Circular Bioeconomy Research for Development in Sub-Saharan Africa: Innovations, Gaps, and Actions

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Abstract: The International Institute of Tropical Agriculture (IITA) has applied the concept of ‘circular bioeconomy’ to design solutions to address the degradation of natural resources, nutrient-depleted farming systems, hunger, and poverty in sub-Saharan Africa (SSA). Over the past decade, IITA has implemented ten circular bioeconomy focused research for development (R4D) interventions in several countries in the region. This article aims to assess the contributions of IITA’s circular bioeconomy focused innovations towards economic, social, and environmental outcomes using the outcome tracking approach, and identify areas for strengthening existing circular bioeconomy R4D interventions using the gap analysis method. Data used for the study came from secondary sources available in the public domain. Results indicate that IITA’s circular bioeconomy interventions led to ten technological innovations (bio-products) that translated into five economic, social, and environmental outcomes, including crop productivity, food security, resource use efficiency, job creation, and reduction in greenhouse gas emissions. Our gap analysis identified eight gaps leading to a portfolio of five actions needed to enhance the role of circular bioeconomy in SSA. The results showcase the utility of integrating a circular bioeconomy approach in R4D work, especially how using such an approach can lead to significant economic, social, and environmental outcomes. The evidence presented can help inform the development of a framework to guide circular bioeconomy R4D at IITA and other research institutes working in SSA. Generating a body of evidence on what works, including the institutional factors that create enabling environments for circular bioeconomy approaches to thrive, is necessary for governments and donors to support circular bioeconomy research that will help solve some of the most pressing challenges in SSA as populations grow and generate more waste, thus exacerbating a changing climate using the linear economy model.

Keywords: circular bioeconomy; sustainability; agriculture; outcome tracking; gap analysis; sub-Saharan Africa

1. Introduction

Throughout its modern history since the industrial revolution, the world has conveniently relied on a linear economic model that can be summarized as take the resources you need, make the goods for sale and profit, and dispose of what you do not need [1,2]. This extractive industrial model has benefited humanity for decades in material wealth creation. However, it has created a situation that will no longer sustainably support future generations. Scientific modeling results suggest that the current level of resource use has already exceeded what is considered sustainable [3]. According to the Global Footprint Network [4], the world’s population would need 1.7 Earths to support its demands on renewable natural resources. These findings have led to a realization that the linear economic
model will not be tenable in the face of an increasing global population and our associated consumption needs [5].

With over 140 million children born every year, the global population estimated at 7.4 billion people in 2017 is projected to reach 9.7 billion by 2050 and 11.2 billion by 2100 [6]. The Food and Agriculture Organization of the United Nations (FAO) estimates that if current population growth trends continue, by 2050, the caloric demand will increase by 70%, and crop demand for human consumption and animal feeds will have to double in low-income countries [7]. The gap between demand and supply would lead to food price increases that disproportionately affect the poor.

In Africa, the population is projected to reach 2.5 billion by 2050, accounting for about 27% of the global population [8]. The African middle class (defined as the section of society with earnings of between US$4 and US$20 per day) is also projected to top 1.1 billion people by 2060, accounting for 42% of the continent’s population [9]. The middle class is expected to stimulate demand for food, fiber, fuel, and medicines and change the pattern of material and food consumption (e.g., increase intake of livestock-based products). In SSA, population pressure is already more increasingly forcing farmers to cultivate marginal lands. Current African farming systems remain relatively unsustainable due to land degradation. Approximately 25% of productive lands are degraded mainly due to the loss of nutrients and soil organic carbon under continuous cropping [10]. Trending in parallel with land degradation is the substantial waste generation, contributing to greenhouse gas (GHG) emissions. Nearly 7% of Africa’s GHG emissions are generated from the decomposition of wastes in open dumps [11]. Associated with GHG emissions is climate change. While the adverse effect of climate change is global, SSA is more vulnerable to climate change because of its low adaptation capacity [12]. It is projected that SSA will lose $3.33 billion in gross domestic product (GDP) by 2050 due to climate change, equivalent to 0.2% of the region’s GDP [13]. These impacts suggest that more sustainably-produced products are needed that respect the limits of available resources [14].

Circular bioeconomy, defined as the intersection of bioeconomy and circular economy [15], holds considerable potential to address the challenges that SSA is facing today—low economic growth, climate change, and environmental degradation. For instance, the circular bioeconomy approach helps minimize resource use per unit of economic product, leading to significant cost savings [16]. The limited use of chemical inputs in the circular bioeconomy could contribute to climate change mitigation. The reuse of especially biowaste into the production system would reduce environmental degradation by removing decomposing waste. In SSA, the wide availability of productive land and more sunlight hours present ample opportunity for biomass production used as renewable energy sources, thus contributing to climate change mitigation [17].

Circular bioeconomy focuses on “the sustainable, resource-efficient valorization of biomass in integrated, multi-output production chains (e.g., biorefineries) while also making use of residues and wastes and optimizing the value of biomass over time via cascading” ([18], p. 6). Optimization of the value of biomass over time can focus on either economic, social or environmental aspects, but ideally, a consideration of all three of the pillars of sustainability [18]. The key elements of the circular bioeconomy include: sustainable biomass sourcing; circular and durable product design; use of residues and waste; integrated, multi-output production chains; bioenergy and biofuels; bio-based products, food, and feed; prolonged and shared use; energy recovery and composting; and recycling and cascading [18]. In Africa, public research for development (R4D) is an important driver of the bio-based economy responding to several challenges such as (i) improving agricultural productivity, (ii) reducing resource demands and environmental pressures, (iii) adjusting to climate change impacts, (iv) expanding bio-resource value addition opportunities and converting waste to useful products such as energy, and (v) revitalizing rural communities and improving rural livelihoods [19].

Over the past decade, the International Institute of Tropical Agriculture (IITA) has applied the circular bioeconomy approach in several agricultural R4D projects in SSA, with
the intent to design and pilot innovations that aim to address natural resource degradation, climate change, hunger, and poverty. IITA’s application of the circular bioeconomy concept has focused on efficient resource utilization involving nutrient recycling, sustainable biomass for bio-fuel production, value addition, minimization of the use of toxic chemicals (chemical fertilizers and pesticides), and postharvest losses through breeding improved varieties using gene editing. While IITA’s application of the circular bioeconomy concept has occurred in different SSA countries for over a decade now, empirical evidence is lacking on the contributions of the circular bioeconomy focused R4D in terms of benefiting the environment and economy and bringing about positive social benefits. This study’s objectives are to (i) assess the contributions of IITA’s circular bioeconomy focused innovations to economic, social, and environmental outcomes, (ii) identify the institutional factors that helped facilitate delivery of innovations, and (iii) identify gaps and opportunities to support the transition toward a sustainable circular bioeconomy in SSA.

