CHAPTER 8

A Nutrition-Sensitive Circular Bioeconomy for Food Systems Transformation in Africa

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Introduction

Arica's commitment to creating a sustainable and self-sufficient economy for its rapidly growing population has led to programmatic actions aimed at meeting local food, energy, and material demands sustainably and without compromising planetary boundaries (Africa Business Page 2022; Agri SA 2023). The bioeconomy has become a primary focus of this transformative blueprint, generally positioned as a vehicle for generating and using bioresources in meeting local demands for abundance, sustainable goods, and services (Gatune, Ozor, and Oriama 2021; Malabo Montpellier Panel 2022). However, the implementation momentum of the bioeconomy is incumbent on a well-planned and objective-oriented policy framework that supports generation of scientific evidence and reasonable investment structures, among other requirements for implementation (East African Community 2022; Pachón et al. 2018).

This chapter provides research-based evidence on the potential for leveraging the African bioeconomy to address the continued challenge of malnutrition. Existing strategies include local biofortification programs and genetic modification, among other agrarian improvement strategies. Another promising, but rarely discussed pathway is a nutrition-sensitive circular bioeconomy intervention that creates a closed loop system for upcycling biowaste for nutrition-based interventions. This can be pursued in various ways, including exploring the applicability of biowastes as primary ingredients for food or feed production; using biowastes as second-generation nutrient-dense substrates for producing sustainable and nutritious food or feed products and ingredients; and transforming biowastes into sustainable farm inputs such as biofertilizers, biopesticides, or organic composts for improving sustainable agricultural production. The wide availability of bioresources and underutilized biomass across Africa can provide the basis for a nutrition-based circular bioeconomy that confers benefits in both nutrition security and planetary health (Sekabira et al. 2022).

Pursuing a nutrition-sensitive circular bioeconomy can be pivotal for a transformative African food systems agenda that addresses the region's significant malnutrition and food insecurity challenges. This concept can be adopted as a timely and strategic waste management approach that integrates agrifood system development with food security and nutritional outcomes.

Nutrition-oriented or -sensitive initiatives are not new to Africa (Hodge et al. 2015; McLachlan and Landman 2013). However, incorporating circular thinking into these initiatives is a quite novel approach and has potential to thrive, given the practical need and the promising impacts of nutrition-sensitive initiatives in enhancing dietary diversity and household food security in countries such as Ethiopia, Ghana, Kenya, South Africa, Tanzania, and Uganda (Chesoli et al. 2024; Gillespie et al. 2015; Santoso et al. 2021). Nonetheless, like other initiatives, success will depend on creating an enabling environment.

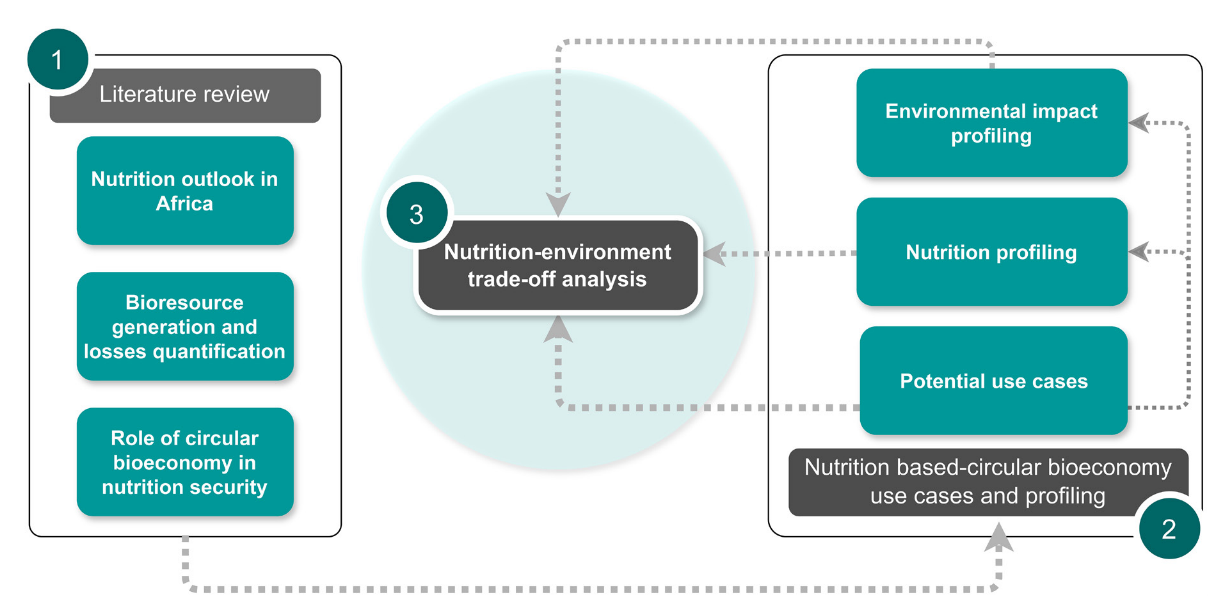
Recent research highlights various strategies within the bioeconomy framework, including the development of bioeconomic models that focus on the production, transformation, and trade of biological goods (Callo-Concha et al. 2020a, 2020b). These models emphasize creating value webs that connect different sectors of the economy, thereby fostering synergies that can lead to improved bioeconomy for promoting food and nutrition security. Subsequent actions should enable a network for creating nutritional value and positive socio-economic outcomes from biowaste. This strategy will facilitate the realization of the potential benefits of a nutrition-sensitive circular bioeconomy.

This chapter explores the potential of a nutrition-sensitive circular bioeconomy in transforming Africa's food systems, examining both the challenges and opportunities that lie ahead. This lens provides a better understanding of how to harness bioeconomic principles to achieve sustainable development goals, ensuring that food systems not only support economic growth but also advance health and environmental objectives across the continent.

Conceptual Framework

This chapter is structured in three key sections. The first section reviews nutrition challenges in Africa, emphasizing the double burden of malnutrition and highlighting the associated consequences. The section ends with an overview of some existing nutrition interventions in response to the prevailing challenges. It provides the basis for the second section to examine the role of circular bioeconomy in addressing the identified nutrition challenges. The application of circular bioeconomy in edible mushrooms, edible insects, and edible fiber production is discussed and linked with an analysis of Africa's bioresource generation and losses to identify current potential for a circular bioeconomy. Following this, the third section explores potential local cases in which Africa's variety of generated biowastes could be used as primary substrates for nutrition-based circular bioeconomy interventions. These use cases are then profiled for their nutritional and environmental impact performance, based on literature data scraping and analysis. Finally, the chapter illustrates the environmental–nutrition–sustainability trade-offs associated with the potential use cases to help identify "sweet spots" and challenges for embracing local nutrition-based circular interventions in Africa's bioeconomy revolution. Figure 8.1 summarizes the conceptual framework of this chapter.

FIGURE 8.1—FLOW OF STUDY



Source: Authors.

Overview of Nutrition Challenges in Africa

Malnutrition remains one of the most important challenges in both advanced regions and developing countries. It occurs either in the form of overnutrition or undernutrition, with the general perception that overnutrition is prevalent in advanced or urban regions while undernutrition occurs mostly in developing or rural regions (Guldan 2020). In developed countries, obesity, a form of malnutrition, has escalated, affecting more than 30 percent of adults and leading to increased healthcare costs and reduced productivity (Kohutek, Homolova, and Bystricky 2024). Conversely, developing nations face high rates of undernutrition, with more than 1 billion people suffering from micronutrient deficiencies, known as hidden hunger (Dessie et al. 2024). This issue contributes to stunted growth, weakened immunity, and increased mortality rates, particularly among children. In Africa, malnutrition has been prominent among food system challenges, driven by complex and interconnected economic factors including rapid population growth, urbanization, poverty, inefficient food supply chains and corresponding infrastructural inadequacy, marginal intervention strategies, climate change, and other geopolitical instabilities (Adeyeye et al. 2017; Gooding et al. 2024; Seifu et al. 2024; Shipanga, Kappas, and Wyss 2024). These factors have worsened the regional malnutrition crisis, significantly increasing undernourishment among vulnerable groups, including children and the elderly (Okyere et al. 2024; Us, Sembiring, and Safitri 2024), and food availability projections show that the existing malnutrition challenges in Africa are likely to remain unchanged unless radical food system policies are implemented rapidly (Abe-Inge and Kwofie 2023). This section explores the main challenges and implications of the double burden of malnutrition across the continent.

