BIO4AFRICA

Diversifying revenue in rural Africa through circular, sustainable and replicable biobased solutions and business models

Research and Innovation Action (RIA)
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D4.2: Report on cross-case comparisons of findings and evaluation of diversification potential - initial version

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MAIN AUTHORS	
Name	**Organisation**
Tracey O'Connor, Aleksandra Augustyniak, Helena McMahon, James Gaffey	MTU

QUALITY REVIEWERS	
Name	**Organisation**
Jean-Michel Commandre	CIRAD

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1. Executive Summary

This document details an initial comparison of product trial cases, and associated income diversification potential in four African countries, **Uganda, Ghana, Côte d'Ivoire, and Senegal.** The product trials described are being undertaken as part of the European Union Horizon 2020-funded **BIO4AFRICA** project. The document describes the trials that are being undertaken in single countries with products produced by different technologies, and those that are being implemented in multiple countries using the same technologies. This report also examines income diversification potential for rural households in areas in which small-scale bio-based technologies and their products are being implemented.

Three main categories of product are being piloted through a total of 22 different pilot trials: **animal feed** and **whey** from **green biorefinery** technology, **biochar** products from **carbonisation** technology, i.e. **slow pyrolysis** and **hydrothermal carbonisation (HTC)**, and **pellets** and **briquettes** from **densification** technologies. In addition to the work carried out to date on **WP4 - Evaluation and validation of products, solutions and integrated value chains**, this deliverable builds on the knowledge generated through other BIO4AFRICA project activities, namely:

- **WP1 - needs analysis, technology screening and knowledge integration with rural African communities,**
- **WP2 - development and adaptation of robust small-scale bio-based solutions,**
- **WP3 - technology transfer and testing in real life conditions across rural Africa,**
- **WP5 - development and assessment of circular, replicable and sustainable business models.**

Section 2 of this report introduces the BIO4AFRICA project, the small-scale bio-based technologies that are being deployed through this project, and the trials of the technology products in Uganda, Ghana, Côte d'Ivoire, and Senegal. **Section 3** describes the methodology for cross-case comparison of pilot trials and income diversification potential that is used in this report and will be used in **D4.5 - Report on cross-case comparisons of findings and evaluation of diversification potential -final version (M44)**. **Section 4** of this report compares trial designs of pilot trials suitable for within country comparison and between country comparison. Overall, nine trials are suitable for within country comparison, while 12 trials are suitable for between country comparison. **Section 5** evaluates the potential for income diversification from the products based on review of the relevant literature, including completed BIO4AFRICA deliverables, and interviews with project partners involved in technology adaptation, transfer and implementation.

Section 6 describes the next steps for cross-case comparison based on trial results, and deeper exploration of income diversification potential based on stakeholder interviews, to be reported on in **D4.5**. Final comparison of pilot trial cases in and between countries will be reported on in **D4.5**, while interim trial results of all pilot trials will be available in **D4.3 – Report on BIO4AFRICA trials and validation results- interim version (M34)**.

2. Introduction

This document describes a cross-case comparison of pilot trials and initial evaluation of income diversification potential of the four pilot cases of the BIO4AFRICA[1] project, in Uganda, Ghana, Côte d'Ivoire, Senegal and Kenya. The BIO4AFRICA project has the primary aim of supporting local bioeconomy development in rural African regions. The project, comprising Partners form five African countries (Uganda, Ghana, Côte d'Ivoire, Senegal, and Kenya) and six European countries (Denmark, France, Greece, Ireland, the Netherlands, and Spain), was initiated in June 2021 (**M1**), and has a duration of 48 months, finishing in May 2025 (**M48**).

2.1 BIO4AFRICA Project Strategy

BIO4AFRICA aims to support the bioeconomy in rural African regions through the development of circular, bio-based solutions and value chains to promote the cascading use of local resources and income diversification for rural households. In order to achieve this, the project will support the implementation of small-scale, robust bio-based technologies with high replication potential and adapted to local needs, socio-economic and agri-environmental conditions, and biomass types. The technologies involved have been co-defined by the BIO4AFRICA partners (**WP1**) and adapted for local conditions, biomass types, and integrated in viable combinations (**WP2**), to support development of novel, bio-based business models (**D5.2: Inclusive and sustainable bio-based business models for rural Africa**). Three technologies in particular will be combined and transferred: small-scale green biorefineries, carbonisation, including hydrothermal carbonization (HTC), and densification technologies, e.g. briquetting and pelletizing. Bio-composite and bioplastic production will also be evaluated at laboratory-scale, while screening of bio-based products for further value addition opportunities will take place, e.g. high-value components of bio-based side-streams.

A total of four pilot cases in Uganda, Ghana, Côte d'Ivoire, and Senegal, with more than eight testing sites across the cases, will allow farmers and farmer groups to test these products in their local context. The use of novel biomass types in existing local technologies, e.g. local slow pyrolysis technology, and in the novel, adapted technologies, e.g. green biorefinery, will enable farmers to add value to local biomass and produce diverse bio-based products, including:

- biochar as a soil amendment product
- biochar as a solid biofuel product
- biochar as an additive to enhance biogas production
- biochar powder for water filtration
- green biorefinery presscake as ruminant feeds (e.g., cattle)
- green biorefinery protein concentrate as a feed supplement for pigs, poultry and fisheries
- whey as animal feed for piglets

[1] This project has been funded by the European Union (EU) Horizon 2020 Research and Innovation programme under Grant Agreement No 101000762.

- biomass pellets as animal feed
- biomass and protein concentrate pellets as fish feed

In addition, the potential for further value addition through side-stream valorisation, e.g. biorefinery whey extracts, will be explored through screening trials of whey applications.

The implementation of pilot trials using existing, local technologies and novel, adapted technologies will allow farmers and other local, bio-based value chain actors to compare the benefits of adapted technologies with local technologies, under their own agro-ecological and socio-economic conditions, e.g. soil, climate, agricultural practices, prevailing ownership models, market access, etc. **Table 1** summarises the technologies, biomass types (inputs), and products (outputs) that will be evaluated, including those to be evaluated at pilot-scale.

At least 300 farmers, farmer groups and other local bio-based value chain actors are expected to benefit from the pilot case trials, including pastoralists, small dairy farmers, low-income farmers, and female farmers. The pilot cases are embedded in a multi-actor, collaborative, and evidence-based value chain development strategy that engages communities, extension services, policy development, business supports and science and technology specialists, in the development of sustainable business models and at least 10 novel, bio-based value chains, including life cycle analysis of the products developed. This approach should result in performance improvements for the triple bottom-line of local agri-food systems in Uganda, Ghana, Côte d'Ivoire and Senegal, i.e. environmental, economic, and social performance.

Table 1: Testing and validation activities in BIO4AFRICA project (l = laboratory-scale validation tests, p = pilot-scale validation tests; s= product application screening tests)

Country	Technologies / processes	Inputs	Outputs	Validation tests
Uganda	• Green biorefinery • Carbonisation (hydrothermal carbonisation) • Densification (briquetting)	• Protein-rich leguminous plants, cassava leaves, banana leaves • Napier (elephant) grasses • Manure from cattle/dairy cows • Green biorefinery whey • Biochar for briquetting	• Animal feed: a) Presscake for ruminants, b) Protein concentrate for pigs & poultry, c) Whey as animal feed for pigs and for high-value ingredients screening • Biochar briquettes for cooking fuel • Biochar with struvite & manure for soil improvement	• Animal feed trials (dairy cows, pigs, piglets, poultry) (p) • High value whey ingredients screening (s) • Field trials of soil amendments (p) • Biochar briquettes for use as cooking fuel (l)
Ghana	• Green biorefinery • Carbonisation (slow pyrolysis) • Densification (pelletizing)	• Various local forage species • Green biorefinery whey • Green biorefinery protein concentrate for pelletizing • Crop residues (corn cobs, soybean husk, cowpea	• Animal feed: a) Presscake for ruminants, b) Protein concentrate for fish & pigs, c) Whey as animal feed for pigs and for high-value ingredients screening • Fish feed pellets	• Animal feed trials (dairy cows, bulls, pigs, piglets) (p) • Aquaculture feed trials (Tilapia and catfish) (p) • High value whey ingredients screening (s)