The rest of the article is organized as follows. The Section 2 presents a brief background on circular bioeconomy, focusing on its linkage to circular economy and bioeconomy. Section 3 presents the methodology. Section 4 presents the results of the study under six subsections. The Section 5 provides a conclusion to the article and presents limitations of the study.

2. Brief Background on Circular Bioeconomy

The circular bioeconomy concept evolved from circular economy and bioeconomy. The circular economy aims to promote the maximum use of resources and reduce waste by closing economic and ecological loops of resource flows [20]. It eliminates waste by design and keeps the added value of a product for as long as possible [2]. The circular economy views waste as a resource in a production process, suggesting that there is less extraction of fresh materials and energy consumption. As such, the use of the circular economy approach contributes to arresting the trend of resource depletion and mitigating climate change and builds a foundation for resilient production-consumption systems that foster sustainable economic growth and improved social well-being.

The circular economy distinguishes between two types of nutrients, namely biological nutrients and technical nutrients [1,21]. The former can be safely returned to the environment, while the latter can be circulated in closed-loop industrial cycles. Given the challenge of keeping the value of biomass during cascading, biological nutrients have not received as much attention as technical nutrients in the circular economy [22]. Nonetheless, the principles of the circular economy—reduce (i.e., minimum use of raw materials), reuse (i.e., maximum reuse of products and components), and recycle (i.e., high-quality reuse of raw materials)—can be successfully applied to bioeconomy [23].

The bioeconomy represents the part of the economy that uses renewable biological resources to produce food, materials, and energy and aims to reduce GHG emissions by replacing fossil carbon from non-renewable resources [24]. The bioeconomy is defined as “the production of renewable biological resources and converting these resources and waste streams into value-added products, such as food, feed, bio-based products, and bioenergy” [25]. An important feature of the bioeconomy is extending biomass production and processing beyond food, feed, and fiber to include a range of value-added products with potential applications in many sectors, such as the food, health, and energy sectors [26]. The bioeconomy is not complete without the circular economy and vice versa, and they are also not entirely part of each other [15]. For example, many new developments in the bioeconomy, such as precision farming and gene editing, are not part and parcel of the circular economy’s framework. These present a strong economic, social, and environmental justification for bringing together aspects of the two concepts into a single framework called circular bioeconomy (see [27] for a more nuanced understanding of the concept).

The circular bioeconomy framework has been proposed recently. Hence, circular bioeconomy focused R4D is still in its infancy. Existing studies on circular bioeconomy mainly originate from governmental institutions. They are primarily concerned with
strategic agendas than with the identification of challenges and measures to implement a circular bioeconomy focused R4D [28]. SSA faces significant challenges in implementing bioeconomy R4D. These include weak economic, technical, and institutional conditions that restrain the production, postharvest, and processing sectors of the bioeconomy [14,17]. In a systematic review of bioeconomy R4D interventions from around the world, 26 successful case studies of sustainable bioeconomy interventions have been identified in different sectors [29]. Of the 26 cases, five (listed below) are from SSA, predominantly dealing with biomass production in the agriculture sector with linkages to the food and agro-industry sector:

1. Biochar production and use in Ghana
2. Biomassweb (interlinked value chains of specific biomass), sub-Saharan Africa (Ghana, Ethiopia and Nigeria)
3. Integral use of oil palm, Ghana
4. Seaweed value addition, United Republic of Tanzania
5. From Farmer to Pharma, South Africa

These case studies aimed to (i) safeguard food security, (ii) incentivize the sustainable and efficient use of biological resources while protecting biodiversity, water, and the soil, (iii) mitigate and adapt to the effects of climate change and reduce environmental pollution, (iv) increase profitability by adding value to biomass, (v) create and secure employment through in situ value addition and enhance rural and urban economic resilience, and (vi) substitute fossil-based or unsustainably-sourced products with sustainable bio-products. The bio-products produced in the above case studies included: biochar from crop residue (e.g., corn cobs); food, feed, and bioethanol from cassava; palm kernel oil, animal feed, organic fertilizer, briquettes, and biogas; food, soap, body cream, pharmaceuticals and cosmetics (e.g., using seaweed (algae)); and healthcare and biopharmaceutical products (e.g., using indigenous plants).

Similar to the above case studies, IITA’s circular bioeconomy focused interventions led to the production of animal feed, organic fertilizer, and biogas. However, unlike the above cases, IITA’s interventions also led to the development of Aflasafe, a bio-control product against aflatoxin, genetically modified (GM) crops, edible insects and insect-based animal feed, biochar, and bio-diesel. These products were developed using insects, fungi/bacteria, urban biowaste, and agro-processing waste (cassava peels), crop residues, and second-generation bio-fuel production from non-edible oil plants.

3. Materials and Methods

The study addresses three research questions (i) what are the contributions of IITA’s circular bioeconomy focused innovations to economic, social, and environmental outcomes in SSA countries, (ii) which institutional factors helped facilitate the development of these innovations and delivery of outcomes, and (iii) what are the gaps in the developed innovations that require attention when moving towards a circular bioeconomy? To address these research questions we applied qualitative research methods. To collect data, we followed a three-step procedure (Figure 1). First, we identified circular bioeconomy interventions from IITA’s archive of research projects through a computer search of key terms (e.g., circular, bioeconomy, biowaste, recycling). The search in the project archive was complemented by a web search using the same terminologies. We also refined the identified interventions by checking their relevance to circular bioeconomy based on specific indicators related to circular bioeconomy objectives (Table 1). In this step, a total of ten circular bioeconomy focused interventions were identified for the study. The interventions were designed to achieve system optimization using the circular efficiency approach, whereby upstream inputs are minimized, and downstream by-products are circulated via technological pathways [30].
Second, we consulted and scrutinized secondary data sources (e.g., scientific literature, IITA progress reports, annual reports, media reports, policy documents, and blogs) for citations of the interventions. In our review of this literature, we focused on research development and delivery, highlighting the research findings and how they inspired changes in policies and practices.

