupta_Review_Full_Report.pdf. Accessed: March 29, 2025.

Del Borghi, A., L. Moreschi, and M. Gallo. 2020. Circular economy approach to reduce water-energy-food nexus. Current Opinion in Environmental Science and Health 13:23-28.

Diogo, R. V., E. Schlecht, A. Buerkert, et al. 2013. Increasing nutrient use efficiency through improved feeding and manure management in urban and peri-urban livestock units of a West African city: A scenario analysis. Agricultural Systems 114:64-72.

Duncan, A. J., A. Ayantunde, D. Moran, et al. 2023. Applying circular economy principles to intensification of livestock production in sub-Saharan Africa. Outlook on Agriculture 52(3):327-338.

Ellen MacArthur Foundation. 2015. Towards a circular economy: Business rationale for an accelerated transition. Available at: ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition. Accessed: March 28, 2025.

Ellen MacArthur Foundation. 2019. Cities and Circular Economy for Food. 66 pages. Available at: pacecircular.org/sites/default/files/2019-03/Cities-and-Circular-Economy-for-Food.pdf. Accessed: March 28, 2025.

Figge, F., A. Thorpe, and M. Gutberlet. 2023. Definitions of the circular economy – circularity matters. Ecological Economics 208:107823.

Food and Agriculture Organization of the United Nations (FAO). 2017. Strategic work of FAO for sustainable food and agriculture. Available at: fao.org/3/a-i6488e.pdf. Accessed: March 27, 2025.

Food and Agriculture Organization of the United Nations (FAO). 2018. The Future of Food and Agriculture: Alternative Pathways to 2050. FAO. Rome, Italy.

Frankema, E. 2014. Africa and the Green Revolution: A Global Historical Perspective. NJAS-Wageningen Journal of Life Sciences, 70-71:17-24.

Gatune, J., N. Ozor, and R. Oriama. 2021. Modelling bioeconomy futures for Eastern Africa. Foresight 23(2):226-241.

Geissdoerfer, M., P. Savaget, N. M. P. Bocken, and E. J. Hultink. 2017. The circular economy – A new sustainability paradigm. Journal of Cleaner Production 143:757-768.

Gerke, J. 2022. The central role of soil organic matter in soil fertility and carbon storage. Soil Systems 6:33.

Gesing, F. 2023. The material politics of slurry: Mobilisations and transformations along the waste-fertilizer continuum. Political Geography 101:102832.

Ghisellini, P., C. Cialani, and S. Ulgiati. 2016. A review on circular economy: The expected transition to a balanced interplay of environ-mental and economic systems. Journal of Cleaner Environment 114:11-32.

References (Continued)

Greco, C., A. Agnello, G. La Placa, M. M. Mammano, and K. Navickas. 2019. Biowaste in a circular bioeconomy in Mediterranean area: A case study of compost and vermicompost as growing substrates alternative to peat. Rivista di Studi Sostenibilità X(2):345-362.

Herrero, M., P. K. Thornton, D. Mason-D'Croz, et. 2020. Innovation can accelerate the transition towards a sustainable food system. Nature Food, 10.1038/s43016-020-0074-1.

Jurgilevich, A., T. Birge, J. Kentala-Lehtonen, et al. 2016. Transition towards circular economy in the food system. Sustainability 8(1):69.

Kalfas, D., S. Kalogiannidis, F. Chatzitheodoridis, and E. Toska. 2023. Urbanization and land luse planning for achieving the sustainable development goals (SDGs): a case study of Greece. Urban Science 7(2):43.

Kalogiannidis, S., D. Kalfas, F. Chatzitheodoridis, and O. Papaevangelou. 2022a. Role of crop-protection technologies in sustainable agricultural productivity and management. Land 11(10):1680.

Kalogiannidis, S., D. Kalfas, E. Loizou, and F. Chatzitheodoridis. 2022b. Forestry bioeconomy contribution on socioeconomic development: evidence from Greece. Land 11(12):2139.

Kalogiannidis, S., E. Loizou, D. Kalfas, and F. Chatzitheodoridis. 2022c. Local and regional management approaches for the redesign of local development: a case study of Greece. Administrative Sciences 12(2):69.

Kaza, S., L. Yao, P. Bhada-Tata, and F. Van Woerden. 2018. What a Waste 2.0. A Global Snapshot of Solid Waste Management to 2050. The World Bank. Washington, D.C.-USA.