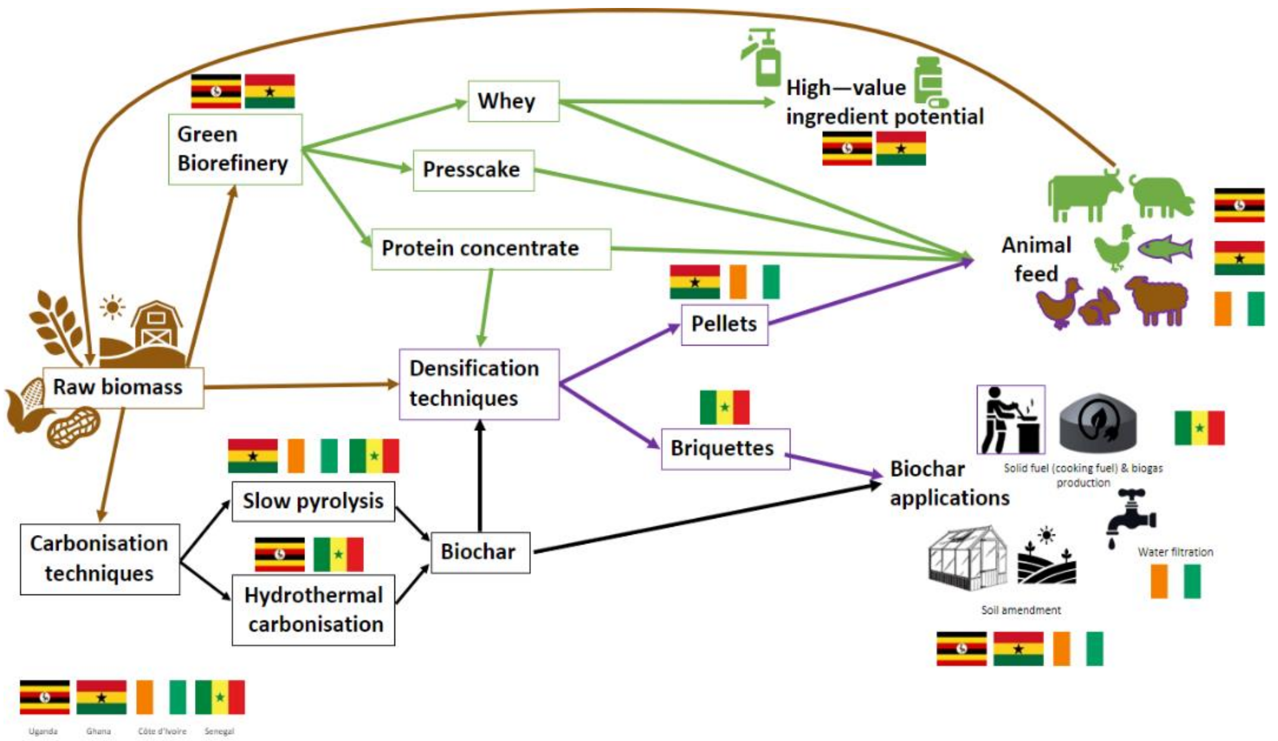
		husk, rice bran, cassava peels, groundnut husk, maize stalks, cocoa husk)	• Biochar for soil improvement	• Field trials of soil amendments using biochar (tomatoes, okra, chilli pepper) (p)
Côte d'Ivoire	• Carbonisation (slow pyrolysis) • Densification (pelletizing) • Bioplastics & bio-composites	• Cocoa pod shells • Cashew nut • Cashew shells • Cashew apple juice & molasses • Millet husks/stems • Leafy green biomass: *Cajanus cajan* (pigeon pea), *Leucaena leucophela* leaves, *Stylosanthes guianensis* (Stylo) leaves • Rubber seed • Coconut fibre • Palm tree branch fibre	• Biomass pellets for animal feed • Biochar granules for adsorption of water pollutants • Biochar for soil improvement • Bio-composites/bio-plastics	• Animal feed trials (sheep, rabbits, poultry) (p) • Tests of water filters using biochar (l, p) • Bioplastics/bio- composites tests (l) • Greenhouse and field trials of soil amendments (tomato and maize crops) (p)
Senegal	• Densification (briquetting) • Carbonisation (slow pyrolysis, hydrothermal carbonisation) • Bio-composites	• Peanut shells • Cashew hulls/apples • Rice husk • Typha	• Biochar briquettes for solid fuel (cooking fuel) • Biochar as biogas production additive & biogas pollutant adsorbent • Bio-composites	• Solid fuel (cooking fuel) tests (l, p) • Anaerobic digestion tests: biogas production with biochar additives and pollutant adsorption (p)

2.2 Cross-case comparison and income diversification potential reporting

The pilot trial period has been scheduled to take place between **M18-M44** of the Bio4Africa project. This report is the first of two comparing the trials within and between regions, and assessing income diversification potential. This report presents the pilot trial strategies, but as this report is presented early in the implementation of the pilot trials **(M31)**, with technology transfer still ongoing, there is limited scope for cross-case comparison. Trial results will be compared in the **Final Report (D4.5, M44)**, including a detailed evaluation of income diversification potential. The following sections describe the methodology for cross-case comparison of the product trials, and evaluation of income diversification potential (**Section 3**), comparison of trial designs and description of initial trial results (**Section 4**), initial evaluation of income diversification potential in the four target regions (**Section 5**), and a final section describing conclusions and the next steps for cross-case comparison and evaluation of income diversification potential over the next 13 months until the final report (**Section 6**).

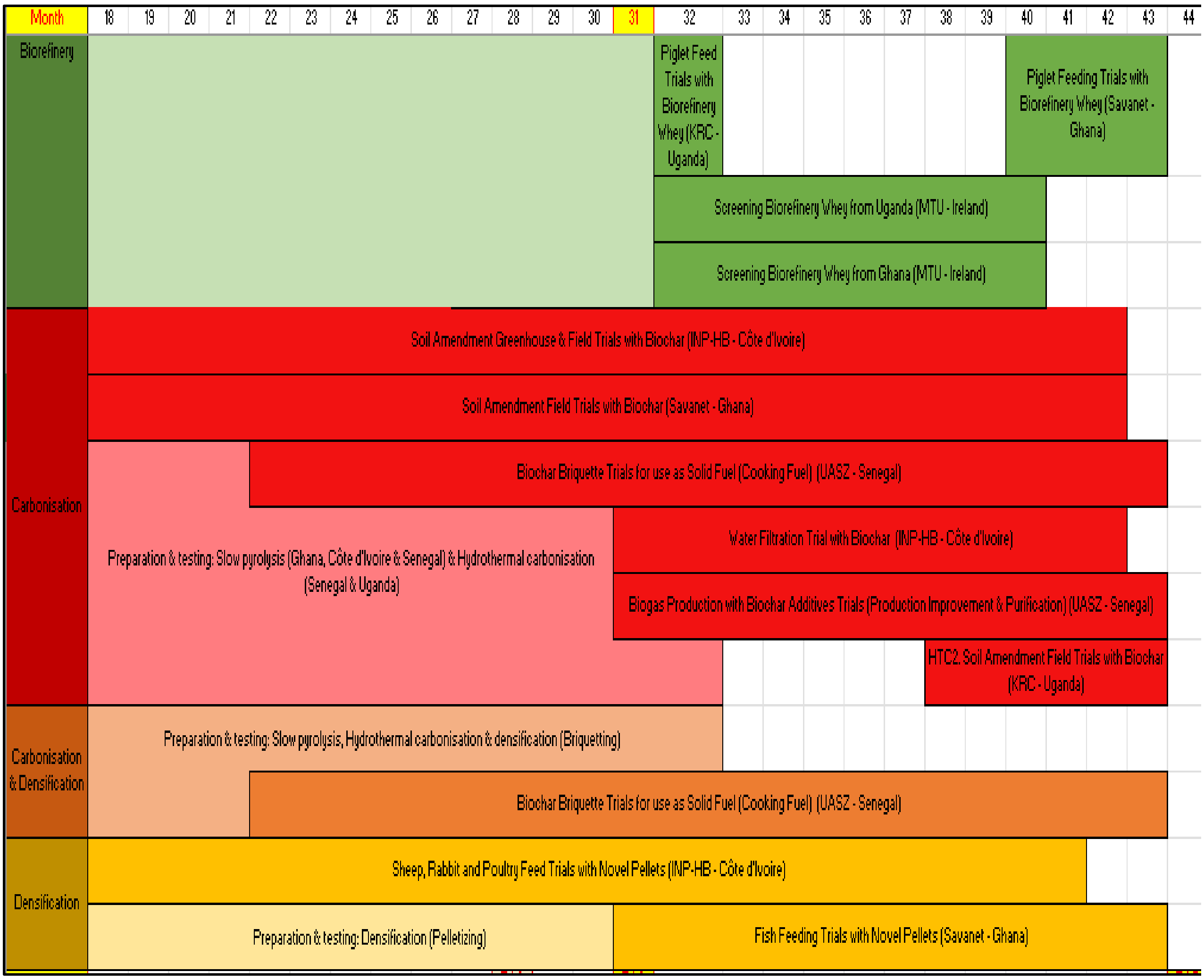
Fourteen types of novel bio-based product will be tested at pilot trial scale or screened for novel applications (biorefinery whey), from three of the technology types to be implemented in the BIO4AFRICA project, **green biorefinery**, **carbonisation**, and **densification,** and combinations of those technologies. The products that will be evaluated during the pilot trials, and the technologies involved in their production, are described in **Fig. 1**, and in greater detail below.