Third, using data from the literature, we applied the outcome tracking approach adapted from relevant sources [31,32]. Tracking outcomes provide early indications on whether interventions are on course to contribute to the long-term effects of circular bioeconomy—resource use efficiency. We applied both the forward tracking and backward tracking approaches to achieve objectives 1 (i.e., assess the contributions of IITA’s circular bioeconomy focused interventions) and 2 (i.e., identify institutional factors). With forward tracking, we started with a specific circular bioeconomy intervention. We followed it through the interface with the intervention’s output (innovation), users (e.g., farmers), and subsequent knowledge exchanges (e.g., with government extension personnel or non-governmental organizations, policymakers) to facilitate the dissemination of the innovation.

In addition, we identified and tracked the changes that have stemmed from applying an output of an intervention by ascertaining its use in practice. For example, we started with IITA’s intervention to develop a bio-control innovation (e.g., Aflasafe) and tracked the innovation through its incubation for commercialization, awareness creation about its aflatoxin reduction potential in maize and groundnuts, certification, and dissemination, and ended with its adoption by smallholder farmers in maize and groundnut farming systems in Nigeria and Kenya. This process allowed us to identify and track changes over time, from research to uptake. The forward approach contrasts with the more traditional way of carrying out monitoring and evaluation, which starts with activities and traces changes forward through output, outcome, and impact levels.

With the backward tracking approach, we started with the change in practice (e.g., adoption of Aflasafe) at the farmers’ or users’ level. We tracked this change back through the interface with researchers involved in developing and testing the output. In tracking back, we identified a range of key actors and institutional factors that facilitated the development of the circular bioeconomy innovations and delivery of outcomes. The backward tracking approach is similar to outcome harvesting in that both collect evidence of change and then work backwards to assess contributions to that change. Outcome harvesting is an alternative approach to the traditional monitoring and evaluation used to identify, describe, verify and analyze the changes brought about through a development intervention [33].

The advantage of using both the forward and backward tracking approaches is that they deal best with methodological challenges of attribution [32]. Within these approaches, we primarily relied on scrutinizing IITA’s progress reports, annual reports, scientific litera-
ture, policy documents, media reports, and blogs, and others for citation of IITA’s circular bioeconomy research.

To achieve objective 3 (i.e., identify gaps and opportunities), we applied a qualitative gap analysis following a three-step process. First, we framed the desired state of the selected interventions based on expected outcomes or performance objectives that the interventions were supposed to deliver in the first place (Table 1). Second, we assessed the current status of each intervention. Third, we identified gaps using specific indicators related to the five circular bioeconomy objectives (Table 1). After completing the gap analysis, we suggested a set of practical actions to bridge identified gaps and provided direction to facilitate a sustainable circular bioeconomy in SSA.

Table 1. Circular bioeconomy objectives and indicators applied in the identification of interventions.

| Circular Bioeconomy Objective                        | Indicator                                                                 |
|------------------------------------------------------|---------------------------------------------------------------------------|
| Ensuring food security                               | Production of new food products                                          |
|                                                      | Production of new livestock feed products                                |
|                                                      | Competition for land for food production                                 |
| Sustainable management of natural resources          | Production of organic and bio-fertilizer                                 |
|                                                      | Organic waste diverted from landfills                                    |
|                                                      | Land use change                                                          |
|                                                      | Environmental protection/reduction of negative environmental impact (provide alternatives to synthetic fertilizers, pesticides, and fossil fuels, and reduce water and soil pollution and GHG emissions) |
| Climate change mitigation and adaptation             | Carbon sequestration and reduction in GHG emissions                      |
| Reducing dependence on fossil resources             | Biofuel production and change in renewable energy consumption            |
|                                                      | Biowaste and residue recycling for nutrient recovery                     |
|                                                      | Provide alternatives to fossil fuels                                    |
| Creating jobs                                        | Number of persons employed                                               |

4. Results and Discussion

4.1. Circular Bioeconomy Interventions

Table 2 presents the ten interventions identified for analysis. The interventions were designed to address various problems, including rapid postharvest physiological deterioration (PPD), food insecurity, poor quality and unhygienic food, climate change, soil infertility, youth unemployment, and biowaste management. Results show that the identified interventions covered four circular bioeconomy areas—crop production (#1), food and agro-processing (#4), bioenergy (#8), and biowaste management sectors (#5 and #10). The interventions also covered one or more stages of the biomass value chain. For example, #5 covered two biomass chain stages, including second-generation biofuel production and bio-diesel processing. The interventions covered technical aspects of circular bioeconomy development (technological) and its enabling environment (institutional). The interventions focused on bio-product development and delivery, serving various purposes, including food, feed, and bioenergy production.

The interventions used different biological materials such as micro-organisms (fungi, bacteria), non-edible oil plants (jatropha), insects (termites, black soldier fly), biomass residue and waste from fruit and vegetable markets, and by-products of agro-processing (e.g., cassava peels). The interventions aimed to manage soil fertility, ensure food is safe from toxic fungi, reduce high carbon footprint using second-generation biofuel production, decrease food insecurity, and mitigate climate change using edible insects and insect-based feed.
Table 2. IITA’s circular bioeconomy interventions.

| Intervention                                                                 | Source of Material                        | Country                      | Problem to be Addressed          | Approach          |
|-----------------------------------------------------------------------------|-------------------------------------------|------------------------------|----------------------------------|-------------------|
| Variety development for tolerance to postharvest physiological deterioration | Crop (e.g., cassava)                     | Nigeria                      | Physiological deterioration       | Bio-technology    |
| Bio-fertilizer development for soil fertility management through nitrogen-fixation | Bacteria (e.g., rhizobium)               | Nigeria                      | Soil not having enough rhizobia   | Bio-technology    |
| Bio-control development for management of aflatoxin in food crops           | Fungi (e.g., atoxigenic types of A flavus) | Nigeria                      | Food safety                      | Bio-technology    |
| Second-generation biofuel development                                       | Oil plants (e.g., jatropha)              | Benin; Mali                  | High carbon footprint             | Bio-resource      |
| Safe and nutritious food product development                                | Edible insects (e.g., termites); edible mushroom | Benin; Democratic Republic of Congo (DRC) | Food insecurity; climate change | Bio-ecological    |
| Safe and nutritious animal feed product development                         | Insects (e.g., black soldier fly fed on fruit/vegetable market waste) | Benin; Rwanda               | High cost of fishmeal and soymeal; climate change | Bio-ecological    |
| Animal feed development                                                     | Agro-processing waste (e.g., cassava peels) | Nigeria; Rwanda              | Pollution; climate change         | Bio-ecological    |
| Biochar development for carbon sequestration                                | Biomass residue                          | Kenya                        | Low soil quality; climate change  | Bio-ecological    |
| Organic fertilizer development                                             | Urban biowaste                           | DRC; Ethiopia; Rwanda; South Africa | Urban waste management; external inputs use | Bio-ecological    |
| Biogas production                                                           | Organic waste                            | Nigeria                      | Organic waste management; external inputs use; deforestation; climate change | Bio-ecological    |