Overnutrition Burden

The impacts of overnutrition on health include overweight, obesity, and associated noncommunicable diseases. As mentioned earlier, overnutrition has previously been deemed a major concern in the advanced or urban regions of the world, and thus may be expected to be of lesser concern in less developed or poorer regions. However, a recent World Health Organization (WHO) study (2022) revealed that 24 percent of African children under age five are overweight. The analysis showed that by 2023, obesity prevalence among adults in 10 high-burden African countries could range from 13.6 percent to 31 percent, and among children and adolescents from 5 percent to 16.5 percent (WHO Africa 2022). Countries with the highest burdens include Algeria, Eswatini, Gabon, Kenya, Libya, Mauritius, South Africa, Tanzania, Uganda, and Zimbabwe (SciDev.net 2022). Rising obesity rates are seen as a growing problem requiring an urgent strategy. Data retrieved from the WHO Global Health Observatory (2024), as summarized in Table 8.1, show a high prevalence of overweight among African adults, indicating the potential increase in obesity prevalence in Africa. The data further show the share of adults (ages 18 years and older) who are overweight is highest (60–67 percent) in North Africa and lowest (22 percent) in Niger, Eritrea, Burundi, and Uganda.

Nutrition-related overweight is linked to high consumption of calorie-dense foods such as roots, tubers, cereals, grains, fats, oils, and sugar. A study by Abe-Inge and Kwofie (2023) reported that Africa's food supply is largely dominated by starchy staples, especially in North Africa. The findings further indicated that the apparent consumption rate (566–816 grams per capita per day) of starchy staples among Africans exceeds the average recommended intake (282 g/capita/day) recommended by the EAT–Lancet diet (Willett et al. 2019). Similarly, the same study revealed an average excess consumption of sugar, alcohol, fats, and oils. In addition, there is growing prevalence, convenience, and availability of ultra-processed foods and the supermarkets where they are usually purchased. These excessive consumption rates coupled with more sedentary lifestyles signal the need for healthier and nutrition-sensitive food systems.

Undernutrition Burden

Despite ongoing interventions, undernutrition remains critically high in Africa, even as overnutrition rates are rising. This double burden of malnutrition in Africa is highlighted in the study by Mbogori and colleagues (2020), which showed that African countries with high GDP had the highest rates of overnutrition impacts, while low GDP countries recorded high rates of undernutrition.

TABLE 8.1—AGE-STANDARDIZED SHARE OF ADULTS WHO ARE OVERWEIGHT IN AFRICA

Country	Shares (%)	Country	Shares (%)
Libya	66.8	Benin	29.5
Egypt	63.5	Nigeria	28.9
Algeria	62.0	Sudan (former)	28.9
Tunisia	61.6	Senegal	28.4
Morocco	60.4	Somalia	28.4
South Africa	53.8	Mali	28.1
Yemen	48.8	Togo	28.1
Botswana	43.4	Zambia	27.8
Namibia	40.6	Sierra Leone	27.7
Gabon	40.2	Tanzania	27.7
Lesotho	38.7	Angola	27.5
Djibouti	38.6	Comoros	27.1
Eswatini	38.4	Equatorial Guinea	26.7
Zimbabwe	38.2	Guinea	26.6
Seychelles	36.8	Mozambique	26.4
Sao Tome and Principe	35.4	Central African Republic	26.2
Cabo Verde	34.8	Kenya	25.5
Mauritania	34.4	DR Congo	25.3
Cameroon	33.6	Rwanda	25.1
Mauritius	32.3	Madagascar	23.9
Ghana	32.0	Malawi	23.4
Gambia	31.9	Burkina Faso	23.2
Côte d'Ivoire	31.6	Chad	23.1
Africa (WHO)	31.1	Uganda	22.4
Rep. of Congo	30.9	Burundi	22.2
Liberia	30.9	Eritrea	22.0
Guinea-Bissau	29.9	Niger	22.0

Source: Adapted from WHO Global Health Observatory (2024).
Note: WHO = World Health Organization.

Undernutrition occurs when there is an inadequate intake of nutrients, leading to nutrient deficiencies and their related diseases. The 2023 Global Hunger Index report showed that the share of undernourished individuals across the world rose from 7.5 percent in 2017 to 9.2 percent in 2022 due to the combined effects of COVID-19, the Russia-Ukraine war, climate change, prolonged political unrest, and economic stagnation (Global Hunger Index 2023). Deficiencies in protein, carbohydrates, and fats are termed *macronutrient deficiencies*, while deficiencies in vitamins and minerals are known as *hidden hunger* or *micronutrient deficiencies*. Hidden hunger can occur without deficits in energy intake (Lowe 2021). Details of the undernutrition burden of Africa are provided in the subsections that follow.

Micronutrient Deficiency

Micronutrient deficiencies persist in Africa, with high risks for iron, iodine, vitamin A, vitamin D, vitamin B12, zinc, calcium, folate, and selenium deficiencies (Bationo, Savadogo, and Goubgou 2022; Gebremedhin 2021; Theuri and Wachira 2022; Joy et al. 2014). The most common and prevalent is iron deficiency, affecting about 70 percent of households in Africa (Christian and Dake 2022).

Micronutrient insufficiency is a major health concern in Africa, particularly in the region south of the Sahara. Over 98 percent of malnourished people worldwide live in developing countries, with African countries south of the Sahara accounting for more than half of these cases (Engidaw et al. 2023; Nxasana et al. 2023). One of the primary factors causing micronutrient deficiency is poor diet. Dietary causes of micronutrient deficiency in Africa include insufficient intake of animal-source foods, fruits, and vegetables due to inadequate availability (Abe-Inge and Kwofie 2023). Animal-source foods, fruits, and vegetables are widely known to be rich sources of several nutrients, including micronutrients. For instance, liver is the richest source of iron, and dairy milk is a great source of calcium and other micronutrients. Hence, the low intake of animal-source foods among Africans could account for the high prevalence of iron deficiency in the region. Mushrooms and edible insects are seemingly less popular yet rich sources of micronutrients such as B vitamins, selenium, copper, vitamin D, and potassium. Their intake among Africans is likely inadequate, although there is no comprehensive publicly available evidence on their supply and consumption rates among Africans. The inadequate intake of micronutrients is associated with neural tube defects, osteoporosis, impaired cognitive function, impaired immune function, cardiovascular diseases, and certain types of cancer (Fulgoni III and Agarwal 2021). It is therefore necessary to consider more strategies and pathways to ensure the adequacy of micronutrient supply to Africans through dietary interventions.

Aside from poor diet, factors such as disease conditions, agronomic factors, restricted access to healthcare, and low literacy levels all contribute to the prevailing micronutrient deficiency in the region (Ohanenye et al. 2021). Research undertaken in South Africa shows a high frequency of micronutrient deficiencies—particularly zinc, iron, and folate—among HIV-infected people with unsuppressed viral loads (Kihara et al. 2020). Moreover, agronomic studies in Africa south of the Sahara show widespread micronutrient inadequacy in arable soils, with zinc being the most inadequate, highlighting the need for strategic interventions to address micronutrient deficiency in Africa (Githanga 2019).

Macronutrient Deficiency

Macronutrient deficiency results from inadequate intake of proteins, carbohydrates, lipids, or a combination of these. In instances where deficiency involves all macronutrients, the terms *protein-energy malnutrition* or *protein-energy undernutrition* are applied. The repercussions of macronutrient deficiency range from mild to life-threatening depending on the type of nutrient, degree of deficiency, health status, and cooccurrence of other deficiencies (Espinosa-Salas and Gonzalez-Arias 2023).

Among the different macronutrient deficiencies in Africa, protein deficiency is the most common (Abe-Inge and Kwofie 2023). Research shows that protein intake in Africa is inadequate. For instance, protein intake among Africans was estimated to be around 30 g/capita/day (Schönfeldt and Gibson Hall 2012), and a recent report indicated the availability of animal-source foods (81–258 g/capita/day), which remain the source of high-quality proteins for Africans (with the exception of southern Africa), is lower than the daily intake of animal-source foods recommended by the EAT–Lancet and African-based dietary guidelines (Abe-Inge and Kwofie 2023). The inadequate intake of quality protein could also be linked to the inadequate availability of legumes, seeds, nuts, and animal-source foods in all regions of the continent other than North Africa (Abe-Inge and Kwofie 2023).