Kershaw, H. E., C. Hartley, C. McLeod, and P. Polson. 2021. The sustainable path to a circular bioeconomy. Trends in Biotechnology 39(6):542-546.

Khan, I., S. Chowdhury, and K. Techato, 2022. Waste to energy in developing countries -A rapid review: Opportunities, challenges, and policies in selected countries of sub-Saharan Africa and South Asia towards sustainability. Sustainability 14:3740.

Khanna, M., D. Zilberman, G. Hochman, and B. Basso. 2024. An economic perspective of the circular bioeconomy in the food and agricultural sector. Communications Earth and Environment 5:507.

Kirchherr, J., D. Reike, and M. Hekkert. 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling 127:221-232.

Kirchherr, J., L. Piscicelli, R. Bour, et al. 2018. Barriers to the circular economy: Evidence from the European Union (EU). Ecological Economics 150:264-272.

Klammsteiner, T., V. Turan, M. Fernández-Delgado Juárez, et al. 2020. Suitability of black soldier fly frass as a soil amendment and implication for organic waste hygienization. Agronomy 10(10):1578.

Klein, O., S. Nier, and C. Tamásy. 2022. Towards a circular bioeconomy? Pathways and spatialities of agri-food waste valorisation. Tijdschrift voor Economische en Sociale Geografe 113:194-210.

Klerkx, L. 2022. Advisory support and learning on non-technical aspects of farming: a key topic for extension and education research. Journal of Agricultural Education and Extension 28:251-253.

Kurniawan, T. A., X. Liang, E. O'Callaghan, et al. 2022.Transformation of solid waste management in China: Moving towards sustainability through digitalization-based circular economy. Sustainability 14:2374.

Kusumastuti, R. D., D. P. Van Donk, and R. Teunter. 2016. Crop-related harvesting and processing planning: a review. International Journal of Production Economics 174:76-92.

Lago, C., H. Israel, C. Natalia, and L. Yolanda. 2019. Nexus bioenergy-bioeconomy. In: The role of bioenergy in the bioeconomy. Elsevier, pp 3-24.

Lam, S., G. Pham, and H. Nguyen-Viet. 2017. Emerging health risks from agricultural intensification in Southeast Asia: A systemic review. International Journal of Occupational and Environmental Health 23:250-260.

Lambers, H., and W. F. Cong. 2022. Challenges providing multiple ecosystem benefits for sustainable managed systems. Frontiers of Agricultural Science and Engineering 9:170-176.

Lazaridou, D. C., A. Michailidis, and M. Trigkas. 2021. Exploring environmental and economic costs and benefits of a forest-based circular economy: a literature review. Forests 12(4):436.

References (Continued)

MacArthur, E. 2013. Towards the circular economy, economic and business rationale for an accelerated transition. Cowes, UK: Ellen MacArthur Foundation, 21-34.

Maiangwa, M. G., R. A. Omolehin, O. B. Adeniji, and U. S. Mohammed. 2010. Food insecurity: challenges of agricultural extension in developing countries. Journal of Agricultural Extension 14:73-015.

Majumdar, K., S. K. Sanyal, S. K. Dutta, et al. 2016. Nutrient mining: Addressing the challenges to soil resources and food security. In: Singh, U., C. Praharaj, S. Singh, and N. Singh (eds.) Biofortification of Food Crops. Springer, New Delhi.

McIntire, J., D. Bourzat, and P. Pingali. 1992. Crop-livestock interaction in Sub Saharan Africa. The World Bank. Washington, D.C. 246 pp.

Msuya, C. P., F. K. Annor-Frempong, M. N. Magheni, et al. 2017. The role of agricultural extension in Africa's development, the importance of extension workers and the need for change. International Journal of Agricultural Extension 5:51-58.

Muoni, T., A. P. Barnes, I. Öborn, et al. 2019. Farmer perceptions of legumes and their functions in smallholder farming systems in East Africa. International Journal of Agricultural Sustainability 17:205-218.

Muscat, A. E. M. de Olde, R. Ripoll-Bosch, et al. 2021. Principles, drivers and opportunities of a circular bioeconomy. Nature Food 8:561-566.

Ncube, A., P. Sadondo, R. Makhanda, et al. 2022. Circular bioeconomy potential and challenges within an African context: from theory to practice. Journal of Cleaner Production 367:133068.

Nkansah-Dwamena, E. 2023. Why small-scale circular agriculture is central to food security and environmental sustainability in Sub-Saharan Africa? The case of Ghana. Circular Economy and Sustainability 4(2):1-25.