The interventions are clustered under three major categories—bioecology, bio-technology, and bio-resource. Most of these interventions were designed using a bio-ecological approach (#5–9) that promotes low carbon footprint, low input, and low energy use. They aimed at nutrient recovery through bioconversion of organic wastes into animal feed, organic fertilizer, and carbon sequestration (e.g., biochar). A few interventions were based on bio-technological and microbiological processes (#1–3). The bio-technology approach aims to optimize resource yields by applying genetic techniques to major food crops such as cassava. The bio-resource approach offers substitutes for non-renewable and non-biodegradable materials with renewable solutions (#4). The interventions were implemented in different African countries, for instance, Benin Democratic Republic of Congo, Ethiopia, Kenya, Nigeria, Rwanda, and Tanzania. However, the outputs of the interventions were deployed in several other African countries. The development of the interventions and deployment of the innovations were financially supported by different...
development donors, including the German Corporation for International Cooperation (GIZ), the Swiss Agency for Development and Cooperation (SDC), the United States Agency for International Development (USAID), the University of Liverpool in the UK (UoL-UK), and the Bill & Melinda Gates Foundation (BMGF).

### 4.2. Outputs of the Interventions

Table 3 presents outputs of the interventions implemented by IITA and its international and local partners. In the context of our study, outputs are technological innovations, including new bio-based products (e.g., genetically modified cassava, bio-fertilizer, Aflasafe, biodiesel) and valorizing crop residue and biowaste streams (high-quality cassava peels (HQCP), organic fertilizer, biogas and biochar).

| Intervention | Output |
|--------------|--------|
| (1) Variety development for tolerance to postharvest physiological deterioration | Genetically modified cassava |
| (2) Bio-fertilizer development for soil fertility management through nitrogen fixation | Soybean inoculant (Nodumax) |
| (3) Bio-control development for control of aflatoxin in maize and groundnuts | Aflasafe |
| (4) Second-generation biofuel development | Biodiesel |
| (5) Safe and nutritious food product development | Edible insects (e.g., termites); edible mushroom |
| (6) Safe and nutritious animal feed product development | Insect-based feed (black soldier fly larvae) |
| (7) Animal feed development | High-quality cassava peels |
| (8) Biochar development for carbon sequestration | Biochar |
| (9) Organic fertilizer development through urban-rural nexus (targeting sites of nutrient concentration) | Organic fertilizer |
| (10) Biogas production | Biogas (methane) and bio-fertilizer |

GM cassava: IITA partnered with the Swiss Federal Institute of Technology (ETH-Zurich) to address PPD in cassava by developing cassava varieties with longer storage quality [34]. Cassava is vulnerable to PPD within two days after harvesting, leading to a substantial output loss in solid matter and starch quality. PPD is a significant constraint to cassava production and utilization [35]. The current practice of mitigating the PPD is to prune shoots without uprooting. However, this practice results in degradation of stored starch, leading to lower yield and quality.

Bio-fertilizer (NoduMax): NoduMax, a soybean inoculant developed with rhizobium as an active ingredient, adds beneficial bacteria to soils that lack such bacteria, thus enhancing the ability of soybean to fix nitrogen from the atmosphere. The inoculant produced
by the business innovation platform (BIP) at IITA headquarters in Nigeria can increase soybean yields by 25% and facilitate biological nitrogen fixation to the equivalent of 100 kg of nitrogen fertilizer per hectare [36].

Aflasafe: IITA, in collaboration with the United States Department of Agriculture (USDA) Agricultural Research Service (ARS), developed Aflasafe, an all-natural product, to reduce aflatoxin contamination in maize and groundnuts. Aflatoxin is a significant food safety issue. Consumption of contaminated products can lead to sickness and death. Aflatoxin contamination also negatively impacts farm income due to grain quality deterioration, and implies the loss of all resources that went into producing the agricultural commodities.

Bio-diesel: IITA, in collaboration with the Center for Information, Research & Action for the Promotion of Farmers Initiatives (CIRAPIP), is developing a jatropha-based biofuel in Benin and Mali. The preliminary investigation provided promising results that showed the feasibility of using jatropha oil as a substitute for diesel fossil fuel in Benin’s and Mali’s socio-economic and agroecological context. The by-product of biodiesel production is also used as a substitute for inorganic fertilizer.

Edible insects: IITA, in partnership with the UoL-UK, is developing insects for human consumption to replace or reduce consumption of farmed animals in Benin by examining the nutritional value and safety of edible insects like termites. Insects are known to be part of the human diet in many parts of the world [37]. For example, caterpillars, termites, crickets, and palm weevils are among the most commonly consumed insects in Africa [38]. Edible insects can replace or reduce the need to consume farmed animals, thus contributing to reductions in carbon footprint. Livestock production is a significant source of GHG emissions, especially beef cattle [39].

Insect-based feed: IITA, in collaboration with the International Center of Insect Physiology and Ecology (ICIPE), is developing chicken feed using black soldier fly (BSF) larvae reared and fed on different substrates as an alternative to using animal or plant-based protein sources such as small pelagic fish and soybean, respectively. Insect-based feeds can replace or reduce the need for large acres of land to produce the required amounts of soybean or other crops for incorporation into feeds [40].