Figure 1: Diagram of bio-based technologies and products to be transferred and piloted during the BIO4AFRICA project



An overview of the pilot trial plan (current as of M31) is provided in **Fig. 2**. Due to variation in local technology availability and technology adaptation requirements, trials in some countries have been able to start earlier than in others. Up to **M31** trials in two main trial categories have begun: carbonisation product trials (biochar as soil amendment trials in Ghana and Côte d'Ivoire), densification product trials (sheep feeding trials in Côte d'Ivoire) and combined carbonisation and densification product trials (biochar briquettes as solid fuel (cooking fuel) in Senegal). Over the remaining 13 months of **WP4** these trials will be concluded with products from the novel, adapted technologies which are being implemented as part of **WP2** and **WP3**, allow for cross-case comparison within regions. The remaining trials, involving green biorefinery products (Uganda and Ghana), carbonisation products (Uganda, Ghana, Côte d'Ivoire, and Senegal) and densification products (Ghana and Côte d'Ivoire) will also be implemented and concluded in this period.

Figure 2: Overview of pilot trials taking place between M18-M44 of the BIO4AFRICA project



2.3 Technology Types and Products

The technologies deployed as part of the BIO4AFRICA project and the products that will be evaluated through pilot trials are described below. The technologies and associated product testing plans are described in greater detail in **D3.1**, the **Initial Testing, Monitoring and Assessment Plan**.

Green Biorefinery

Green biorefinery involves mechanical refining of leafy biomass to generate multiple bio-based value streams, including a fibrous "presscake" that can be fed to ruminants, protein concentrate that can be fed to monogastric animals, and concentrated whey with multiple uses, e.g. as animal feed (piglets), silage preservative, fertiliser. Small-scale green biorefinery technology developed by GRASSA has been adapted for use in the BIO4AFRICA test sites in Uganda and Ghana. The adaptation and implementation processes are described in detail in **D2.3** (**Small-scale green biorefinery units - initial version**) and **D3.1** (**Initial version of testing, monitoring and assessment plan**).

Carbonisation

Carbonisation of biomass involves transformation of the material to biochar at high temperatures (300 - 900°C) in the absence of oxygen (Zhang et al., 2019). At least three different approaches for transforming bio-based waste from primary and secondary production, and Typha, an invasive species, to novel value-added products will be examined during the pilot phase. Materials with a high moisture content, e.g. manure and cashew apple pulp, will be carbonised using **hydrothermal carbonisation** technology (**HTC**) in the BIO4AFRICA test sites in Senegal and Uganda. Materials with a low moisture content, e.g. rice husks and dried maize cobs, will be carbonised using **slow pyrolysis**, through a combination of locally constructed kilns and Brazilian kiln technology adapted to local conditions in the BIO4AFRICA test sites in Ghana, Côte d'Ivoire, and Senegal. Biochar produced through these carbonisation technologies will be applied for a number of purposes, including soil amendment, water filtration, solid fuel (cooking fuel) and an additive to improve biogas production. The carbonisation technologies implemented in the BIO4AFRICA project are described in greater detail in **D2.4** (**Pyrolysis units – initial version**), **D2.7** (**Small-scale hydrothermal carbonization units - initial version**) and **D3.1** (**Initial version of testing, monitoring and assessment plan**).

Densification

Densification techniques involve applying pressure to dry materials through different mechanical means, such as flat die or ring die pellet mills, in order to compact and compress the materials into a desired shape and size, e.g. pellets (small size), or briquettes (larger size). In BIO4AFRICA, briquetting and pelletising processes will be enlarged to accommodate the local feedstocks with greater efficiency than that offered in existing systems. Novel feedstocks, in both raw form and transformed through carbonisation (i.e. into biochar) or green biorefinery (as protein concentrate), will also be employed to explore value addition potential for these biomass types. The densification technologies implemented in the BIO4AFRICA project are described in greater detail in **D2.5** (**Densification units - initial version**) and **D3.1** (I**nitial version of testing, monitoring and assessment plan**).

3. Methodology: Cross-Case Comparison and Income Diversification Potential

3.1 Cross-case comparison methodology

The pilot trial cases are compared within countries, where local technology exists which is similar to that being adapted and transferred to the four regions, and between countries where similar trials are being implemented, e.g. biochar as soil amendment in Uganda, Ghana and Côte d'Ivoire.

3.1.1 Within country comparison

Within country comparison is possible for products derived from carbonisation and densification, as existing slow pyrolysis and densification technology was available in Ghana (pelletizing line), Côte d'Ivoire (pelletizing line) and Senegal (briquetting press) were available prior to the project start. **Table 2** describes the nine cases that are comparable within countries. A similar technology to green biorefinery was not present in Ghana and Uganda before the BIO4AFRICA project. However, the results of the feed trials will be compared to other animal feedstuffs used in the regions, as per the trial designs described in **section 4**.

Table 2. Pilot trial cases that are suitable for within country comparison (green)

Production technology type	Uganda	Ghana	Côte d'Ivoire	Senegal
	Product pilot trials			
Green biorefinery	No local equivalent for comparative pilot trial	*See densification, below*	Technology not implemented	Technology not implemented
Carbonisation	No local equivalent for comparative pilot trial	Soil amendment field trials	Soil amendment greenhouse & field trials	Biogas additive trials (production enhancement and purification)
Combined carbonisation & densification	No product trials	Technology not implemented	Technology not implemented	Solid fuel (cooking fuel) trials
Densification	*See above*	Fish feed pellet trials	Sheep feed pellet trials	*See combined carbonisation & densification above*

			Rabbit feed pellet trials	

3.1.2 Between country comparison

While each of the technologies is being implemented in two or more countries, the products are being applied for different uses depending on local needs and agronomic practices. Between country comparison is therefore not possible for all pilot trials. **Table 3** describes the 12 cases that are comparable between countries. Preliminary results of trials completed to date are available in **D4.1 - Report on BIO4AFRICA trials and validation results- initial version**, and further results will be reported on in **D4.3 - Report on BIO4AFRICA trials and validation results- interim version (M34)** and **D4.4 - Report on BIO4AFRICA trials and validation results- final version (M44)**.

Table 3. Pilot trial cases that are suitable for between country comparison (green) or are not directly comparable (orange).

Production Technology Type	Product Pilot Trials	Uganda	Ghana	Côte d'Ivoire	Senegal
Green biorefinery	Biorefinery presscake feeding trials	Dairy cows	Dairy cows		
			Bulls		
	Biorefinery protein concentrate feeding trials	Pigs	Pigs		
		Poultry	Fish		
	Biorefinery whey feeding trials	Piglets	Piglets		
	Biorefinery whey evaluation	Screening for high value application	Screening for high value application		
Carbonisation	Biochar soil amendment trials	Field trials	Field trials	Field trials	
				Greenhouse trials	

Production Technology Type	Product Pilot Trials	Uganda	Ghana	Côte d'Ivoire	Senegal
	Biochar water filtration			Village-scale water filtration	
	Biochar additive for biodigestion				Biogas production enhancement
					Biogas purification
Combined carbonisation & densification	Biochar briquettes				Solid fuel (cooking fuel)
Densification	Animal/fish feed pellet trials		Fish	Sheep	
				Rabbits	
				Poultry	

3.1.3 Trial designs and trial reporting

Both trial designs and trials results are used to enable comparison of cases within and between countries, where appropriate. Trial designs have been prepared by WP4 task leaders working on **Task 4.1 - Validation of products, solutions and integrated value chains in Uganda** (**Task lead: KRC**), **Task 4.2 - Validation of products, solutions and integrated value chains in Ghana** (**Task lead: Savanet**), **Task 4.3 - Validation of products, solutions and integrated value chains in Côte d'Ivoire** (**Task lead: INP-HB**), and **Task 4.4 - Validation of products, solutions and integrated value chains in Senegal** (**Task lead: UASZ**) as part of the trial preparation phase for the respective trials (see **Fig. 2**). These have been described in full in **D4.1 - Report on BIO4AFRICA trials and validation results- initial version**, and form the basis of the cross-case comparison for this deliverable.

Trial results are reported by the work package 4 task leaders, KRC, Savanet, INP-HB and UASZ, using a standardised reporting template (**Fig. 3**). This has been modelled on scientific abstracts, such as those used for conference submissions. The reporting template will therefore support those implementing trials to communicate the trial outcomes more broadly, e.g. in conferences and peer-reviewed journals. Trial reports will be used to enable comparison of cases within and between countries, where appropriate (as indicated in **Tables 2** and **3**).