Northrup, D. L., B. Basso, M. Q. Wang, and C. L. S. Morgan, and P. N. Benfey. 2021. Novel technologies for emission reduction comple-ment conservation agriculture to achieve negative emissions from row-crop production. Proceedings of the National Academy of Sciencies:e2022666118.

Oosting, S, J. van der Lee, M. Verdegem, et al. 2022. Farmed animal production in tropical circular food systems. Food Security 14:273-292.

Pandey, S. and N. Dwivedi. 2020. Utilisation and management of agriculture and food processing waste. P. Mishra, R.R. Mishra, C.O. Adetunji (Eds.), Innovations in Food Technology, Springer (2020), pp. 269-288.

Papadopoulou, C-I., F. Chatzitheodoridis, E. Loizou, and P. Jurga. 2024. Operational taxonomy of farmers' towards circular bioeconomy in regional level. Operational Research 24(2):1-27.

Paul, B. K., J. Koge, B. L. Maass, et al. 2020. Tropical forage technologies can deliver multiple benefits in Sub Saharan Africa. A meta-anal-ysis. Agronomy for Sustainable Development 40:1-17.

Pauliuk, S. 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resources, Conservation and Recycling 129:81-92.

Powell, J. M., S. Fernández-Rivera, P. Hiernaux, et al. 1996. Nutrient cycling in integrated rangeland/cropland systems of the Sahel. Agricultural Systems 52:143–170.

Powell, J. M., R. A. Pearson, and P. H. Hiernaux. 2004. Crop-livestock interactions in the West African drylands. Agronomy Journal 96:469-483.

Priefer, C., J. Jörissen, and O. Frör. 2017. Pathways to shape the bioeconomy. Resources 6(1):10.

Ramankutty, N., Z. Mehrabi, K. Waha, et al. 2018. Trends in global agricultural land use: Implications for environmental health and food security. Annual Review of Plant Biology 69:789-815.

Robinson, R. A., and W. J. Sutherland. 2002. Post-war changes in arable farming and biodiversity in Great Britain. Journal of Applied Ecology 39:157-176.

Rosa, S. F. P., and C. Martius. 2021. Forest-based bioeconomy in sub-Saharan Africa: Looking at benefits, barriers, and burdens from a social sustainability standpoint. Occasional Paper 219. Bogor, Indonesia. CIFOR.

Rosenzweig, C., C. Mbow, L. G. Barioni, et al. 2020. Climate change responses benefit from a global food system approach. Nature Food, 10.1038/s43016-020-0031-z.

RUNRES. 2020. RUNRES city-region context studies. 302 pages. Swiss Agency for Development and Cooperation SDC.

References (Continued)

Rusliyadi, M., A. Jamil, M. Othman, and R. T. Kumalasari. 2018. Agricultural extension policy, agricultural growth and poverty reduction in Indonesia. Internation Journal of Engineering and Technology 7:5539-5550.

Schöggl, J. P., L. Stumpf, and R. J. Baumgartner. 2020. The narrative of sustainability and circular economy-a longitundial review of two decades of research. Resources, Conservation and Recycling 163:105073.

Schulte, L. A., B. E. Dale, S. Bozzetto, et al. 2022. Meeting global challenges with regenerative agriculture producing food and energy. Nature Sustainability 5(5):384-388.

Sekabira, H. G. T. Tepa-Yotto, R. Djouaka, et al. 2022. Determinants for deployment of climate-smart integrated pest management practices: A meta-analysis approach. Agriculture 12(7):1052.

Sekabira, H., S. Feleke, V. Manyong, et al. 2024. Circular bioeconomy practices and their associations with household food security in four RUNRES African city regions. PLOS Sustainability and Transformation 3(4):e0000108.

Selvan, T., L. Panmei, K. K. Murasing, et al. 2023. Circular economy in agriculture: unleashing the potential of integrated organic farming for food security and sustainable development. Frontiers in Sustainable Food Production 7:1170380.

Sheldrick, W., J. K. Syers, and J. Lingard. 2003. Contribution of livestock excreta to nutrient balances. Nutrient Cycling in Agroecosystems 66:119-131.

Smith, J. L., H. P. Collins, and V. L. Bailey. 2020. The significance of soil microbial diversity for agriculture: A review. Applied Soil Ecology 156:103706.

Stangel P. J. 1995. Nutrient cycling and its importance in sustaining crop-livestock systems in Sub Saharan Africa: an overview. In: International Conference on Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa, Addis Ababa (Ethiopia), 22-26 Nov 1993, 1995. ILCA.