Organic fertilizer: IITA, in collaboration with ETH Zurich, is developing organic fertilizer through urban-rural nutrient recycling efforts, targeting urban centers (the sites of nutrient concentration) in Rwanda, the Democratic Republic of Congo (DRC), Ethiopia, and South Africa. The organic fertilizer is being developed to replace or reduce the use of chemical fertilizers that are energy-intensive to produce as their production requires a large amount of natural gas. In essence, IITA and its partner collect accumulated organic waste generated by urban households from their consumption of food produced in rural areas. These wastes are transported to and subsequently composted in rural dumpsites, thus producing organic fertilizer that is then sold to farmers at affordable prices for use in their farm production.

Biochar: IITA, in partnership with the Swedish University of Agricultural Sciences (SLU), is developing biochar to sequester carbon using different feedstock and to enhance soil quality in Kenya. A World Bank study indicates that biochar can be used as a tool to fight climate change while also improving soil fertility [41].

HQCP: Given the successful development and dissemination of improved cassava technologies and some policy support in the past several years, there is a growing interest in taking up cassava root production in SSA. Associated with this growth is a substantial agro-processing waste generation, with significant implications for environmental pollution. IITA was involved in a multi-center CGIAR research effort, led by the International Livestock Research Institute (ILRI), to produce animal feed using cassava processing waste. The innovation has currently been scaled from Nigeria to Rwanda. When farmers sell fresh cassava to processors in peri-urban centers, cassava is sold unpeeled. Upon peeling cassava during processing, a significant amount of waste is generated in the form of cassava peels.
Using hydraulic press machines, chopped peels are pressed to eliminate cyanide water, forming a solid matter that is used as an ingredient in livestock and poultry feeds.

Biogas: IITA is developing biogas using anaerobic digestion applied to various organic wastes in Nigeria. Anaerobic digestion is an efficient alternative technology that combines biofuel production with sustainable waste management [42]. The process also leads to the production of a bio-fertilizer, thus reducing the reliance on chemical fertilizers for increased crop productivity.

4.3. Outcomes

Figure 2 presents the outcomes that resulted from the outputs developed by the IITA’s circular bioeconomy interventions. Outcomes are defined as the expected or achieved short- and medium-term effects of the outputs produced by the circular bioeconomy interventions. The outcomes are increased crop productivity, food security, job creation, natural resource efficiency, and reduced GHG emissions. These outcomes show how the agriculture sectors in the project focal countries can transition to a circular bioeconomy for increased food production, livelihoods and a better environment. The bio-based products (bio-fertilizer, Aflasafe, biodiesel, biogas, biochar) are alternatives to chemical fertilizers, pesticides and fossil fuels, and thus contribute to reducing water and soil pollution and GHG emissions.

**Figure 2.** Outputs and outcomes of the circular bioeconomy interventions.

Increased crop productivity: Crop productivity is a short-term outcome linked to three outputs (biochar, organic fertilizer, and bio-fertilizer (NoduMax)). Crop productivity is achieved through soil fertility improvement. For example, NoduMax increases soybean productivity by 25% [36].

Food security and food safety: Food security is linked to three outputs (GM cassava, edible insects (termites) and mushrooms). Improved food safety results from the use of Aflasafe. Aflasafe reduces aflatoxin contamination in maize by 80–100% [36]).

Natural resource efficiency: Resource efficiency (i.e., producing the same with less land) is a medium-term outcome linked to four outputs (edible insects (termites) and mushroom, GM cassava and insect-based feed (BSF larvae)). Resource efficiency with GM cassava is achieved by reducing food loss and hence less land, water and fertilizers are needed. It is also achieved because of minimal land requirements for producing edible insects, mushrooms, and insect-based feed. Using insects for human food and in animal feeds results in savings on arable land brought under cultivation for feed production (soybean, maize), the use of marine resources like small pelagic fish in animal feeds, and savings on...
production costs [40]. For example, production of mealworms as a protein source requires less land and feed and produces lower amounts of GHGs than the production of traditional animal protein sources. Therefore, it can be deduced that rearing insects as a source of animal protein is more sustainable than traditional livestock meat production [43]. While the nutritional value of insect ‘meat’ is comparable to that of meat from traditional livestock [43], it is important to consider socio-cultural factors to change consumers’ mindsets as consumption of edible insects may not be perceived as comparable to consuming meat. Promoting edible insects as pleasurable, rather than healthy or environmentally friendly, could be the most effective marketing strategy for these currently taboo or unappealing foods in certain contexts [44]. Promoting insects as tasty or even as a luxury food or exotic delicacy could begin to change attitudes and achieve more sustainable food production and healthier diets.

Job creation: Job creation is linked to four outputs Aflasafe, animal feed (HQCP), edible mushroom, and organic fertilizer. The pathway for the job creation outcome is the establishment of Aflasafe manufacturing facilities, distribution and commercialization, agro-processing and urban biowaste processing plants in several African countries, and bio-enterprise development (e.g., mushroom farming in DRC).

Reduction in GHG emissions: Reduction in GHG emissions is linked to seven outputs (biochar, bio-diesel, biogas (methane), insect-based feed (e.g., BSF-larvae), edible insects (termites), animal feed (HQCP), and organic fertilizer (urban-rural nexus)). The pathway for the reduction in GHG emissions is by replacement of fossil-based energy (diesel fuel—refined from crude oil at petroleum refineries) and through minimizing the dependence on external inputs like chemical fertilizers, reducing the cultivation of new lands, minimizing livestock consumption, increasing the valorization of wastes from processing plants and increasing carbon sequestration.

4.4. Institutional Factors

Many institutional factors facilitated the development, delivery, and commercialization of technological innovations and their transformation into outcomes. These factors included the BIP for incubation of research outputs for commercialization, the biotech partnership with ETH Zurich for the development of GM cassava, IITA Youth Agripreneurs (IYA) for scaling-out of agribusiness skills, and policy engagement on regulatory approval standards, certification, and licensing for Aflasafe, bio-fertilizer and research permits for the implementation of confined trials on GM cassava.

BIP: The BIP at IITA’s headquarters in Ibadan, Nigeria, accelerates commercialization of the institute’s proven and profitable technological innovations. The BIP played an active role in commercializing two major products developed by IITA and its partners (Nodumax and Aflasafe) and ensuring their delivery to smallholder farmers, as well as small and medium enterprises (SMEs). The BIP also participated in capacity development of youth agripreneurs and built a network of public and private-sector partners, and provided SMEs with technical support.

IYA working in bio-enterprises: IITA has built human capacity by providing agribusiness development skills to young college graduates under IYA. The program has enabled these graduates to develop profitable agribusinesses of their own choice. For example, IYA in Kinshasa, DRC, run an edible mushroom farming business, while IYA in Dar es Salaam, Tanzania, run a cassava processing business making baking flour and bakery products.