Figure 3: BIO4AFRICA Standardised Trial Reporting Template

Title

Author 1[a], Author 2[b], Author 3[a,b...]

a: institution 1, b: institution 2, c...

Introduction (c. 100-150 words)

Materials and Methods (c. 400-500 words, including tables, figures, diagrams, etc.)

Results and Discussion (c. 400-500 words, including tables, figures, diagrams, etc.)

Conclusion (c. 100-150 words)

References

Total: 1,000 – 1,200 words

3.2 Evaluation of income diversification potential

Bio-based income diversification opportunities, such as those developed through the BIO4AFRICA project, can enable valorisation of production and processing co-products and sidestreams that might otherwise have low value, no value, or even present a net cost to the producer/processor, society and the environment as a waste product that requires management. Co-product valorisation can arise at different stages in the value chain of bio-based materials, and can also be coordinated to enable cascading use of the material, whereby the highest value uses are exploited first, and the lowest value uses last. The evaluation of income diversification potential arising from the technologies and products deployed in the BIO4AFRICA project therefore takes account of the opportunities that arise at different stages of the value chains associated with the feedstocks and bio-based products that are being trialled.

3.2.1 Income diversification through the value chain

In the context of rural households, such as smallholder farmers, income diversification is the process by which households develop diverse livelihood portfolios to improve and secure income and wellbeing through different combinations of resources and assets available to the household, including farm assets and resources (Abdul-Nasser Salifu, 2019; Davis et al., 2014; Niehof, 2004). Abdul-Nasser Salifu (2019) describes four main factors motivating income diversification among rural households:

- push factors, i.e. stressful factors that motivate households to seek additional income in order to mitigate risk and income volatility, e.g. during dry seasons;
- pull factors, i.e. incentives to seek additional income in order to grow household resources and capital that can subsequently be re-invested in income-generating activities;
- social factors, i.e. part of social processes and household position in social networks and membership of associations, e.g. farmer cooperatives;
- and institutional factors, i.e. the extent to which income diversification activities are facilitated by governance at local, regional, national and international levels.

The above factors highlight the role of institutional, social, economic, and environmental factors in income diversification activities, e.g. economic shocks, geographic context and environmental change, social networks and governance institutions. Income diversification can also be applied to businesses (Lee et al., 2020). In the business context, technological capabilities and characteristics have been identified as factors that influence the potential for income diversification (Lee et al., 2020).

3.2.2 Evaluation framework

The evaluation of income diversification potential offered by the bio-based technologies and products trialled in the BIO4AFRICA project will:

1. Map the income diversification opportunities associated with the technologies and products to the value chain stages in which they arise;
2. Identify the opportunities and challenges that rural households and businesses face to mobilise these income diversification opportunities, through PESTLE analysis

The PESTLE analysis draws on the institutional, social, economic, environmental and technological influences on income diversification activities described above. PESTLE analysis refers to political, economic, social, technological, legal and environmental factors (Achinas et al., 2019). **Figure 4** describes the income diversification potential evaluation framework, including data sources (further described in **section 3.2.3** below)

3.2.3 Data collection

Data for the initial evaluation of income diversification potential was gathered through:

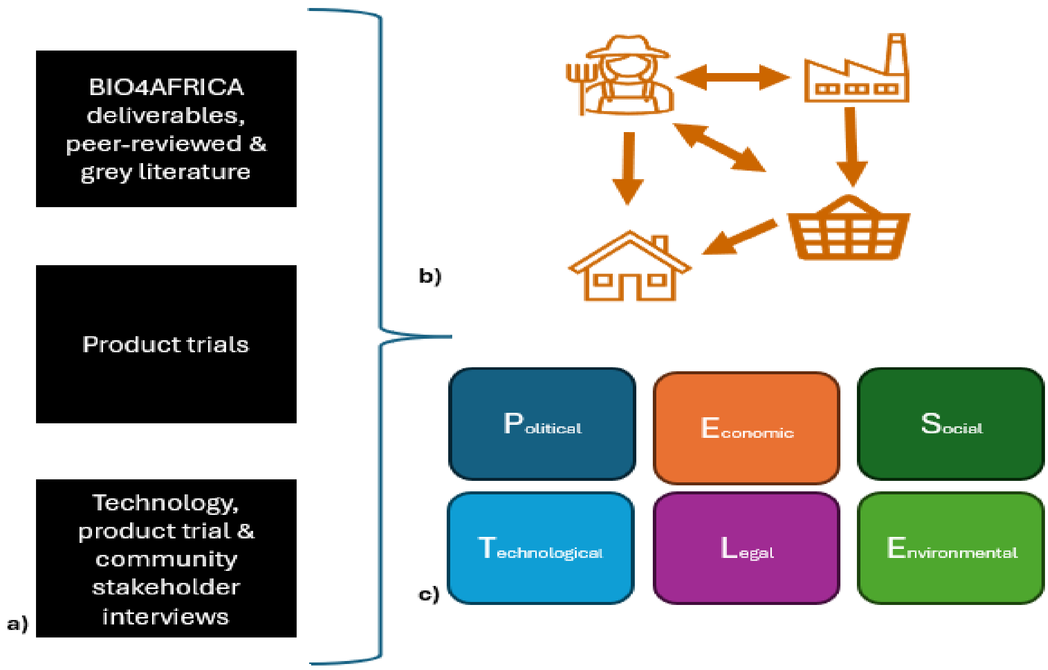
1. Review of early BIO4AFRICA deliverables from Work Package 1, 2, 3, 4 and 5, peer-reviewed literature, and grey literature, e.g. institutional reports;

2. Product trial designs and early trial reports;
3. Semi-structured interviews with key project stakeholders involved in technology development and implementation and product trials in the BIO4AFRICA project (in collaboration with Q-PLAN) and consultation by email and during monthly meetings of BIO4AFRICA work package leaders (meeting key points documented) and work package three and four partners (meeting minutes documented).

For the final evaluation of income diversification potential (**M44**), additional data will be collected, including:

1. Review of additional deliverables from other BIO4AFRICA Work Packages, including final deliverables form Work Packages 2 and 3, peer-reviewed literature, and grey literature, e.g. institutional reports;
2. Final trial reports from product trials;
3. Review interviews with stakeholders involved in technology development and implementation and product trials in the BIO4AFRICA project, and consultation by email and during monthly meetings of BIO4AFRICA work package leaders (meeting key points documented) and work package three and four partners (meeting minutes documented).
4. Semi-structured interviews with prospective technology users as identified in the development of inclusive bio-based business models (Work Package 5) and the BIO4AFRICA Accelerator programme (Work Package 6).

Figure 4: Income diversification evaluation framework indicating a) data sources, b) income diversification mapping and c) PESTLE analysis



4. Initial Cross-Case Comparison

Six pilot trials have been initiated since the beginning of the pilot trial activities **(M18)**, using locally available technologies. These include:

- In Ghana: soil amendment field trials with biochar and fish feeding trials using novel pellets.
- In Côte d'Ivoire: soil amendment trials with biochar in a) greenhouse and b) field trials, and sheep feeding trials with raw biomass pellets.
- In Senegal: solid fuel (cooking fuel) trials with biochar briquettes.

During the same period, novel technologies have been deployed in these regions, including:

- Green biorefinery in Uganda and Ghana (**M18-M30)**;
- Slow pyrolysis (Brazilian kiln) technology in Ghana, Côte d'Ivoire and Senegal (**M28-M30**);
- HTC technology in Senegal (**M30**).

In these regions, preparation for product trials is underway, and in some instances has already begun, e.g. with slow pyrolysis technology. However, results are not yet available from these trials, and comparison of these results within and between countries, including those trials completed up to **M31**, will be made in **D4.5** (**M44**). The final cross-case comparison in **D4.5** will also include comparison of trials that will be undertaken in the next 12 months with products from novel technologies that are due to be deployed, including:

- HTC technology in Uganda (**M32**);
- Densification technologies in Ghana, Côte d'Ivoire and Senegal (**M31-M34**).

This initial cross-case comparison will examine the pilot trial methodologies for trials for which within country comparison is applicable (see **Table 2**) and for trials for which between country comparison is applicable (see **Table 3**).

4.1 Initial cross-case comparison within countries

Nine cases are being undertaken with products derived from local technologies and one or more novel technologies, enabling comparison of cases within the countries in which they are carried out (Ghana, Côte d'Ivoire and Senegal). The trial designs for these trials are described below, including the parameters that will be compared for trials involving products from local technologies and novel technologies. Comparison of the results of these trials will be provided in **D4.5**.

4.1.1 Ghana

Two trials are being undertaken in Ghana with products produced using both local and novel technologies:

- Soil amendment field trials using biochar,
- Fish feed trials using feed pellets from different biomass sources, including green biorefinery-derived protein concentrate.