Stegmann, P., M. Londo, and M. Junginger. 2020. The circular bioeconomy: its elements and role in European bioeconomy clusters. Resources, Conservation and Recycling X(6):100029.

Steinfeld, H. 1998. Livestock and their interaction with the environment: An overview. BASP Occasional Publication 21:67-76.

Stoate, C., and P. Wilson. 2020. Historical and ecological background to the arable habitats of Europe. In: The Changing Status of Arable Habitats in Europe: A Nature Conservation Review. Springer: Cham, 3-13.

Tabler, T., M. L. Khaitsa, S. H. Mbaga, J. N. Jeckoniah, J. Moon, and J. Wells. 2020. Poultry extension personnel needed across East Africa. Mississippi State University Extension Publ. No. 3494. July.

Tahiru, A. W., S. J. Cobbina, W. Asare, and S. U. Takal. 2024. Unlocking energy from waste: A comprehensive analysis of municipal solid waste recovery potential for Ghana. World 5:192-218.

Tan, E. C. D., and P. Lamers. 2021. Circular bioeconomy concepts – a perspective. Frontiers in Sustainability 2:1-8.

Tilman, D., C. Balzer, J. Hill, and B. L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Science 108:20260-20264.

Tindwa, H. J., E. W. Semu, and B. R. Singh. 2024. Circular regenerative agricultural practices in Africa: Techniques and their potential for soil restoration and sustainable food production. Agronomy 14(10):2423.

United Nations (U.N.). 2015. The 2030 Agenda for Sustainable Development's 17 Sustainable Development Goals (SDGs). Available at: sdgs.un.org/goals. Accessed on: March 29, 2025.

United Nations. 2019. World population prospects. U.N. Department of Economic and Social Affairs. Available at: un.org/development/desa/en/news/population/world-population-prospects-2019.html. Accessed: March 27, 2025.

Van Der Peet-Schwering, C. M. C., Aarnink, A. J. A., H. B. Rom, et al. 1999. Ammonia emissions from pig houses in The Netherlands, Denmark and France. Livestock Production Science 58:265-269.

van der Wiel, B. Z., J. Wejima, C. van Middelaar, et al. 2019. Restoring nutrient circularity: A review of nutrient stock and flow analyses of local agro-food-waste systems. Resources, Conservation and Recycling X(3):100014.

Van Loon, J., L. Woltering, T. J. Krupnik, et al. 2020. Scaling agricultural mechanization services in smallholder farming systems: Case studies from Sub Saharan Africa, South Asia, and Latin America. Agricultural Systems 180:102792.

References (Continued)

Van Zanten, H. H., W. Simon, B. Van Selm, et al. 2023. Circularity in Europe strengthens the sustainability of the global food system. Nature Food 4:320-330.

Velasco-Muñoz, J. F., J. A. Aznar-Sánchez, B. López-Felices, and I. M. Román-Sánchez. 2022. Circular economy in agriculture. Analysis of the state of research based on the life cycle. Sustainable Production and Consumption 34:257-270.

Virgin, I., A. Lutta, J. Senyagwa, et al. 2024. The state of bioeconomy in Eastern Africa. Stockholm Environment Institute, The East African Science and technology Commission and Bioinnovate Africa.

Wudil, A. H., M. Usman, J. Rosak-Szyrocka, et al. 2022. Reversing years for global food security: A review of the food security situation in Sub-Saharan Africa (SSA). International Journal of Environmental Research and Pubic Health 19(22):14836.

Yanfika, H., I. Effendi, Sumaryo, and A. Ansari. 2024a. The role of agricultural extension services on supporting circular bioeconomy in Indonesia. Frontiers in Sustainable Food Systems 8:1428069.

Yanfika, H., K. K. Rangga, S. Gitosaputro, D. T. Gultom, and I. Nurmayasari. 2024b. Building appropriate strategy for improving the capabilities of agricultural extension services in Indonesia. Bulgarian Journal of Agricultural Science 30.

UTIA
INSTITUTE OF
AGRICULTURE
THE UNIVERSITY OF TENNESSEE

UTIA.TENNESSEE.EDU

Real. Life. Solutions.™

W1328 07/25 25-0460 Programs in agriculture and natural resources, 4-H youth development, family and consumer sciences, and resource development. University of Tennessee Institute of Agriculture, U.S. Department of Agriculture and County governments cooperating. UT Extension provides equal opportunities in programs and employment.