Biotech partnership: IITA has collaborated with advanced bioscience research institutes worldwide, contributing directly to the development of advanced technologies such as GM crops. For instance, IITA, in collaboration with ETH Zurich, has set up an effective genetic transformation platform for developing farmer-preferred cassava varieties that are tolerant to PPD [34,45]. IITA also collaborated with the University of Arizona and USDA ARS in developing Aflasafe.

Policy environment: One of the challenges that constrains the application of the outputs is the lack of an enabling policy environment and incentives. For instance, although
IITA was recently given a permit to carry out confined field trials on GM cassava in Nigeria, GM crop production by farmers is not yet approved in cassava producing countries in Africa.

4.5. Identified Gaps in the Circular Bioeconomy Innovations

4.5.1. Gaps That Apply to Specific Circular Bioeconomy Innovations

Table 4 presents the gaps in the outputs (innovations) developed by the circular bioeconomy interventions. The gaps are characterized by a lack of an enabling regulatory framework, technological innovations and evaluations. These gaps were identified by assessing the current state of innovations relative to their desired state when conceptualized. For example, concerning the GM cassava, the current state is that IITA has received a permit to undertake confined field trials in Nigeria [34,45]. The intervention's desired state is an approved GM cassava variety that tolerates PPD and maintains its starch quality. Therefore, the gap is a missing enabling environment as governments in cassava producing countries in SSA lack regulatory guidelines for GM crops. This gap suggests that it is essential to keep engaging policymakers on regulatory approval of GM cassava use.

Table 4. Gaps in IITA’s circular bioeconomy innovations.

| Circular Bioeconomy Innovation | Current State                                                                 | Desired State                  | Gap                                                                 |
|--------------------------------|-------------------------------------------------------------------------------|--------------------------------|----------------------------------------------------------------------|
| Genetically modified (GM) cassava | Confined field trial of cassava for tolerance to postharvest physiological deterioration in Nigeria | Approved GM cassava varieties | Regulatory guidelines are missing                                      |
| Nodumax (soybean inoculant)     | Incubated for commercialization and received regulatory approval in Nigeria   | Impact at scale                | Economic viability at a commercial scale and environmental performance |
| Aflasafe                        | Certified and licensed                                                        | Impact at scale                | Economic viability at a commercial scale and environmental performance |
| Biodiesel                       | Bio-enterprise development                                                   | Commercialization              | Economic viability at a commercial scale and environmental performance |
| Edible insects (e.g., termites) | Bio-enterprise development                                                   | Commercialization              | Social acceptance                                                    |
| Edible mushroom                 | Bio-enterprise development                                                   | Commercialization              | Social acceptance                                                    |
| Insect-based feed (black soldier fly larvae) | Technically feasible                                                       | Commercialization              | Economic viability at a commercial scale and environmental performance; optimality of choices between competing uses (feed vs. de-fattened feed, biodiesel) |
| High-quality cassava peels      | Commercialized                                                               | Impact at scale                | Optimality of pathways for nutrient recovery                          |
| Biochar                         | Explored                                                                    | Adoption by smallholders       | Environmental performance                                             |
| Organic fertilizer              | Explored                                                                    | Adoption by smallholders       | Economic viability at a commercial scale and environmental performance |
| Biogas                          | Preliminarily investigated                                                   | Commercialization              | Economic viability at a commercial scale and environmental performance |
The missing evaluations pertain to economic viability, social acceptance and environmental performance of technical innovations, optimality of pathways for nutrient recovery, and competing uses of products and co-products at a commercial scale. This finding is consistent with a study which suggested that environmental and social impacts of bioeconomy are often foreseen but not measured [46]. The missing technologies are related to entomophagy (e.g., limited use of insects as food and for feed) and lack of functional value chains for secondary bio-products.

The economic viability of technical innovations at a commercial scale: The bio-fertilizer and bio-control products developed by IITA are currently certified and licensed. The jatropha-based biodiesel, edible insects (termites), and insect-based animal feed are under development. The desired states are widespread commercialization and adoption of products to bring about impact at scale. The lack of economic, social, and environmental evaluations at different levels of commercialization as a follow up to the technical feasibility study impedes businesses’ abilities to make investment decisions in new bio-based SMEs. It is thus essential to evaluate the economic, social, and environmental sustainability of the circular bioeconomy interventions and the innovations they develop using appropriate tools (e.g., see [47] for the assessment tool to integrate sustainability principles into global supply chains.

Optimality of pathways for nutrient recovery: The HQCP from cassava-processing proved useful in recovering biological nutrients extracted from cassava farms through closed-loop agriculture and contributing to the broader economy. Closed-loop agriculture recovers nutrients by recycling them back into agriculture. Farmers supply fresh cassava roots to cassava processors to produce high-quality cassava flour (HQCF). The cassava producers or other farmers in the region purchase the HQCP as feed for their livestock. The nutrients utilized by livestock are returned to the farm in the form of manure for use by and benefit of crop producers. However, since part of the HQCP is exported out of the cassava producing region, these would be lost nutrients. From the perspective of closed-loop agriculture, nutrients can be considered lost since they are not recycled back to the producing region where they originated. However, the export revenue from converting the waste (cassava peels) into a resource (animal feed) contributes to the broader bioeconomy. While both pathways are practical options, a knowledge gap exists about the optimal pathway that provides the most value creation out of cassava processing waste, considering economic, social, and environmental parameters.

Optimality of choices between competing uses: Currently, the research on non-edible insects has focused mostly on the technical feasibility of using BSF larvae for chicken feed. BSF larvae can give rise to different product forms (Figure 3). It can be dried for direct sale as chicken feed or first defatted. The de-fatted, dried BSF larvae can be sold as an ingredient for compounding chicken feed while also making money from the sale of larvae oil. Similarly, the substrate waste residue can be subject to aerobic digestion and composted to produce quality organic fertilizer or processed anaerobically to produce biogas. Given that all these possibilities lead to different value creation, a knowledge gap exists on the economic and environmental optimality of their use that provides the most value creation from organic waste processing using BSF larvae, thus creating uncertainty to establishing bio-based SMEs.