In both instances, the trials have already begun using products produced from local technology: traditional Ghanaian kilns and a local pelletizing mill. These will be replicated with the Brazilian kiln technology (for biochar), and modern pelletizing mill for producing feed pellets. Further details of both the local and novel technologies are provided in **section 2.2.1** (carbonisation and densification). Feed pellets containing green biorefinery-derived protein concentrate will also be evaluated as part of the fish feed trials. Further details of green biorefinery technology are provided in **section 2.2.1**.

Biochar as soil amendment

Groundnut husk, rice husk/hulls, and corn stover are being used as feedstock to produce biochar from both the traditional kiln and Brazilian kiln. To evaluate biochar as a soil amendment, a complete randomized block design is being used, with half-acre plots for each of three different crops (tomato, okra, and chili pepper) in different parts of the North-East region of Ghana: Zangum, Nabari, and Gbeligu. Three replications will be carried out using biochar from each kiln type, and the plots will be irrigated during the dry season, and rainfed otherwise. The biochar is being applied as a soil amendment in two different experimental treatments: alone (5t/ha application rate) and in combination with compost[1] (5t/ha application rate), while two different control treatments were used: no fertilizer application, and compost (5t/ha application). The parameters being examined are described in **Table 4**. Partial budget analysis will also be applied to conduct an economic analysis of biochar-based soil amendment.

Table 4: Parameters being examined in soil amendment trials in Ghana

Soil Characteristics	Crop characteristics
Soil Structure	Plant Height
Soil pH	Branches/Plant
Water Retention Rate	No. Leaves
Nutrient content: Nitrogen, Phosphorus & Potassium	Stem Diameter
Compost Characteristics	Chlorophyll Content
Moisture	Days to 50% Flowering (DFF)
Volatile Matter	Leaf Area Index (LAI)

[1]Comprised of blended compost components, rice husk, and cow dung.

Soil Characteristics	Crop characteristics
Fixed Carbon	Intercepted Photosynthetically Activate Radiation (IPAR)
Ash Content	No. Fruit/Plant
Water Retention	Average Fruit Weight
Permeability	Fruit Yield/Plot
Water Infiltration	Fruit characteristics (ash content, protein content, moisture content, fibre, vitamins)
Aeration	
Structure	

Fish feed

The fish feed pellets are being produced using diverse biomass types to create a balanced fish food, initially using local pelletizing technology and, after deployment, novel pelletizing technology. The control treatment diet will include protein sources (fish meal, palm kernel meal, cowpea husk, soybean husk), carbohydrates (fermented corn cob, rice bran, cassava meal/peels), lipids (palm kernel oil, palm oil), vitamins and minerals (premix), salt, and starch or other binder. Four experimental treatment diets will be examined, including one in which some of the protein content will be substituted with green biorefinery protein concentrate, when available.

The feed trials will involve two species, Nile Tilapia (*Oreochromis niloticus*) and Catfish fingerlings, with separate trials for each species. The trials will be replicated twice, with each species divided into five groups of five (no. tilapia = 30, no. catfish = 30). During the experiment, water quality (acidity, alkalinity, salinity, water temperature, and the rate of water circulation) will also be analysed, and the system of production and feeding schedule will be consistent across treatments. The parameters to be examined are described in **Table 5**.

Table 5: Parameters to be examined in protein pellet fish feeding trials in Ghana

Fish performance	Biochemical parameters	Hematological parameters
Growth	Total cholesterol	Red blood cells
Feed utilisation	High-density lipoprotein in cholesterol	Haemoglobin

Fish performance	Biochemical parameters	Hematological parameters
Digestibility	Low-density lipoprotein in cholesterol	Packed cell volume
Liver histology	Total protein	Mean corpuscular volume
Proximate composition (Protein, lipid, ash, moisture)	Albumin	Mean corpuscular haemoglobin & haemoglobin concentration
Fatty acids	Globulin	White blood cells
Amino acids	Alanine	**Other**
	Aminotransferase	Digestive enzyme activity in the gastrointestinal system (protease, amylase, lipase)
	Aspartate aminotransferase	Gene expression of growth-related genes (n = 5)

4.1.2 Côte d'Ivoire

Three trials are being undertaken in Côte d'Ivoire with products produced using both local and novel technologies:

- Soil amendment greenhouse and field trials using biochar,
- Sheep feed trials using biomass-based feed pellets,
- Rabbit feed trials using biomass-based feed pellets.

In all instances, the trials have already begun using products produced from local technology, traditional Côte d'Ivoire kilns and a local pelletizing mill. These will be replicated with the Brazilian kiln technology (for biochar), and modern pelletizing mill for producing feed pellets. Further details of both the local and novel technologies are provided in **section 2.2.1** (carbonisation and densification).

Biochar as soil amendment

Millet husks and stems will be used as feedstocks for creating biochar from both the traditional kiln and Brazilian kiln technologies. This will be used in greenhouse trials for the production of tomato and maize (**Fig. 5**), and from Brazilian kiln technology only for field trials.

Figure 5: Greenhouse trials using biochar-based soil amendments for a) tomato production and b) maize production in Côte d'Ivoire

a)

b)

For the greenhouse trials, three types of soil will be treated with three different rates of biochar amendment and a control treatment (no biochar) with 12 blocks for each of tomato and maize plants. The experiments will be replicated three times (total tomato plants = 36, total maize plants = 36). The parameters to be examined are described in **Table 6**.

Table 6: Parameters to be examined in soil amendment trials in Côte d'Ivoire

Soil characteristics	Soil and crop characteristics
pH	Leaf-scale gas exchange
Nutrient content: Nitrogen, Phosphorus, Potassium	Chlorophyll fluorescence
Cation-Exchange Capacity	Plant growth
Enzymatic Activity	Fruit yield
Mycorrhizae	

Sheep & rabbit feed

Feeding trials will be carried out with sheep and rabbits using feed pellets produced from novel biomass combinations, using a local pelletizing line initially followed by a higher throughput line adapted to the needs of regional stakeholders. The parameters evaluated in these trials are described in **Table 7.**

For sheep feeding trials, the pellets have been designed to supplement sheep nutrition and control of gastro—intestinal parasites. The pellets have been produced using *Cajanus cajan* (pigeon pea) and *Leucaena leucocephala* leaves, locally available fodder with parasitic control potential. The pellets are being trialled in a multi-location trial, with three study areas (the South, the Centre, and the North of Côte d'Ivoire), and six farms in each zone, with 12 sheep selected per farm (no. farms = 18, no. sheep = 216). On each farm, half of the animals are randomly assigned to the experimental treatment diet, and half to the control diet of standard feed supplementation. Further trials will take place using cashew apple pulp when novel pelletizing technology is available.

For rabbit feeding trials, three trials will be carried out, two experimental treatments with pellets containing either cashew apple or cassava peelings, and one control treatment with standard rabbit feed pellets used in the region. The treatments will be replicated twice, with twelve rabbits per treatment.

Table 7: Parameters to be examined in sheep feeding trials in Côte d'Ivoire

Sheep intake/performance	Rabbit intake/performance
Daily feed intake	Consumption index
Animal weight	Average daily gain
Feed conversion ratio	Morbidity
Health status, including parasite load	Mortality
Carcass characteristics/composition	Health risk index
Lamb mortality	

4.1.3 Senegal

Three trials are being undertaken in Senegal with products produced using either both local and novel technologies, or two different types of novel technology:

- Biochar briquettes for solid fuel (cooking fuel),
- Biochar as biogas additive for production improvement and purification.

In the trial of biochar briquettes, the trial has already begun using products produced from local technology, locally constructed Senegalese barrel reactor kilns and a small-scale briquetting press. This will be replicated with the Brazilian kiln and larger-scale briquetting line for producing biochar briquettes and with both the Brazilian kiln and HTC technologies for producing biochar as a biogas additive. Further details of both the local and novel technologies are provided in **section 2.2.1** (carbonisation and densification).

Biochar briquettes for solid fuel (cooking fuel)

Dry agri-food residues, including peanut shells, corn stalks or millet stalks, will be used to create biochar for fuel use using local barrel reactor kilns and adapted Brazilian kilns. The biochar will be transformed into biochar briquettes. UASZ and ENERGECO will evaluate the application of these biochar briquettes as solid fuel for cooking using traditional Malgache stoves and improved Jambar stoves with an extractor chimney. The parameters to be examined are described in **Table 8**.