Protein deficiency contributes significantly to the prevailing health and economic burdens of Africa and can take a significant toll on the health, growth, and development of an individual. Health burdens include stunting, muscle wasting, edema, anemia, loss of bone mass, impaired nutrient absorption, immunodeficiency, intrauterine growth restriction, cardiovascular dysfunction, hypoalbuminemia, skin atrophy, and impaired hormone production, particularly of growth and thyroid hormones and insulin (Espinosa-Salas and Gonzalez-Arias 2023; Wu 2016). Although protein intake is generally low and of poor quality in Africa, instances of excessive consumption could be equally economically burdensome due to associated risks of renal, digestive, and vascular abnormalities. Unlike protein, lipid and carbohydrate deficiencies are not common. While both are used in the production of energy in daily activities and metabolic functions of the body, essential fatty acids (part of lipids) play a more essential role in brain and retina development, especially during pregnancy and early life stages (Huffman et al. 2011). Data on the prevalence of essential fatty acid deficiencies in Africa are limited. However, populations that consume low amounts of seeds and animal-source foods are likely to be deficient in essential fatty acids. Research confirms that populations in Africa have an inadequate supply of seeds and animal-source foods to support the required daily intake levels (Abe-Inge and Kwofie 2023, Huffman et al. 2011). The supply of seeds is more inadequate than that of animal-source foods, particularly in Southern Africa, followed by Central Africa, North Africa, East Africa, and then West Africa (Abe-Inge and Kwofie 2023).

Animal food sources of essential fatty acids include meat, seafood, and edible insects such as termites, locusts, crickets, flies, worms, and larvae (Kolobe et al. 2023; Parker et al. 2017). Edible insect consumption has long existed and is noticeable in several African countries such as Angola, Botswana, Burkina Faso, Cameroon, Democratic Republic of Congo (DR Congo), Ghana, Guinea, Kenya, Madagascar, Malawi, Namibia, Nigeria, Rwanda, South Africa, Sudan, Tanzania, Uganda, Zambia, and Zimbabwe (Matandirotya et al. 2022). Due to a lack of data, it is not evident how much insect consumption has contributed to combating fatty acid deficiency in these countries. However, its existence in the region signals the need to adequately integrate its production in African food systems to achieve food and nutrition security.

Existing Interventions and Their Limitations

Overall, the African region south of the Sahara is said to be more affected by malnutrition generally due to the simultaneous presence of persistent poverty (Delisle, Faber, and Revault 2021). As of 2023, out of the 48 African nations south of the Sahara, 22 were low-income countries and 19 were lower-middle-income (Hamadeh, Rompaey, and Metreau 2023), confirming the magnitude of the poverty burden in Africa.

Consequently, several interventions have been made, stemming from the United Nations' Sustainable Development Goals (SDGs) 2 and 3. SDG2 aims to achieve zero hunger with a focus on food security and sustainable agriculture, and SDG3 aims to achieve healthy living and enhanced well-being across all ages. Under these goals, three main strategies are currently employed: biofortification, education, and economic empowerment. Efforts to combat food and nutrition insecurity in Africa have been diverse, encompassing a range of community-level and national initiatives. Despite significant investments, these interventions often face critical limitations that hinder their effectiveness.

Research has shown that current food availability is insufficient to support healthy and adequate daily nutrition among Africans (Abe-Inge and Kwofie 2023). This observation implies that educating consumers on healthy eating and designing food-based dietary guidelines and food guides are not enough to achieve SDG2 and SDG3 in Africa. Extra efforts are required to maximize the efficiency of nutritious food production and reduce food losses and waste. Biofortification programs, on the other hand, face barriers such as low accessibility and adoption by farmers (AU 2023), consumers' skepticism about health impacts, and significant nutrient losses during cooking at the household level (Eyinla et al. 2019). These challenges are reinforced by the inherent general difficulty of behavioral change.

Furthermore, many interventions are not sustainable due to limited funding, poor policy integration, and insufficient government backing, which limit their scalability and impact on larger regional or national food security concerns. Furthermore, social and cultural issues such as resistance to changing conventional eating patterns can impede successful acceptance of suggested nutritional practices and are not sufficiently considered in program design.

Role of Circular Bioeconomy in Addressing Nutrition Challenges

Africa's shift toward a bioeconomy for sustainable food systems transformation has recently embraced the circular bioeconomy. This approach addresses regional challenges such as unsustainable agricultural practices, waste generation, food and nutrition insecurity, and climate change (D'Amato, Veijonaho, and Toppinen 2020; Feleke et al. 2021; Sekabira et al. 2022). Thus, its adoption supports the regional quest for achieving an economically resilient, environmentally favorable, and socially equitable economy (D'Amato and Korhonen 2021; D'Amato, Veijonaho, and Toppinen 2020).

For example, converting biowaste to vermicompost, biofertilizers, and biopesticides can reduce the costs and environmental burdens of synthetic chemicals while improving agricultural productivity and food availability. Similarly, by exploring the vast potential of agricultural and agro-industrial biowaste for nutrient-dense bioingredients, biofoods, and feed, a circular bioeconomy could be structured as a vehicle for accelerating strides toward meeting food and nutrition security. These possibilities have been observed in some African regions, with institutions such as the International Institute of Tropical Agriculture, International Centre of Insect Physiology and Ecology, and the Africa Circular Economy Alliance implementing advocacy and programmatic actions to explore the possible interactions between circular bioeconomy, food and nutrition security, and climate adaptation (Sekabira et al. 2022).

Currently, Africa's circular bioeconomy trend prominently captures low-value composting, animal feed, and bioenergy pathways, leaving the nutrition-oriented possibilities barely explored. A nutrition-based circular bioeconomy would offer Africa a chance to bridge gaps in nutrition, health, and environmental sustainability while creating value and wealth from waste and underused byproducts. Recent advances in this direction are seen in research and microenterprise exploration of some potential waste-to-product circularity pathways including the transformation of waste into food products such as dietary fiber, juices, powders, and jams (Abasubong et al. 2023; Aidoo, Kwofie, and Ngadi 2022); cultivation of edible mushroom and insects for food and feed (Madau et al. 2020; Nyakeri et al. 2017; Tanga et al. 2021); and second-generation microbial protein, biopesticides (Akutse et al. 2020; Ashaolu et al. 2021; Kusumaningtyas et al. 2020), and biofertilizers, especially in the eastern and western corridors (Sekabira et al. 2022). For instance, a Ghanaian start-up converts spent mango and pineapple pulp from juice extraction into edible dietary fiber products (Pneuma Food Scientifics 2023), thus exemplifying a practical application of circular bioeconomy to create value-added products and achieve nutrition security.

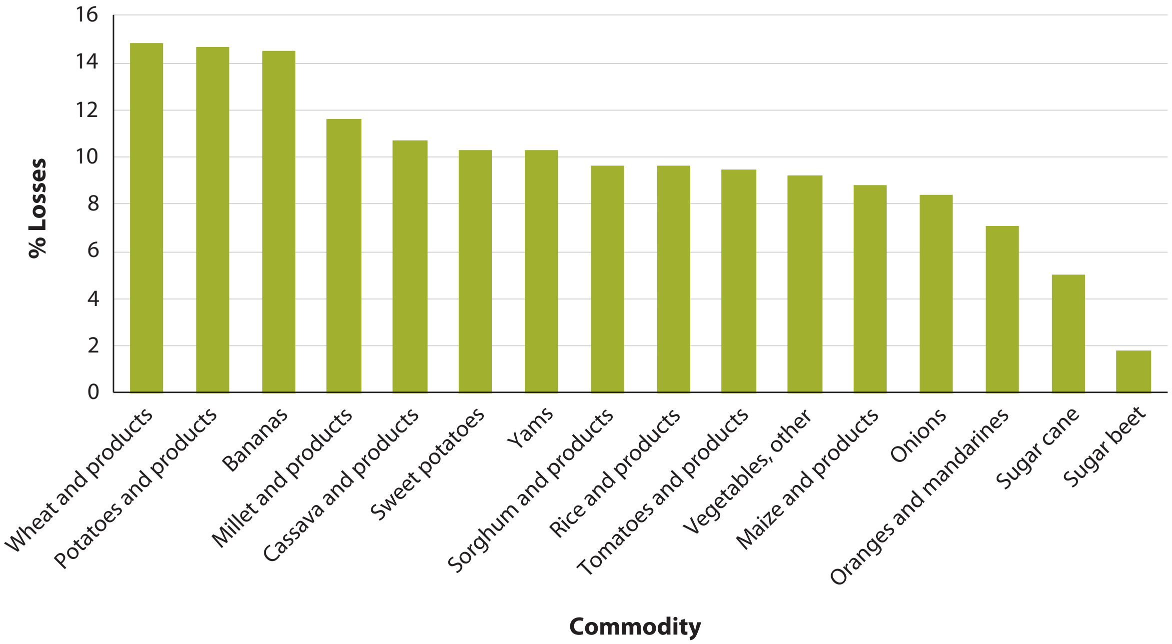
Focusing on Ghana, researchers explored the practical applications of the circular bioeconomy framework, particularly through the multiple R approach (reduce, reuse, refuse, rethink, repair, recycle) in agriculture (Boon and Anuga 2020). Their findings suggest that the circular bioeconomy can lead to more efficient resource use, increased agricultural yields, and improvements in the quality of agricultural products, which in turn enhance food and nutrition security. However, the successful application of these principles requires overcoming significant technological and investment challenges, as well as fostering a greater understanding of the economic, social, and environmental impacts of such transitions.