Limited focus on the diversity of biowaste feedstocks and composition: The current focus of IITA’s collaborative research on the recycling of biowastes is limited to a few common waste types, such as vegetable or fruit market waste and manure. Given that different contexts (e.g., urban versus rural) generate different types of biowastes, the technical feasibility of using a certain biowaste in one context may not necessarily apply in other contexts. Research on value pathways for organic wastes has been steadily increasing in recent decades [48]. There have been few broad overview studies of such materials and their valuation potential in the bio-based economy in part because of the multitude of materials and processes that can be used to produce bioenergy carriers (e.g., biogas, biodiesel), chemicals, and materials of value [49].
Similarly, the research on the uses of insects as food and animal feed inputs is currently focusing on a few insects like termites (food) and BSF larvae (for feed) in a few countries in SSA. Entomophagy research shows that caterpillars, termites, crickets, and palm weevils are among the most commonly consumed insects in the region [38]. Edible insects can help substitute part of the demand for expensive livestock products and mitigate GHG emissions as livestock production is a significant source of GHG emissions [39]. Related research on non-edible insects used in animal feeds shows that common housefly larvae, silkworms, and yellow mealworms are essential sources of protein and fat contents [50]. Insect production creates less GHGs and emits less ammonia (NH3), suggesting that insects could serve as a more environmentally sustainable source of animal protein compared to farmed animals [51].

4.5.2. Gaps That Apply across All Circular Bioeconomy Innovations

Environmental performance of the innovations: Under IITA’s research framework, the environmental performance of technologies is rarely assessed before their delivery. For example, performance of crop varieties (e.g., nutrient and water-efficient crop varieties) under optimal use of chemical fertilizers and pesticides are assessed using a technical indicator (e.g., yield as measured by the output of the edible parts per unit area) and an economic indicator (e.g., crop income from the sale of the edible part). The environmental impact of crop varieties and crop residues (e.g., the calculation of their carbon footprints) is barely considered, making it difficult to evaluate the eco-efficiency performance of the crop production process. Experience in several countries shows that crop residues can play an important role in climate change mitigation in the coming decades, as an energy source with significant potential to substitute fossil fuels and contribute to the reduction of GHG emissions [52,53]. However, one of the most acknowledged limitations to large-scale crop residue exploitation is its likely impact on long-term soil functioning, productivity and associated ecosystem services due to reduction of the soil organic carbon pool [54,55]. The same holds true with the use of external inputs. In SSA, although not as intensive as the case in high-income regions, the use of external inputs in agriculture is increasing, including the use of synthetic nitrogen and phosphorus fertilizers, agrochemicals, and fossil fuels [24]. While the intensive use of these inputs has resulted in increased agricultural productivity, experiences from the green revolution in Asia have shown that such practice can result in adverse soil health conditions expressed by the deficiency of certain micronutrients (e.g., zinc, copper, and iron), the emergence of new pests, and increased resistance of the existing pests to pesticides [56]. These conditions will make it increasingly difficult for farmers to sustain high yields. To ensure greater sustainability, environmental performance of technologies should be considered.
Limited focus on phytomass: Under the existing research framework, IITA biotechnologists primarily focus on improving crop yield and quality, such as the dry weight or nutrient content. Except for leguminous crops such as cowpea and soybean, crop residues are not factored in the development of new varieties, although they produce most of the phytomass (the above-ground plant biomass). More than half of all dry matter in the global harvest is in crop residue [57]. The lack of this consideration to incorporate novelty in crop residues hampers their suitability to optimal circular use. A research conducted in Ethiopia demonstrated that increasing the quantity of maize biomass has a positive direct and indirect effect on farm household food security because the extra biomass is used as animal feed, an alternative source of fuelwood, and used as a material when constructing houses and storage structures [58].

Absence of cascaded uses before energy use: Circular bioeconomy’s contribution to agriculture depends on the cascading use of crop residues, which implies the efficient use of these resources by prioritizing other uses over that of energy [29]. Crop residues are important sources of fiber, fuel, and plant nutrients, presenting greater opportunities even when compared with the largest commercial sources of these commodities—wood pulp, fossil fuels, and synthetic fertilizers [57]. However, they are usually not put to cascaded uses because of the critical shortage of electricity in rural Africa, making it difficult for farmers to make use of crop residues as material before energy use (e.g., household firewood). The once-through use of crop residues to energy production, which is the least preferred option, limits farmers’ abilities to benefit from their use as livestock feed or soil fertility management (e.g., cowpea). A circular bioeconomy encourages the cascading use of biomass, where energy uses come in the last phase [15]. Yet, cascading seems to be underrepresented in the circular bioeconomy literature [18]. Due attention should be given in prioritizing the use of crop residues, particularly, of legume crops such as soybean and cowpea for soil fertility management or cattle feed.

Limited focus on secondary production: IITA’s R4D is currently applied to the agricultural sector, mostly to produce food, feed, and organic fertilizer. There is limited application to agro-industrial and value-added products with potential applications in the industrial, chemical, and energy sectors. The exceptions are the utilization of cassava starch, ethanol, glucose, and jatropha-based biodiesel initiatives. IITA and its partners’ research on cassava led to developing suitable varieties to produce HQCF and high-quality cassava starch (HQCS). The application of cassava in biorefinery is insignificant in SSA. A research conducted in Asia showed that the fermentation profile of cassava starch, in terms of ethanol production and formation of glycerol, was similar to that of dent corn and waxy corn starch, which suggests the potential of cassava starch use for commercial production of bioethanol in SSA [59].

4.6. Actions

Drawing on both identified achievements and gaps, we propose some actions that could prove useful to strengthen the contribution of circular bioeconomy focused interventions for sustainable resource use in Africa.

Undertaking economic, social, and environmental analysis at a commercial scale: IITA’s current evaluation framework is limited to technical evaluations. Research outputs should be rigorously evaluated not only for their technical feasibility but also for their economic performance at a commercial scale and to determine if they are socially and environmentally sustainable. The evaluation framework should also address the optimality of pathways and utilization options to make a persuasive business case for the private and public sectors to take up these innovations. A study led by ICPE has provided evidence on the technical and economic feasibility of the use of insect meal in poultry feed in Kenya [60]. The BSF larvae reared in biowaste can be used as poultry feed and the bio-fertilizer for vegetable production. The study showed that replacing soybean meal or fishmeal in poultry feed with BSF larvae meal reduced the cost of feed and improved the cost-benefit ratio by 16% and the return on investment by 25%. Replacing the conventional feed sources
(fishmeal, maize and soybean meal) by 5 to 50% with BSF larval meal in the commercial poultry sector can generate additional income of US$16 to 159 million in Kenya per year.