Table 8: Parameters to be examined in trials of solid fuel for cooking in Senegal

Briquette characteristics	Emissions characteristics
Proximate analysis	Toxic emissions during combustion
Ultimate analysis	Gas production
Bulk density	Carbon dioxide (CO_2)
Impact resistance	Carbon monoxide (CO)
Ease of ignition	Particulate matter (PM2.5)
Calorific value	
Mechanical resistance	
Moisture uptake	
Cooking applications (time required to prepare a pre-defined meal)	

Biochar as biogas additive

Both wet and dry feedstocks will be processed into biochar for use as a biogas additive. The HTC technology, which can process wet feedstocks, will be used to produce biochar from cashew apple pulp and typha. Local barrel reactor kilns and the adapted Brazilian kiln will be used to produce biochar from rice husk and peanut shells. The biochar will be used as a biogas additive with two different purposes:

1. During anaerobic digestion to enhance biogas production (performance improver),

2. As pollution adsorbent to purify the biogas post-production (purification).

To evaluate the influence of biochar on **biogas production performance**, the biochar will be added as an inoculum to an agri-food residue substrate which includes cow dung, rice husk, and cashew apple, generated by a $10m^3$ digestor on the UASZ campus in Ziguinchor. The rate of biochar addition will be controlled, ranging from 0% biochar addition to a 1:1 biochar and substrate mixture, in increments of 5% increase in biochar and a corresponding 5% decrease in substrate concentration, per trial. A continuously stirred tank reactor of 20L effective volume will be used, working under mesophilic conditions.

The biochar will also be tested as a **pollution adsorbent** for the removal of H_2S present in biogas generated using the pilot digestors. Trials will be conducted in a 6L capacity tubular filter containing a fixed bed of biochar. The trial will evaluate different Empty Bed Contact Times, and the regeneration potential of the adsorbent by repeating the adsorption-desorption cycle using hot and cold water and evaluating the performance of the resulting product. The H_2S adsorption capacity will be evaluated against international standards on a daily basis, and a control trial using a bed of commercial activated carbon will also be run for comparison.

The parameters to be examined in both biogas additive trials are described in **Table 9**.

Table 9: Parameters to be examined in biochar biogas additive trials in Senegal

Biodigester operating parameters	Biogas characteristics	Pollution adsorption parameters
Temperature	Gas composition (CH_4, H_2S, CO_2, N_2, H_2O, trace gases) & proximate analysis	H_2S removal efficiency
Waste feedstock (volume of feeding)	Cumulative biogas and methane yield (total and per kg organic dry matter)	Breakthrough time
TRH	pH (alkalinity)	Regeneration potential
pH of substrate (alkalinity)	Methane production rate	
Kinetics of daily & cumulative biogas production (%N, % organic matter, % dry matter, %C, C/N ration)	Biogas quality analysis	
	Heating value	

4.2 Initial cross-case comparison between countries

Twelve cases are being undertaken with products derived from similar technologies and applied for similar purposes, e.g. same agricultural livestock or crop production context. The products are being produced by both novel technologies (green biorefinery), and a combination of local and novel technologies, (traditional pyrolysis kilns, adapted kilns, and HTC). The similarity of product applications enables comparison of cases between the countries in which they are carried out (Uganda, Ghana and Côte d'Ivoire). The points of comparison of these trials are described below, based on the trial designs. Comparison of the results of these trials will be provided in **D4.5**.

4.2.1 Green biorefinery products

Three different green biorefinery products will be tested through feeding trials in both Ghana and Uganda: presscake, protein concentrate, and whey. This technology is described in greater detail in **section 2.2.1**. Biorefinery whey from both countries will also be evaluated for high-value application potential, such as cosmeceutical and nutraceuticals.

Presscake feed trials

Presscake feed trials will take place with dairy cows in both Uganda and Ghana (**Fig. 6**), and also with bulls in Ghana. Due to the different purposes of both trials (dairy production versus meat production), bull feeding trials will not be included in the cross-case comparison.

Figure 6: Dairy cows demonstrating good uptake of press cake during pilot trial preparation phase in Uganda

Two experimental treatments, of two different presscake types, and one control treatment will be implemented in each case, with one cow per treatment on a randomized basis. The treatments will be replicated three times in Uganda and five times in Ghana. The control treatment in Uganda will be Elephant grass (Pennisetum purpureum). In Ghana, where the presscake is being fed as a supplementary feed to pasture grazing, the control treatment will be pasture grazing without supplementation. The parameters to be examined in each case are described in **Table 10**.

Table 10: Comparison of parameters to be examined in green biorefinery presscake feeding trials with dairy cows in Uganda and Ghana

Presscake feeding trial parameters: dairy cows		Uganda	Ghana
Animal intake/ performance	Voluntary intake	X	
	Milk yield/response	X	X
	Milk composition	X	X
	Feed efficiency		X
	Feed conversion ratio		X
	Haematological parameters		X
Animal manure	Organic matter	X	X
	Nitrogen	X	
	Phosphorus	X	
	Potassium	X	

Comparable trial parameters include milk yield/response, milk composition, and manure organic matter content. These are supplemented by parameters that will be examined in Uganda only (voluntary intake, and manure nitrogen, phosphorus and potassium content) and Ghana only (feed efficiency, feed conversion ratio, and haematological parameters). While there are differences between the trials, that reflect local agricultural practices and agro-ecological conditions, there are similarities such as the number and nature of experimental treatments, and evaluation of presscake feeding effect on milk yield and composition and manure organic matter content. These similarities will allow cross-case comparison of these trials to produce results that are more robust and useful beyond each of these individual regions.

Protein concentrate feed trials

Protein concentrate feed trials will take place with pigs in both Uganda and Ghana. In addition, poultry feeding trials will take place in Uganda, and fish feeding trials will take place in Ghana, but these will not be included in the cross-case comparison due to the difference in the nature of the trials.

The trials will be randomized controlled trials involving both male and female pigs being fed a diet with varying proportions of biorefinery protein concentrate (experimental treatment) or a locally conventional protein source, e.g. soy or fishmeal (control treatment). In Uganda the trials will involve four treatments with three months old pigs, three experimental treatments and one control treatment, replicated three times with two pigs per treatment. In Ghana, the trials will involve three treatments with weaned piglets, two experimental treatments and one control treatment with five pigs per treatment. The same trial parameters will be examined in both trials, as described in **Table 11.**

Table 11: Parameters to be examined in biorefinery protein concentrate pig feeding trials in Uganda and Ghana

Pig intake/ performance	Pig slurry
Daily feed intake	Organic matter
Average daily weight gain	Nitrogen
Feed conversion efficiency	Phosphorus
Carcass characteristics/ composition	Potassium

While the trial designs vary in terms of the number of treatments, replicates, and the number and age of pigs, the use of the same trial parameters will provide a basis for cross-case comparison of results, and shared learning between and beyond these regions.

Whey feed trials

Randomized, controlled biorefinery whey feed trials will take place with male and female weaner piglets in both Uganda and Ghana. In Uganda, the trials will involve four treatments: three experimental treatment diets incorporating biorefinery whey, and a control diet without whey, in three replicates, with two piglets per treatment (one male and one female). In Ghana, the trials will involve five treatments: four experimental treatment diets incorporating biorefinery whey, and a control diet without whey, with three piglets per treatment. The same trial parameters will be examined in both trials, as described in **Table 12**.

Table 12: Parameters to be examined in biorefinery whey pig feeding trials in Uganda and Ghana

Piglet intake/ performance	Pig manure
Daily feed intake	Firmness
Average daily weight gain	Organic matter
Feed conversion efficiency	Nitrogen
	Phosphorus
	Potassium

The strong similarity between these trials in terms of both the trial procedure and parameters to be evaluated provides a very strong basis for cross-case comparison. The results will be able to inform future practice regarding feeding of biorefinery whey to piglets both in these countries and other regions with similar agro-ecological conditions.

Whey screening for high-value applications

Screening of biorefinery whey for high-value applications will take place with whey produced in both Uganda and Ghana. Samples of green biorefinery whey will be transported to MTU in Ireland to evaluate the presence of high-value ingredients, especially bio—active compounds and those with applications for animal and human health, e.g. cosmeceuticals and pharmaceuticals. Screening will include:

- High-Pressure Liquid Chromatography (HPLC),
- Fourier-Transform Infrared Spectroscopy (FTIR),
- Biochemical assays.

Screening will be carried out for bioactivities relating to digestive, immune, skin and hair health using established biomarkers. The samples will be screened in a similar way, providing a good basis for comparison between the two regions, and insight into the applications of biorefinery whey with these feedstocks more broadly.

4.2.2 Carbonisation products

Carbonisation products are being applied for various uses in the BIO4AFRICA project, depending on the needs and feedstocks available in the participating regions. In three countries, Uganda, Ghana and Côte d'Ivoire, biochar is being trialled as a soil amendment in field trials (all three countries) and greenhouse trials (Côte d'Ivoire). The biochar is being produced using local technologies (Ghana and Côte d'Ivoire) and two different novel technologies, HTC (Uganda) and Brazilian kiln (Ghana and Côte d'Ivoire). Further details of these technologies are provided in **section 2.2.1** (carbonisation).