The lack of supportive scientific evidence has been one of Africa's primary barriers to a widespread circular bioeconomy adoption, given uncertainties related to the sustainability trade-offs of associated pathways (Sekabira et al. 2022). Thus, following the proposed nutrition-based circular bioeconomy path would require development of concrete scientific evidence that delineates the possible trade-offs of the paradigm and associated pathways and helps to frame sustainable solutions. The next section of this chapter provides a preliminary exploration of such trade-offs for some potential nutrition-based circular bioeconomy use cases.

Mapping Out Agrifood Waste and Use in Africa

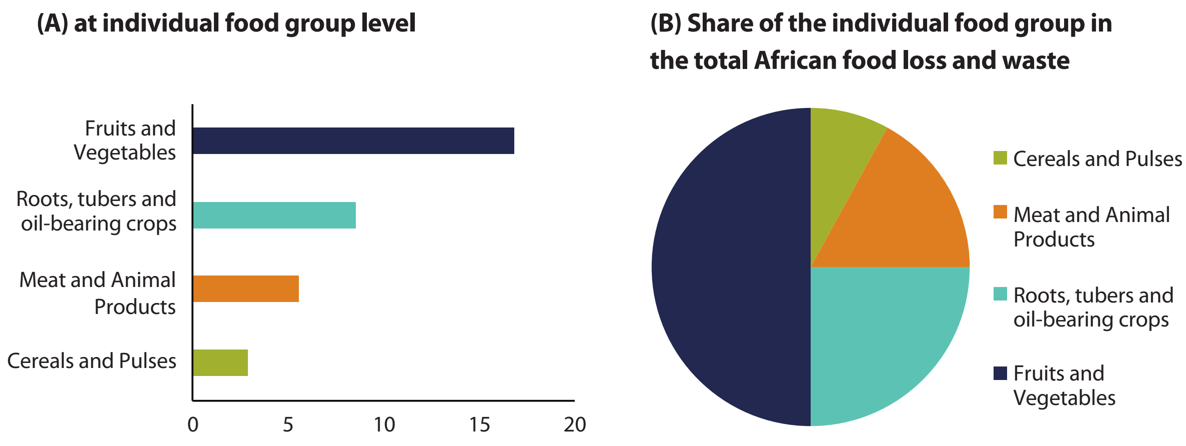
Agrifood waste includes the edible and inedible fractions of food removed from the human food supply chain. It remains a challenging problem in Africa due to the region's tropical weather, as high temperatures promote rapid deterioration of horticultural produce at all the stages of the food supply and value chain. In addition to conditions that favor food spoilage and waste, there is limited technological capacity to use these generated wastes. Although there are limited data on the rates of food waste and loss in Africa, this chapter uses food loss data from the FAOSTAT Food Balance Sheets to represent the continent's agrifood waste levels. As presented in Figure 8.2, the food waste rates in 2021 (the most recent FAOSTAT data available) are highest for wheat, potatoes, and bananas, with sugar beets being the least wasted. In addition, Figure 8.3 demonstrates that food waste rates are highest for fruits and vegetables. By food group (Figure 8.3A), fruits and vegetables showed about 17 percent average waste across Africa between 2000 and 2022. Cereals and pulses were the food group with the least food loss

FIGURE 8.2—PERCENTAGE LOSSES FROM TOP PRODUCED COMMODITIES IN AFRICA



Source: FAOSTATS Food Balance Sheets

FIGURE 8.3—AVERAGE AFRICAN FOOD WASTE AND LOSS RATE AS A PERCENTAGE OF DOMESTIC PRODUCTION FROM 2000 TO 2022



Source: Authors, calculated from FAO (2024).

and waste (8 percent) recorded within the same period. Figure 8.3B further demonstrates clearly that fruits and vegetables account for about 50 percent of the total food lost and wasted in Africa .

Among the top 10 African countries in terms of food loss and waste, Tanzania leads with 152 kg/capita/year of household waste (medium confidence estimate) (FAO 2024; Oluwole 2024). The remaining countries in the top 10 list are Uganda, Seychelles, Rwanda, Nigeria, Mozambique, Madagascar, Niger, Burkina Faso, and Mali, while the country with the lowest food waste rate (48 kg/capita/year) is Zimbabwe (UNEP 2024). Due to aggregation of data, it is not sufficiently clear which individual food commodities and/or stages of the supply and value chain present the highest waste in these countries. In addition, little is reported about the nature of waste generated, such as the proportions that are liquid or solid.

Regardless, it has been estimated from the available data that the majority (60 percent) of agrifood waste in 2022 occurred at the household level (UNEP 2024). Meanwhile, among smallholder farmers who dominate the African agricultural industry, food waste and loss rates are often highest at the farm level due to a lack of timely access to markets, poor road networks, and inadequate preservation and storage techniques, especially for perishable produce. However, information is limited regarding the edible and inedible portions of the generated food waste and their proportions, use rates, and use efficiency. However, researchers have noted that a staggering 90 percent of agrifood waste often ends up in landfills, with the remaining 10 percent is used for either fertilizer or animal feed (Bessa, Agonga, and Monthe 2021).

While there are numerous opportunities for integrating agrifood waste into the circular bioeconomy (as highlighted in subsequent sections of this chapter), there are also significant challenges. These include the need for better policy frameworks, more robust technological solutions for waste processing, and greater public awareness and acceptance of products derived from biowaste. The success of these initiatives also depends on overcoming logistical and economic barriers to ensure that the derived products are safe, economically viable, and socially acceptable (Mak et al. 2020).

Use Cases: Nutrition and Environmental Impact Profiling of Nutrition-Sensitive Circular Bioeconomy Pathways

Following the discussion in the previous section, this section profiles the sustainability performance of some nutrition-based circular bioeconomy interventions. The section begins with an overview of some potential use cases and their advantages and ends with an environmental impact and nutrition profiling based on literature.

Potential Use Cases

Circular Edible Mushroom Production

The unique culinary, nutritional, and nutraceutical benefits of mushrooms for food, feed, and medicinal use have stimulated global demand. This increased demand brought market value of these products to about US$68 billion in 2023, more than double the value in the past decade. With demand still rising, their market value is projected to double again to about US$136 billion in the next decade, with expected market growth in Europe, Asia Pacific, Latin America, and African countries such as South Africa and Nigeria. The rapid rise in global adoption, coupled with threats of extinction of wild edible mushrooms and the desire for more controlled cultivation, has stimulated domesticated edible mushroom farming, which now represents 54 percent of the current global market. The remaining 46 percent is classified under medicinal (38 percent) and wild mushroom (8 percent) production (Dimopoulou et al. 2022).

Domesticated edible mushroom farming has adopted and used agro-industrial food waste materials such as banana leaves, empty oil palm inflorescence, rice straw waste, maize stubble, bagasse, cotton waste, pineapple leaves, cassava peels, and sugarcane as substrates (Kortei, Dzogbefia, and Obodai 2014; Kumla et al. 2020; Munir et al. 2023). Thus, mushroom farming presents an easily adoptable opportunity to implement a nutrition-sensitive circular bioeconomy in Africa for food and nutrition while sustainably converting wastes into organic fertilizer for sustainable food crop production.