Considering value web development for products and co-products that originate from the same biomass. The current value creation in circular bioeconomy has focused on value chain development by independent firms based on a single product. However, using a given resource for multiple outputs, including food, animal feed, and bioenergy, leads to competition for the same biomass. It is thus essential to create a value web for the whole set of products to promote the cascading use of biomass instead of a value chain for each product and by-product. Value web is a useful scientific approach for investigating biomass-related activities given its current and forthcoming challenges [17]. Value web coordinates value chains, creating synergies, and capturing potential uses of the same resource to produce different products and producing the same product from different types of resources [29].

Rethinking genetic improvement and agronomy research: IITA’s current plant breeding program primarily focuses on improving the main products of crops (e.g., the grains, tubers, fruits). Yet, bioeconomy requires efficient utilization of not only the main products but also every part of the biomass generated from agricultural production [29]. The transition towards a circular system implies rethinking the focus of the current traditional R4D [30]. The shift to a circular bioeconomy requires more efficient utilization of the biomass generated from agricultural production. This can be achieved through rethinking research, which offers the potential of creating additional value from biomass by developing novel products [61]. The shift to a circular bioeconomy also requires that management practices be optimal for circular use. Circularity entails diversification of cropping systems, multi-purpose crops, agroforestry, and sequencing of crop rotations. Further, while not directly contributing to circularization, precision agriculture, and gene editing should be part of the circular bioeconomy strategy [15].

Moving beyond primary crop production: IITA and its partners’ research on cassava led to the development of suitable varieties for HQCF, HQCS, and HQCP. This progress should set the stage for further value addition in the industrial sectors.

Sustaining policy engagement: Given that bio-products (e.g., BSF larvae as animal feed or termites as food) are unfamiliar to many urban-based consumers, they face market uncertainties and unreliable supply chains, making it difficult for interested bio-enterprises to flourish. For example, GM crops that may offer a solution to postharvest loss, drought, disease and pest challenges have yet to receive broad policy support in many African countries. Thus far, there have been a few cases of success on the regulatory approval of bio-products. These include approval of the use of Aflasafe in the Gambia, Kenya, Malawi, Mali, Mozambique, Niger, Nigeria, Senegal, Tanzania and Zambia; bio-fertilizer (NoduMax) in Nigeria; dry BSF larvae for compounding chicken feed in Kenya and Uganda; and a permit for confined field trials on GM cassava in Nigeria. Therefore, sustained policy engagement is essential to obtain comprehensive regulatory approval. Lack of enabling policy environment, costs, and the small size of bio-based markets are key challenges impeding the implementation of circular bioeconomy [18].

5. Conclusions

Many scientists question the tenability of the current linear economy model, suggesting the need for a paradigm shift. As an alternative to this inefficient and environmentally unsustainable model, they envision the use of circular economy and bioeconomy approaches to arrest the increasing trend of raw material consumption and delink economic growth from raw material consumption.

Combining the principles of circular economy and knowledge-based processes of bioeconomy in agriculture, IITA has applied circular bioeconomy as an approach to provide solutions that contribute to addressing land degradation, low agricultural productivity, food insecurity, GHG emissions, hunger, and poverty in SSA. Over the past decade, IITA has implemented ten circular bioeconomy interventions in the agricultural sector, focusing
on product development, biowaste valorization, biofuel production, carbon sequestration, nitrogen fixation, and genetic engineering.

Applying an outcome tracking approach to data that came from secondary sources, we showed that circular bioeconomy interventions led to ten outputs that translated into five economic, social, and environmental outcomes, including crop productivity, food security, resource use efficiency, job creation, and reduction in GHG emissions. We also identified institutional factors that facilitated the development of outputs and delivery of outcomes. Furthermore, we identified gaps in the outputs and proposed a portfolio of actions needed to harness the full circular potential of biological resources and enhance the role of circular bioeconomy in SSA. While this article is based on IITA’s experience in SSA implementing circular bioeconomy interventions, the results prove useful as a foundation to develop a framework to guide circular bioeconomy R4D work at IITA and other institutions working in SSA. Such a framework would ensure that all three pillars of sustainability are considered when institutions design their strategies and plan to integrate circular bioeconomy approaches in their overall research strategies. Moreover, it will be critical in the medium term to showcase the utility of integrating a circular bioeconomy approach in R4D work, especially how using such an approach leads to more significant economic, social, and environmental outcomes. Generating a body of evidence on what works, including institutional factors that create enabling environments for circular bioeconomy approaches to thrive, is necessary for governments and donors to continue supporting circular bioeconomy research to solve some of the most pressing challenges as populations continue to grow, generate waste and exacerbate a changing climate using a linear economy model.

Our study’s contributions are limited to examining cases of circular bioeconomy interventions that aimed to produce food, feed, fuel, and fertilizers at a small scale. Further research is needed to examine their feasibility at commercial scales. Research is also needed to explore the technical feasibility of producing high-value products (e.g., bio-based chemicals and polymers) that can be used as building blocks for further processing into bio-based products in the manufacturing industry. The technical and commercial feasibilities of high-value products (e.g., herbicides, biopesticides, food additives, detergent, and cosmetics) are demonstrated in different African countries [29]. Applying multiple methods on a collection of abstracts from over 53 thousand academic articles covering technologies, applications, and products for bio-based wastes, a study identified many value path potentials for secondary organic resources beyond energy and fertilizers [49].

Furthermore, our study relied on cases of circular bioeconomy interventions that focused on independent value chains rather than value webs. In other words, there are no links within and between the considered cases of value chains based on the principle of cascading use and joint use of biomass. Future research should determine how a biomass value web can be created to achieve system optimization in line with the experience of the BiomassWeb project implemented in Ethiopia, Ghana, and Nigeria [29].

Finally, this study used a qualitative analytical framework to determine the economic, environmental, and social outcomes that the circular bioeconomy interventions achieved. It is not easy to justify the scaling of circular bioeconomy innovations that are promising based solely on qualitative analysis. Future research is needed to produce a body of quantitative evidence to adequately convince policymakers to support the development of sustainable bioeconomies.

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