Soil amendment trials

Biochar can be used as a soil amendment to improve soil structure and enhance water and nutrient retention, enhancing soil fertility. The soil amendment trials in BIO4AFRICA will evaluate the impact of biochar on soil, compost (mixed with biochar as a soil amendment), and crops grown in the amended soil. Four randomized controlled trials will be carried out: a greenhouse trial in Côte d'Ivoire, and three field trials, one each in Uganda, Ghana and Côte d'Ivoire. The trials will be replicated in different seasons to reflect local agro-ecological conditions. The different technologies and feedstocks used in each country to produce biochar for soil amendment trials is described in **Table 13**.

Table 13: Technologies and feedstocks used to produce biochar for soil amendment trials in Uganda, Ghana and Côte d'Ivoire

Crops/Trial parameters		Uganda	Ghana	Côte d'Ivoire (green-house)	Côte d'Ivoire (field)
Technology type	HTC	X			
	Slow pyrolysis – local technology		X	X	X
	Slow pyrolysis – Brazilian kiln		X	X	X
Feedstocks used	Cow manure	X			
	Groundnut husk		X		
	Rice husk/hulls		X		
	Corn stover		X		
	Millet husk/stems			X	X

In Uganda, 6 treatments to produce both green vegetables and maize/beans will be examined: a control treatment of manure and struvite, and five experimental treatments of biochar mixed with manure and struvite with biochar amount increasing in 20g increments from 20-100g. The treatments will also be compared with baseline, pre-application data.

In Ghana, 6 treatments will be examined to produce tomato, okra and chili pepper: two control treatments of a) no fertilizer application, and b) application of compost comprised of rice husk and manure; and three experimental treatments of biochar mixed with the compost (two different mixes) and applied without compost. A consistent application rate of 5t/ha will be used across the treatments. The trials will be replicated three times, and will take place on half-acre plots in three different regions in North-East Ghana - Zangum, Nabari, and Gbeligu. In Ghana, compost characteristics will also be examined, and partial budget analysis will be applied to conduct an economic analysis of biochar-based soil amendment.

In Côte d'Ivoire, the greenhouse trials will involve four treatments on three different types of soil: three different rates of biochar amendment and a control treatment with no biochar added. The experiments will be replicated three times with 12 blocks per plant. The field trials will involve two treatments in three different regions: biochar amended soil and a control treatment with no biochar amendment of the soil. The treatments will take place on 0.25 acre plots – an experimental and control plot for each crop and each locality.

The parameters that will be evaluated in the different trials are described in **Table 14.** The range of soil types and cultivation conditions (regional differences, greenhouse vs. field) examined across these trials will provide interesting insights into the influence of biochar application on soil characteristics and crop type. Despite the similar nature of the trials, i.e. evaluating biochar as a soil amendment for crop production, there is a strong degree of variation between them due to the different crops, soil types and application rates examined. Biochar is also a highly variable product with characteristics and subsequent influence on soil differing depending on the feedstock and means of production (Laghari et al., 2016; Singh et al., 2010). The trials of maize production using both manure-based biochar from HTC in Uganda and crop-based biochar from slow pyrolysis in Côte d'Ivoire provides a good opportunity to compare the influence on crop production of these two biochars that are likely to differ substantially due to the difference in feedstock (Windeatt et al., 2014). Similarly, the tomato cultivation trials in both Ghana and Côte d'Ivoire provides an opportunity to compare the influence of biochars from different feedstocks but similar modes of production (identical in the case of the Brazilian kiln technology).

Table 14: Trial characteristics and trial parameters to be examined in soil amendment trials in Uganda, Ghana and Côte d'Ivoire

Crops/Trial parameters		Uganda	Ghana	Côte d'Ivoire (green-house)	Côte d'Ivoire (field)
Soil characteristics	Soil physical parameters	X	X		
	Soil structure	X	X		
	Water retention		X		
	Soil ph	X	X	X	X

Crops/Trial parameters		Uganda	Ghana	Côte d'Ivoire (green-house)	Côte d'Ivoire (field)
	Nutrient content: Nitrogen, Phosphorus and Potassium	X	X	X	X
	Cation-exchange capacity	X		X	X
	Enzymatic activity			X	X
	Mycorrhizae			X	X
Crop characteristics	Crop health	X			
	Crop growth	X	X	X	X
	Crop yield	X	X	X	X
	Chlorophyll fluorescence			X	X
	Leaf-scale gas exchange			X	X
	Chlorophyll content		X		
	Days to 50% Flowering (DFF)		X		
	Leaf area index (LAI)		X		
	Intercepted photosynthetically activate radiation (IPAR)		X		
	Average fruit weight		X		
	Fruit composition (Ash, protein, moisture, fibre, vitamins)		X		

5. Initial Evaluation of Income Diversification Potential

The initial evaluation of income diversification potential draws on a review of early BIO4AFRICA deliverables from Work Package 1, 2, 3, and 5, peer-reviewed literature, and grey literature, e.g. institutional reports; product trial designs and early trial reports; and semi-structured interviews with key project stakeholders involved in technology development and implementation and product trials in the BIO4AFRICA project (in collaboration with Q-PLAN). **Table 15** describes these data sources in more detail. Interviews were further supported through consultation by email and during monthly meetings of work package leaders, e.g. with IHE (work package 2 co-lead), and work package 3 and 4 partners, e.g. UASZ (task 4.4 lead), CIRAD (work package 3 co-lead), and GRASSA (task 4.1 and 4.2 partner).

Table 15: Data sources contributing to initial evaluation of income diversification potential of BIO4AFRICA technologies and products

BIO4AFRICA Deliverables	Trial designs & early trial results	Interviews with technology/product adapters, developers & implementers
WP1 (n = 4) • D1.1 (Context and needs of African rural communities) • D1.2 (Mapping of local forage agri-food systems) • D1.3 (Catalogue of small scale bio-based technologies suitable for rural Africa) • D1.5 (Suitable modes of finance and funding for bio-based technologies in Africa)	**Task 4.1 (n = 6)** • Biorefinery product trial designs (5) • HTC product trial designs (1)	**Green biorefinery (n = 2)** • Savanet (biorefinery implementation & product trials) • MTU (biorefinery whey screening)
WP2 (n = 4) • D2.1 (Feedstock inventory) • D2.2 (Feedstock database and characteristics – initial version) • D2.3 (Small-scale green biorefinery units - initial version) • D2.4 (Pyrolysis units – initial version)	**Task 4.2 (n = 7)** • Biorefinery product trial designs (5) • Densification product trial design (1) • Slow pyrolysis product trial designs (1)	**Carbonisation (n = 2)** • Savanet (slow pyrolysis implementation & product trials) • INP-HB (slow pyrolysis implementation & product trials)

WP3 (n = 1) • D3.1 (Data testing, monitoring and assessment plan – First interim version)	**Task 4.3 (n = 7)** • Densification product trial design (3) • Slow pyrolysis product trial designs (3) • Early trial results (1): Feed pellet trial with sheep	**Densification (n = 3)** • RAGT (densification technology adaptation) • Savanet (slow pyrolysis implementation & product trials) • INP-HB (slow pyrolysis implementation & product trials)
WP4 (n = 1) • D4.1 (Report on BIO4AFRICA trials and validation results – initial version)	**Task 4.4 (n = 4)** • Densification & carbonisation product trial design (1) • HTC product trial designs (2) • Early trial results (1): Biochar solid (cooking) fuel briquettes	
WP5 (n = 2) • D5.1 (Report on novel bio-based value chains and markets analysis) • D5.2 (Validated inclusive and sustainable bio-based business models for rural Africa)		

These data sources have contributed to mapping of income diversification opportunities along bio-based value chains associated with the BIO4AFRICA bio-based technologies and products, which is described below. The mapped income diversification options have subsequently been evaluated, using the data gathered, through PESTLE analysis to understand the opportunities and challenges for rural households and businesses associated with these diversification pathways.

5.1 Income diversification potential of green biorefinery technology

Six main applications for the three green biorefinery products (presscake, protein concentrate, and whey; **Fig. 7**) are being evaluated in the BIO4AFRICA project.

Figure 7: Green biorefinery products produced in Uganda including a) presscake, b) protein concentrate, and c) protein and whey being collected in collection tanks

a) **b)** c)

These include:

- Presscake as a feedstuff for housed dairy cows (Uganda) and pasture-grazing dairy cows and beef bulls (pastoralist system) (Ghana)
- Protein concentrate as a feedstuff for young pigs (Uganda, Ghana)
- Protein concentrate as a feedstuff for laying hens (Uganda)
- Protein concentrate as a protein ingredient in fish feed pellets (Ghana, in combination with densification technology)
- Biorefinery whey as a feedstuff for piglets (Uganda and Ghana)
- Biorefinery whey will be screened to identify high-value components with potential applications as nutraceuticals and cosmeceuticals, e.g. bio-active components.