A chemical profiling of several edible mushrooms, including *Agaricus bisporus*, *Agaricus blazei*, *Amanita caesarea*, *Boletus aereus*, *Boletus edulis*, *Cantharellus cibarius*, *Coprinus comatus*, *Cordyceps militaris*, *Craterellus cornucopioides*, *Craterellus lutescens*, *Ganoderma lucidum*, *Grifola frondosa*, *Hericium erinaceus*, *Lentinula edodes*, *Marasmius oreades*, *Morchella esculenta*, and *Pleurotus ostreatus*, showed significant composition of proteins (13.8–38.5 grams per 100 grams), carbohydrates (32.0–61.4 g/100 g), fats (0.4-5.9 g/100 g), and other vital micronutrients and phytochemicals (Dimopoulou et al. 2022). For most species, a serving size of 100 grams could contribute about 15–30 percent of the recommended daily intake of most vitamins, especially vitamin B complex, and microelements including potassium, phosphorus, iron, zinc (high in most species), magnesium, and copper (Dimopoulou et al. 2022; Gargano et al. 2020; Vetter 2019). This indicates an opportunity to explore the use of mushrooms in micro- and macronutrient deficiency interventions. Already, the strategy is being pushed as a programmatic action in several global contexts, including Algeria, Morocco, Nigeria, Tunisia, and other Central and Southern African countries. There is also growing advocacy concerning the inclusion of edible mushrooms in flexitarian diets as substitutes for animal meat (Das et al. 2021; Valverde, Hernandez-Perez, and Paredes-Lopez 2015). Against this background, the change in the agricultural paradigm toward a restorative culture has augmented concerns about possible sustainability risks, triggering stakeholder actions to streamline local farming practices to attain a balance between sustainability and nutrition security benefits. These efforts have heightened the popularity of circularizing local agricultural and agro-industrial biowastes in domesticated farming, especially in African countries south of the Sahara such as DR Congo (Mpadi and Bangala 2020), Egypt (Yehia 2012), Ethiopia (Gashaw and Getu 2020), and Tanzania (Magingo et al. 2004), where biowastes are used as a nutrient supplement, spawn substrate, or growth substrate (Ekun et al. 2021). In addition, recent literature has outlined several pathways to design for and optimize eco-friendliness (Gashaw and Getu 2020, Magingo et al. 2004; Mlambo and Maphosa 2022; Mpadi and Bangala 2020). Notably, such cultivation techniques could be a cost-efficient and lucrative option for delivering the nutritional value of edible mushrooms while conferring the benefits of carbon emission reduction gained through high-value upcycling of organic waste.

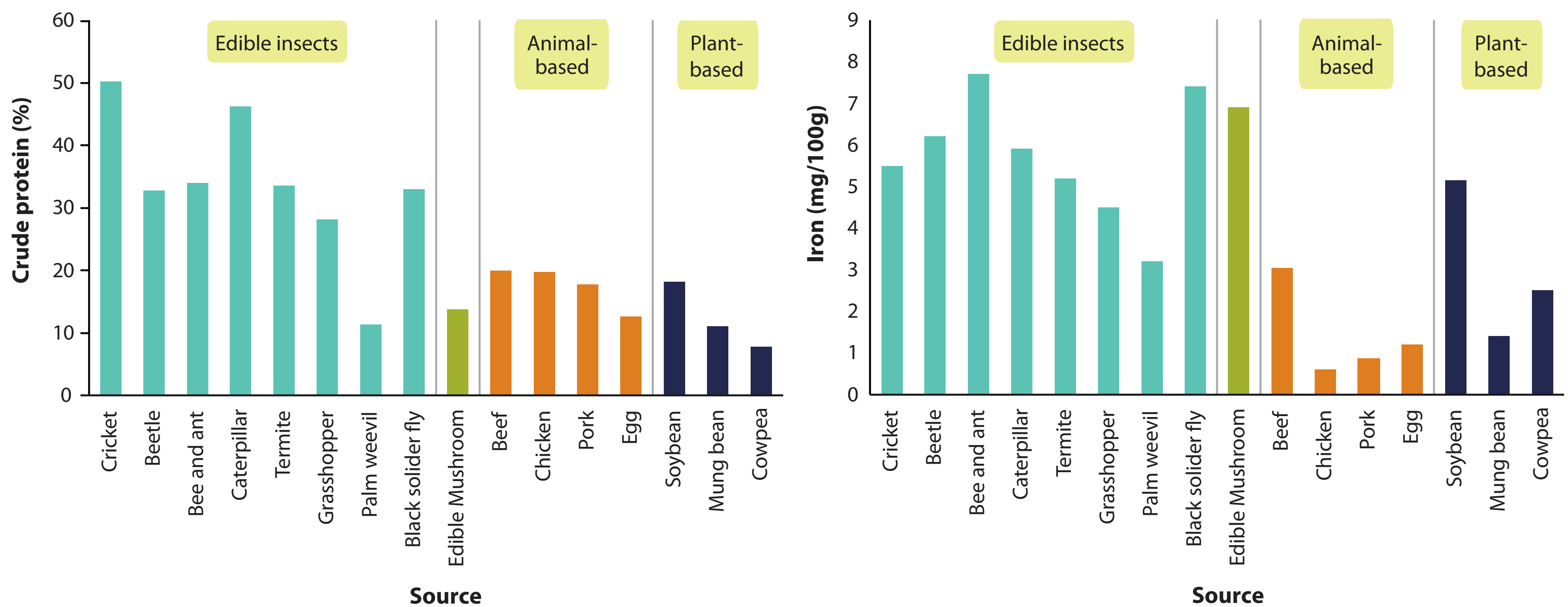
Despite recent progress in circular edible mushroom production in Africa, the overall regional adoption rates are very low. This signals an opportunity for Africa to maximize interest in embracing this nutrition-oriented circular bioeconomy approach for sustainable food systems transformation. In this chapter, a system scenario developed by Ekun and colleagues (2021) is considered and explored as a use case to ascertain the environmental–nutrition co-benefits of circular edible mushroom production.

Use of Biowaste for Conventional and Alternative Proteins Production

The exploration of alternative proteins such as edible insects and microbial proteins for the sustainable and healthy satisfaction of burgeoning consumer protein needs has gained substantial traction. In Africa, interest has been stronger in edible insects, which are becoming prominent because of their ability to grow on wide streams of substrates and potential to advance a sustainable protein supply (Wade and Hoelle 2020). There are roughly 2,000 insect species that can be used for food, 25 percent of which are consumed in Africa (Kelemu et al. 2015). Edible insect farming requires relatively less land, water, and feed compared to conventional meat production and is attractive for its high nutritional value and carbon-saving potential.

Previous studies have compared the nutritional profile of edible insects with prominent meat products, reporting greater potential for edible insects. For instance, a comparison of 100 grams of mealworm larvae and of beef showed about 25 grams and 20 grams of protein, respectively (Liceaga 2021). Likewise, the protein contents of other edible insects cultivated on varying organic wastes have been compared with several meat alternatives, also reflecting relatively greater potential, as shown in Figure 8.4 (Tanga et al. 2021). However, there is a limited uptake of black soldier flies directly as human food due to safety concerns

FIGURE 8.4—COMPARISON OF CRUDE PROTEIN (LEFT GRAPH) AND IRON (RIGHT GRAPH) CONTENTS OF EDIBLE INSECTS WITH CONVENTIONAL PLANT- AND ANIMAL-BASED FOODS

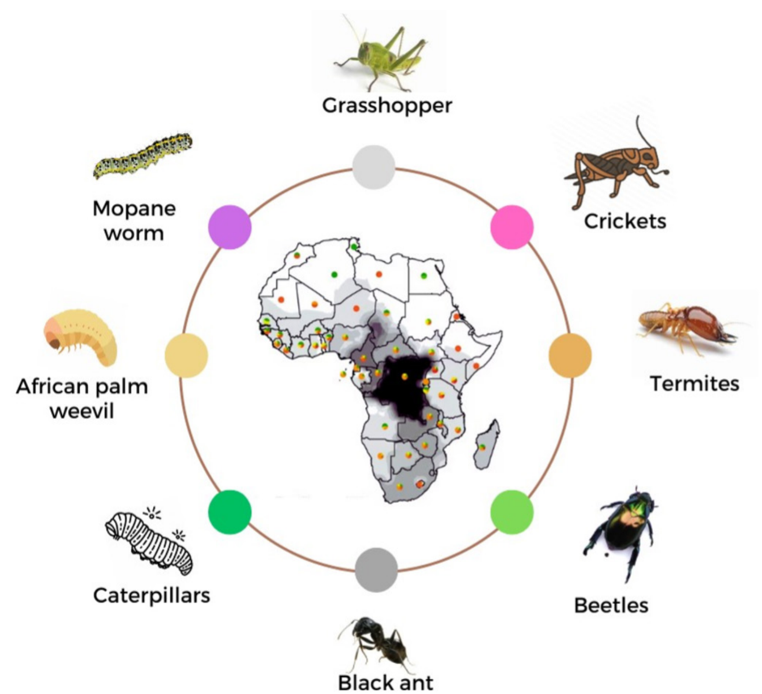


Source: Tanga et al. (2021).

and other consumer misconceptions (Tanga et al. 2021). The common practice is to leverage them as conventional meal substitutes in aquacultural production, which in turn increases productivity and availability of sustainable protein food to meet local protein needs (Nyakeri et al. 2017).

Insects also have a high feed-conversion ratio when compared to livestock and poultry, saving significant economic and environmental costs associated with feed production and processing. In terms of resource demand, Pells (2023) mentioned that cricket production requires less land use than meat production, with offsets of up to sixfold for cattle, fourfold for sheep, and 50 percent for pigs and chickens, emphasizing the potential of edible insect farming in minimizing forest land clearing and degradation. The global market for edible insects is booming, expected to grow at a whopping 47 percent compound annual growth rate between 2023 and 2032, up from a market value of about US$1.2 billion (Global Market Insights 2022).

FIGURE 8.5—PROMINENT INSECTS MOSTLY CONSUMED IN AFRICA



Source: Adapted from Awobusuyi, Siwela, and Pillay (2021); Chakravarthy et al. (2016); Grabowski et al. (2020); Hlongwane, Slotow, and Munyai (2021); and Niassy and Ekesi (2017).

Note: Gray shading indicates the intensity of insect farming.

DISCLAIMER: The designations employed and the presentation of material on this map do not imply the expression of any opinion whatsoever on the part of AKADEMIYA2063, the editors, and the authors.

Africa has contributed comparatively little to this market growth despite the availability of a wide market niche, a strong tradition of insect consumption, and rich diversity of edible insects, which signal an opportunity to leverage local capacities to drive local innovations. Cameroon, Central African Republic, DR Congo, Nigeria, Republic of Congo, South Africa, Uganda, Zambia, and Zimbabwe are the predominant insect-eating countries in Africa (Niassy and Ekesi 2017). Some of the commonly consumed edible insects in Africa are shown in Figure 8.5.

Among the most commonly cultivated insects in Africa are the black soldier fly, followed by crickets, beetles, and palm weevil larvae. Although mealworms, which are probably the most commercialized edible insect, are currently not largely consumed in Africa, the use of available food waste generated in Africa can be explored in its production and consumption in the region.

Table 8.2 shows examples of food waste that have been used or have demonstrated potential as feed materials in insect production for both human food and animal feed. Fruit and vegetable waste, which accounts for the largest share of Africa's food waste output, has shown applicability in the cultivation of black soldier fly (Dzepe et al. 2023; Ganvir et al. 2022), mealworm (Zhang et al. 2019), and Cambodian cricket (Miech et al. 2016). Waste from roots/tubers and cereals/grains are being used for mealworm (Zhang et al. 2019), figeater beetle (Slagle and Davidowitz 2022), and Cambodian cricket (Miech et al. 2016) farming. Palm weevil larvae farming relies on palm yolk sourced from a felled palm tree during the tapping of palm wine (Elemo et al. 2011). This technique of palm weevil larvae cultivation is unsustainable, emphasizing the need to explore sustainable alternative techniques that use household food waste. Africa has an enormous accumulation of more than 125 million metric tons of organic waste annually. Less than 5 percent of this waste is effectively recycled (Linda et al. 2019).

TABLE 8.2—SELECTED FARMED INSECTS' APPLICATION AND FEED MATERIALS

Insect Name	Application	Feed Materials	Reference
Black soldier fly	Human food and animal feed	Fruit peels (summer fruits, papaya, and banana), vegetables, bakery waste, cocoa pods, and kitchen waste	(Dzepe et al. 2023; Ganvir et al. 2022)
Figeater beetle	Human food and animal feed	Dairy cow manure, spent mushroom substrate, spent brewer's grain, and leaves	(Slagle and Davidowitz 2022)
Mealworm	Human food and animal feed	Mushroom spent corn stover, highly denatured soybean meal, watermelon rinds, banana peels, and spirit distillers' grains	(Zhang et al. 2019)
House cricket	Human food and animal feed	Grocery store food waste after aerobic enzymatic digestion, and municipal food waste heterogeneous substrate	(Lundy and Parrella 2015)
Housefly	Animal and fish feed	Mixture of egg content, hatchery waste, and wheat bran	(Makkar et al. 2014)
Cambodian cricket	Human and animal feed	Rice bran, cassava plant tops, water spinach, spent grain, and residues from mung bean sprout production	(Miech et al. 2016)
Palm weevil larvae	Human food	Palm yolk	(Elemo et al. 2011)

Use of Biowaste for Functional Extract and Platform Chemical Production

Functional extracts are natural compounds typically derived from plants and other agricultural sources, which can be added to food products to render certain health or other functional benefits (Lamponi 2021). Platform chemicals are basic chemical building blocks used to produce different kinds of fine and specialty chemicals (Pachapur, Sarma, Brar, and Chaabouni 2016). Africa has great potential to expand the functional extract and platform chemical market for satisfying local needs by leveraging local circular bioeconomy opportunities. Considering the diverse chemical densities of the variety of biowastes broadly reported in the literature, it would be possible to replace a significant portion of the synthetic functional ingredient and platform chemical market with bio-based alternatives to meet local sustainability targets. A typical example for functional extract production is the case of cashew apples, which is a rich source of dietary fiber, potassium, and vitamin C (about 5 and 10 times that of citrus fruits and pineapples, respectively), highlighting opportunities for producing functional products rich in fiber, potassium, and vitamin C (Akyereko et al. 2023). However, aside from the minute portions either consumed in their raw state or processed at small scales into juice and wine, the vast majority of cashew apples produced in Africa, and globally, faces gross underutilization (Das and Arora 2017; Sobhana 2019; Sobhana et al. 2015). Currently, about 80–90 percent of cashew apples produced globally are discarded (Dimoso et al. 2020). Statistics show that Africa produces about 60 percent of the world's cashews, dominated by Côte d'Ivoire, Nigeria, and Tanzania (Jeyavishnu et al. 2021). Thus, assuming Africa contributes 50 percent of the reported 35 million tons of annual cashew apple waste biomass, simple arithmetic likens that to dumping 600,000 standard 40-foot shipping cargo containers with a carrying capacity of 27 metric tons. There is, therefore, a huge opportunity to restructure the value chain in growing regions to embrace the underexplored commercial potential of cashew apple biomass. As mentioned earlier, this could be a viable circular business model for bridging gaps in dietary fiber and vitamin C supply through cashew apple powder and juice production, providing new frontiers in job and incentive stream creation that could empower women and support gender parity within the value chain. Similarly, waste biomass can be explored for platform organic acid or alcohol platform chemicals through biotechnological approaches, considering its high sugar content. The African chemical industry is generally considered an emerging one, and the region relies mainly on imports to satisfy local demand. Thus, the proposed cashew apple–to–platform chemical production pathway could be one of many opportunities to localize production and supply, considering that the continent is poised to sustainably advance the local chemical industry and strengthen intracontinental trade. This could be facilitated by strengthening local small and medium enterprises to spearhead the development of the industry, supported by the necessary financial support. The same can be said for other nutrient-dense waste biomass with such potential for functional nutrient extraction, especially fruit and vegetable wastes that contain a diverse range of useful phytochemicals.

Aquaponics for Fish Protein and Micronutrient-Rich Vegetable Production

Aquaponics is a modern agricultural technique that combines both aquaculture and hydroponics to simultaneously grow fish and plants. In this farming technique, aquaculture is carried out in fish tanks in combination with plants grown in beds. The wastewater generated from fish tanks is fed to the hydroponic system where the plants absorb the nutrients contained in the wastewater inflow, thus acting as biofilters. The aquaponic system can be leveraged to grow fish and vegetables to boost the supply of protein and micronutrients in Africa. The technique could be applied to commonly farmed edible fish such as tilapia, catfish, trout, and nutrient-rich vegetables such as leafy green vegetables, tomatoes, eggplant, and many others (GoGreen Aquaponics 2023). The technique uses less water and no inorganic fertilizers, therefore yielding nutrient-rich foods with little harm to the environment. In addition to its eco-friendly nature, the aquaponics market is growing rapidly, especially in North America and Asia, with an estimated current global market size of US$1.2 billion, forecast to reach US$1.92 billion by 2029 (Mordor Intelligence 2024).

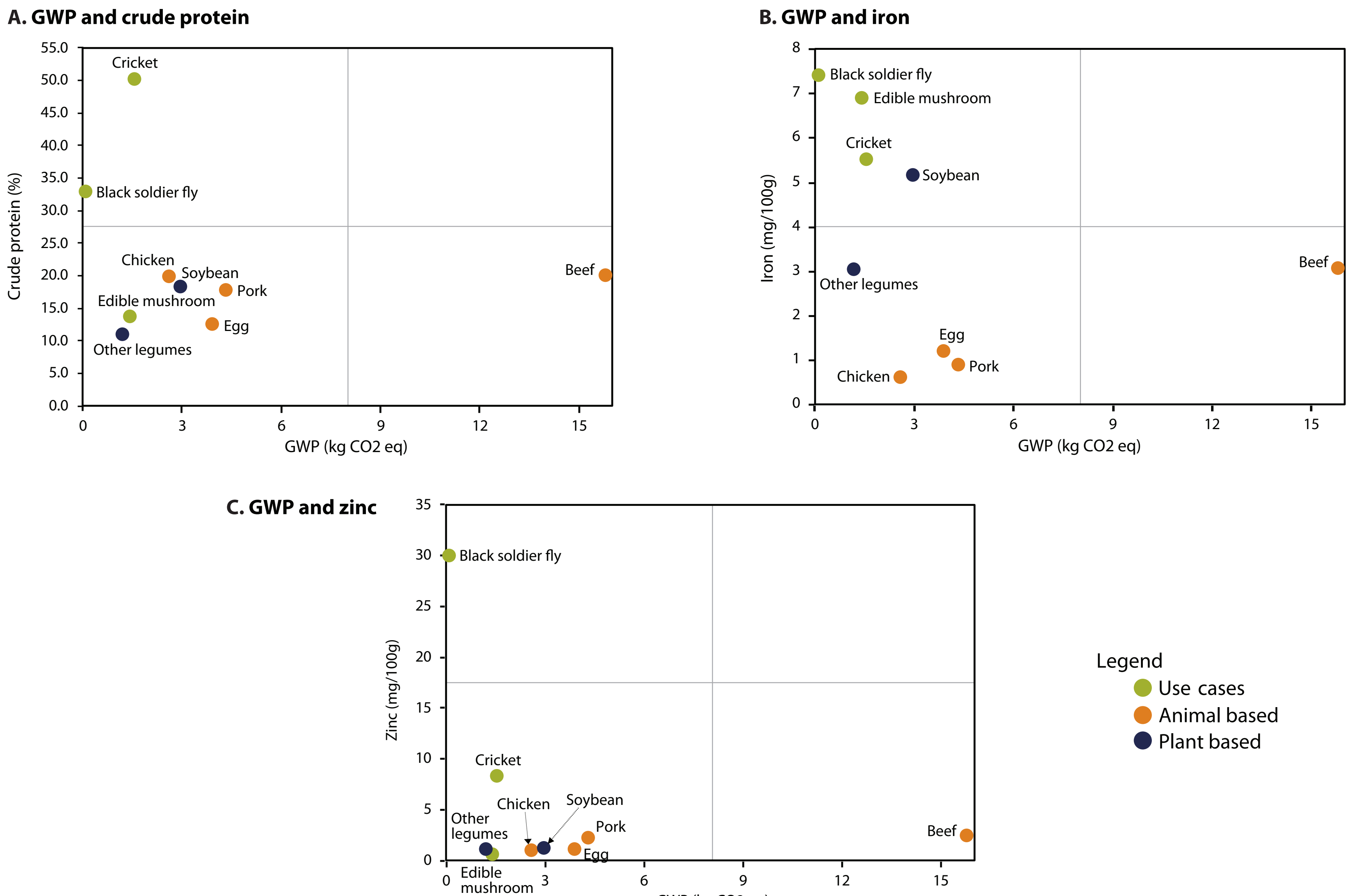
Millions of people in Africa rely on fish as a source of protein, underpinning the rising growth rate of aquaculture and consumption rate in several nations of the region. Notably, the per capita consumption rate increased from 2.8 kilograms in 1961 to 12.2 kilograms in 2010 (Eyayu, Getahun, and Keyombe 2023). In addition, Africa's total annual inland and marine capture fish production grew significantly from 1.47 million tons in the 1980s to 3.21 million tons in 2020 (FAO 2022). In addition to the region's growing population resulting in a higher number of fish consumers, there is a growing European market for African-produced fish (Eyayu, Getahun, and Keyombe 2023; Globefish 2024). The European market constitutes about 70 percent of the African fisheries export market, with Mauritius, Morocco, Namibia, Senegal, and South Africa among the top 50 global exporters (Globefish 2024). This high demand for fish contributes to job opportunities and consequently to the economies of fish-producing nations (Eyayu, Getahun, and Keyombe 2023). These dynamics justify the implementation of modern and sustainable techniques such as aquaponics, which is suitable for leading aquaculture in African countries such as Egypt, Ghana, Kenya, Nigeria, and Uganda (Globefish 2024; Kaleem and Bio Singou Sabi 2021). The technology has already been adopted noticeably across Africa, with Egypt, Ghana, Kenya, and South Africa appearing to be the leading users (Obirikorang et al. 2021). In Ghana, eco-aquaponics—a growing field of aquaponics that exploits the symbiosis between fish and algal production—has been actively promoted by the Bio Green Agro start-up (Okai 2021). In this aquaponic system, algae is grown within the farming pools as primary feed for the fish and later as concentrated fertilizer for crop production application. The system has been inspected and certified by governing bodies such as the Participatory Guarantee System (Ghana) under the auspices of the International Federation of Organic Agricultural Movements (Okai 2021). Similar initiatives are being explored in other African countries such as Nigeria (Okomoda et al. 2022; Benjamin, Tzemi, and Fialho 2021).

While fish and vegetables produced from aquaponics are used as food and nutrient sources for humans, the resulting solid waste from fish and vegetables can be used in insect farming to create both feed for fish farming and protein sources for human consumption. Therefore, aquaponics is a highly promising circular bioeconomy technique with a great potential to contribute to food and nutrition security in Africa, especially in regions with high fish and insect protein consumption.

Nutrition-Based Sustainability Trade-Off Analysis for Food-Based Circularity Pathways

The previous sections of this chapter discussed nutrition challenges in Africa, highlighting the promising potential of a nutrition-based circular bioeconomy as a sustainable pathway for delivering regional nutrition security targets. This section focuses on quantifying the environmental and nutritional profiles of a nutrition-based circular bioeconomy and estimating the potential environmental–nutrition trade-offs with some conventional nutrition sources. The environmental and nutritional profiles are summarized in Tables 9A.1 and 9A.2 of the appendix. Figure 8.6 compares some use cases against some conventional plant- and animal-based protein sources by plotting protein, iron, and zinc profiles and global warming potential. In Figure 8.6a, the use cases of crickets and black soldier flies show a relative advantage in combining protein supply with carbon-zero targets, given their relatively lower global warming potentials and high protein content. Edible mushrooms show similar benefits, but with

FIGURE 8.6—ENVIRONMENTAL–NUTRITION TRADE-OFF ANALYSIS OF USE CASES AGAINST CONVENTIONAL PROTEIN SOURCES: (A) GWP AND CRUDE PROTEIN (B) GWP AND IRON (C) GWP AND ZINC



Source: Authors.

Note: GWP = global warming potential.

less protein content, comparing favorably with other plant- and animal-based proteins while surpassing them in terms of environmental benefits. The same is seen for the micronutrient trade-off analysis (Figure 8.6, panels b and c), where black soldier flies and edible mushrooms surpass conventional nutrient sources in terms of both micronutrient supply and global warming reduction. These trends conform with the existing literature, which positions edible insects and mushrooms as sustainable, high-value nutrient sources for achieving environmental–nutrition co-benefits. It is important to mention that due to data lags, the environmental data for the use cases mainly captured conventional production systems, most of which relied on synthetic substrates. Thus, the visualized benefits may extend even further, considering the claims that organic substrates can offer additional environmental impact offsets (Aidoo et al. 2023, 2024). Therefore, with the analysis indicating that the use cases can achieve greater environmental–nutrition co-benefits, the findings of this study could be used to justify policy or programmatic actions for adopting and expanding these cases as regional nutrition-based circular bioeconomy interventions. The possible environmental impact offsets associated with such implementations are shown in Table 8A.3 of the appendix.

Conclusion and Recommendations

This chapter demonstrates that the circular bioeconomy concept has great potential to enhance Africa's food and nutrient security while also providing environmental benefits. The concept is useful for transforming agrifood waste into nutrients such as protein, dietary fiber, and micronutrients for human consumption.

In regions with high insect consumption, insect farmers should be encouraged to liaise with food producers to use any generated biowaste in their insect farming businesses. While aquaponics should be promoted in countries where fish farming is prevalent, such as Egypt, Ghana, Kenya, Nigeria, and Uganda, it can also be implemented in drought-prone regions of Africa to ensure water conservation and to boost the supply of nutrient-rich vegetables and fish in these regions. In addition, agrifood waste such as fruit waste could be used in the production of edible functional components such as dietary fiber and nutraceuticals useful in the prevention of overnutrition-related noncommunicable diseases.

The circular bioeconomy holds significant promise as a strategy to address the complex challenges of nutrition and sustainability in Africa. By fostering efficient resource use and waste reduction, a circular bioeconomy can contribute to more resilient food systems that support both people and the planet. However, realizing this potential fully will require concerted efforts to overcome existing barriers, particularly in terms of policy, community engagement, and technological innovation. With robust support and a clear understanding of its multifaceted benefits, circular bioeconomy can play a critical role in transforming Africa's food systems for better health and environmental outcomes.

Further research aimed at validating and tackling the potential barriers to scaling up these potential use cases is required. Community-based education and training, behavioral change campaigns, and/or awareness strengthening by agricultural agencies and personnel will then be required to educate all stakeholders along the food value chain about these new production pathways and to trigger consumer demand. Funds from government and funding agencies are necessary to aid producers and individuals in establishing and incorporating circular bioeconomy principles into their current practices. Food processors and entrepreneurs could be targeted in establishing startup businesses that incorporate the use cases outlined in this chapter. Clear policy frameworks incorporating all these proposed approaches should be developed as a guide to advance the application of circular bioeconomy for the purposes emphasized here.

The concept of a circular bioeconomy offers a transformative approach toward sustainable development, particularly in addressing the significant nutrition challenges in Africa. This innovative economic model emphasizes the regeneration of natural systems, efficient use of resources, and reduction of waste, all of which are crucial for creating resilient food systems that can improve nutritional outcomes and enhance food security across the continent. Therefore, establishing robust policy support and enhancing institutional frameworks are essential steps toward leveraging a circular bioeconomy for nutritional and environmental benefits in Africa. Bioeconomy strategies from the East African Community and South Africa, which both contain food security and sustainable agriculture components and specifically edible insect production in the EAC strategy, are two initiatives worth leveraging to ensure a smooth incorporation of a nutrition-sensitive circular bioeconomy across the entire African continent (Virgin et al. 2022). However, region-wide adoption and mass realization of associated benefits would require harmonizing continental capacities, facilitating knowledge sharing, and reimagining national and continental bioeconomy plans or strategies as a conduit for exploring and expanding these opportunities.

Appendix

TABLE 8A.1—ENVIRONMENTAL PROFILE OF SOME POTENTIAL USE CASES AVAILABLE IN LITERATURE

Use cases	Impact profile						References
	GWP (kg CO2 eq)	**MEP** (kg N- eq)	**FEP** (kg P-eq)	**WU** (m3)	**AP** (kg SO2 eq)	**LU** (m2a crop eq)	
Edible insects							
Field/house Cricket	1.55–4.35	0.013–0.033	0.0003– 0.006	0.34–0.82	0.05–0.14	—	Halloran et al. (2017); Salomone et al. (2017); Suckling et al. (2020)
Black soldier fly	0.10	—	0.00004	—	0.0002	—	
Edible mushrooms							
White button mushroom	1.09–2.98	0.00003	0.00002–0.002	0.004–0.29	0.008–0.01	0.05	Robinson et al. (2018); Vinci et al. (2023)
Oyster mushroom	2.34–3.18	—	0.000465	2.42	0.00007	—	Dorr et al. (2021); Gunady et al. (2012); Gundoshmian et al. (2022)
Straw mushroom	0.84–5.40	—	0.0019–0.0425	—	0.008–0.02	—	Usubharatana (2016)
Aquaponics							
Aquaponics	2.304–20.26	0.004–0.023	0.007	—	0.020–0.40	—	Boxman et al. (2017); Chen et al. (2020); Elnour et al. (2023); Ghamkhar et al. (2022); Greenfeld et al. (2022); Hindelang et al. (2014); Hollmann (2017)
Conventional animal and plant-based proteins							
Beef	15.80–48.40	—	—	5.99–15.42	—	19.53–54.82	Berardy et al. (2019); Ferrari et al. (2022)
Chicken	2.60–5.82	—	—	4.33	—	19.22	Berardy et al. (2019); Ferrari et al. (2022)
Pork	4.33–14.79	—	—	—	—	—	Berardy et al. (2019)
Eggs	3.90–5.50	—	—	3.27	—	17.83	Berardy et al. (2019); Ferrari et al. (2022)
Soybeans	2.96	—	—	—	—	—	Berardy et al. (2019)
Legumes	1.20	—	—	9.06	—	6.96	Ferrari et al. (2022)

Note: — = data not available; AP = acidification potential; FEP = freshwater eutrophication; GWP = global warming potential; LU = land use; MEP = marine eutrophication; WU = water use.

Appendix

TABLE 8A.2—NUTRITIONAL PROFILE OF SOME POTENTIAL USE CASES AVAILABLE IN LITERATURE

Use cases	Nutritional profile				References
	Protein (%)	**Fiber** (%)	**Iron** (mg/100g DM)	**Zinc** (mg/100g DM)	
Edible insects					
Crickets	50.20–65.95	5.50–10.6	5.51–12.33	8.24–23.74	Lokeshkumar et al. (2022); Murugu et al. (2021); Musundire et al. (2014);
Beetles	32.8–44.30	6.20–14.00	14.1–23.00	14.40–26.50	Hlongwane et al. (2020)
Bees and ants	33.90–43.10	7.70–12.30	17.80–24.40	7.50–10.00	Hlongwane et al. (2020)
Caterpillars	46.3 –68.00	5.9–11.30	15.40–27.60	10.6–12.80	Hlongwane et al. (2020)
Termites	33.51–60.2	5.2–7.65	53.33–119.43	7.20–19.90	Atowa et al. (2021); Awobusuyi et al. (2021); Chakravorty et al. (2016); Kinyuru et al. (2013)
Grasshoppers	28.2–43.2	4.5–5.7	13.33–161.70	17.84–24.50	Awobusuyi et al. (2021); Ibarra–Herrera et al. (2020); Kababu et al. 2023)
Palm weevil	11.30–36.90	3.2–4.0	1.32–1.88	7.81–23.00	Adepoju and Ayenitaju (2021); Awobusuyi et al. (2021); Kavle et al. (2023); Promwee et al. 2023)
Black solider fly	33.00–48.25	7.41–10.66	30.00–220.00	30.00–120.90	Shumo et al. (2019); Zulkifli et al. (2022)
Edible mushrooms					
Edible mushrooms	13.8–38.5	—	6.9–82.6	0.61–55.7	Dimopoulou et al. (2022)
Conventional animal and plant-based proteins					
Beef	20.0–27.55	—	3.04–3.10	2.39–3.70	FoodStruct (2023); Kababu et al. (2023); Orkusz (2021)
Chicken	19.8–21.2	—	0.60	1.00	FoodStruct (2023); Kababu et al. (2023); Orkusz (2021)
Pork	17.80–27.3	—	0.87–0.90	2.20	FoodStruct (2023); Kababu et al. (2023); Orkusz (2021)
Egg	12.58	—	1.19	1.05	FoodStruct (2023)
Soybean	18.2	6.00	5.14	1.15	FoodStruct (2023)
Mung bean	7.02	7.60	1.4	0.84	FoodStruct (2023)
Cowpea	7.73	6.50	2.51	1.29	FoodStruct (2023)

Note: — = data not available; DM = dry mass.

Appendix

TABLE 8A.3—POTENTIAL ENVIRONMENTAL IMPACT OFFSETS BY SOME USE CASES RELATIVE TO CONVENTIONAL PLANT- AND ANIMAL-BASED ALTERNATIVES

Use cases	% Offsets (relative to beef)	% Offsets (relative to chicken)	% Offsets (relative to pork)	% Offsets (relative to eggs	% Offsets (relative to soybeans)	% Offsets (relative to other legumes)
Cricket	90.19	40.38	64.20	60.26	47.64	-29.17
Black soldier fly	99.37	96.15	97.69	97.44	96.62	91.67

Source: Authors.