The whey also has other potential applications, e.g. silage preservative (including for presscake), fertiliser, and co-digestion in anaerobic digestion systems, resulting in energy production and digestate that can be applied as fertilizer (Jørgensen et al., 2022; Ravindran et al., 2022), but its use for these purposes will not be not explored in the BIO4AFRICA project. The income diversification opportunities associated with the green biorefinery technology and products are described in **Fig. 8**.

Figure 8: Income diversification potential of green biorefinery technology and products for rural households engaged in farming activities (dark green), farming organizations and feed processors (bright green), biotechnology companies (light blue) and retailers involved in food, feed, veterinary and pharmaceutical sales (red). Yellow circles represent products, dark blue parallelograms represent processing by technologies, black lines indicate movement of products without financial flows, lines of other colours represent product movement with trade potential (line colour indicates the value chain actors in receipt of income from product trade).

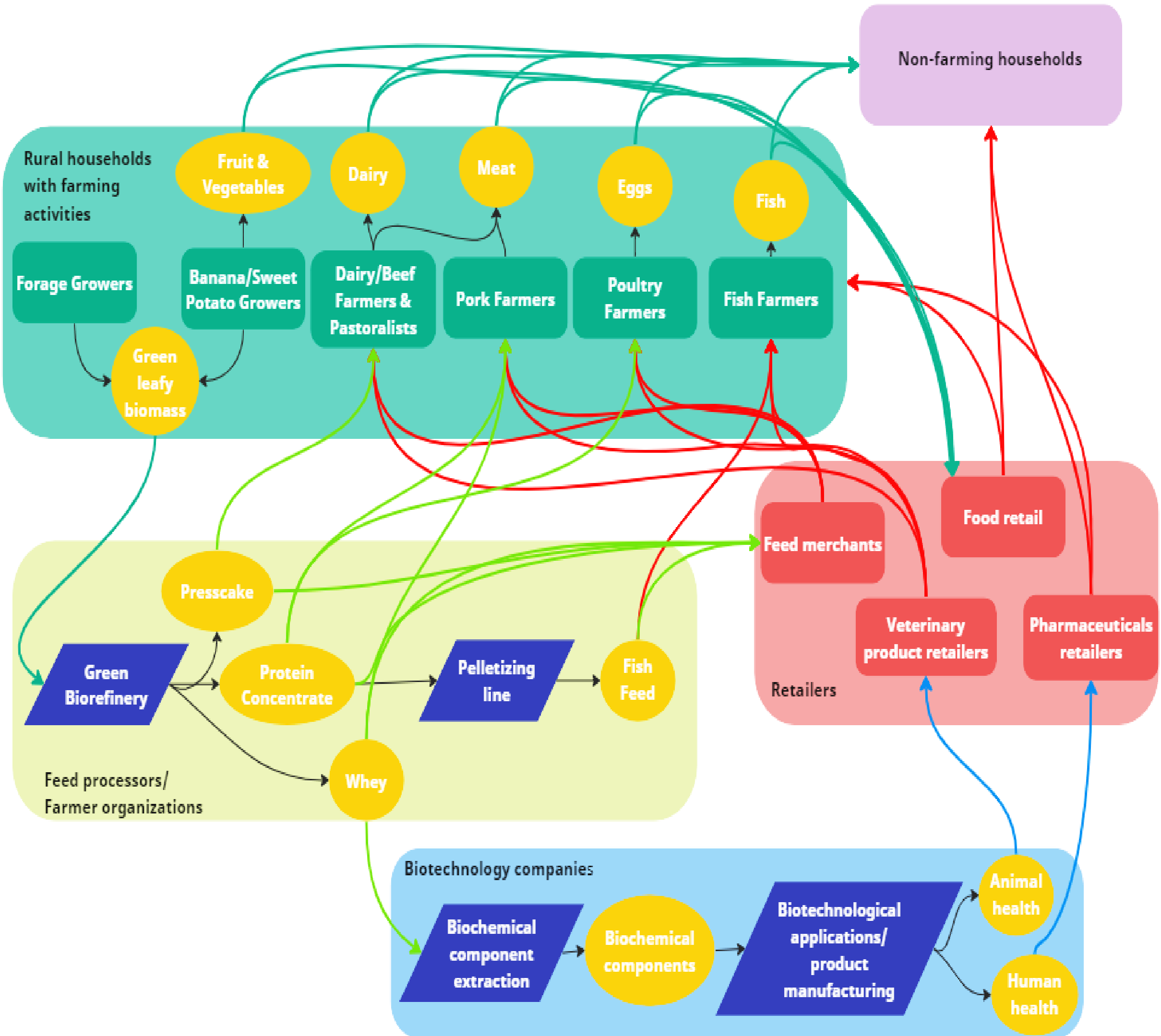


Figure 8 describes the main income generating activity of rural households engaging in farming activities relevant to green biorefinery value chains, i.e. production of food, specifically fruit and vegetables (banana and cassava growers), dairy milk, meat, eggs, and fish. While some products may be consumed in the household, others are traded with other households (with and without farming activities) either directly or through intermediary **food retailers**. The value chain-mapped income diversification opportunities highlight the introduction of an additional revenue stream through green biorefinery technology for **rural households** that produce **green leafy biomass** through their farming activities, e.g. farmers with grazing pasture, but also banana and cassava growers. The green biorefinery technology introduces a business opportunity for **feed processors** or **farmer organizations**, e.g. cooperatives, who can produce three product lines with five associated revenue streams: **ruminant feed** (presscake), **pig feed** (protein concentrate) **piglet feed** (whey), **poultry feed** (protein concentrate), and **whey** as a source of **biochemical components** for **biotechnology companies**. The addition of densification technology (**pelletizing line**) introduces a fourth product line, **fish feed pellets**, and additional revenue stream.

The animal feed products can be sold directly to farmers or to **feed merchants**, that can act as an intermediary in this trade. Farming organizations may choose to make non-financial arrangements for trade of products with farmers, especially farmers supplying green biomass. Similarly, farmers producing green biomass can pay for the biorefining service to obtain multiple value-added products for feeding their own animals or for sale to other farmers. While the green biorefinery products do not directly represent an income stream for rural farming households, with the exception of the latter instance, the products can support rural farming incomes and resilience to economic and environmental change by providing local sources of feed and forage with high-nutrient value during periods of otherwise low availability, e.g. dry season and droughts.

Biotechnology companies purchasing biorefinery whey can extract biochemical components that are of interest for biotechnological applications and product manufacturing, e.g. animal and human health products, which can subsequently be traded with veterinary and pharmaceutical product retailers for use by rural households with and without livestock production activities. The viability of this value chain is uncertain as the analysis of the whey from biorefining of the BIO4AFRICA feedstocks is a highly novel activity. The results of the whey analyses in Tasks 4.1 and 4.2 will thus inform the viability of these income streams for green biorefinery value chains in Uganda and Ghana.

5.1.1 PESTLE analysis of green biorefinery technology and products

Political and legal aspects

No direct or indirect incentives concerning green biorefinery introduction in Uganda and Ghana were identified during the literature review or engagement with relevant project partners, and surveys carried out as part of BIO4AFRICA project activities indicate that more Government support is needed to promote the technology (**D5.1**).

Social and economic aspects

Green biorefinery technology has the capacity to preserve forage during the growing season for use as presscake during periods less advantageous for growth, e.g. seasonal drought, as experienced in Tamale, Ghana, where the biorefinery will be implemented; or for use in a zero-grazing context, e.g. in urban and peri-urban areas around Kampala, Uganda. This capacity to support rural resilience, and urban and peri-urban dairy and beef farming that caters to growing urban populations, can contribute to sustainable agricultural, social and economic development for both rural and urban communities in Uganda and Ghana.

The capacity to extract a substantial portion of the protein content of grass from the fibrous portion increases the value of the forage or other green leafy biomass used as feedstock, and increases local feed availability across different production systems (pigs, poultry, fish), contributing to greater overall efficiency of regional agri-food systems (Jørgensen et al., 2022). The food-grade protein yield is expected to be 50%-200% higher per hectare than forage production alone (**D2.3**). Similarly, the use of whey as a sugar-rich piglet feed is an additional opportunity to gain more value from forage or other green leafy biomass (Jørgensen et al., 2022).

Suppliers of the leafy green biomass can gain additional revenue opportunities compared with grazing alone, while also generating a local supply of high-protein animal feed (protein concentrate) and storable ruminant fodder that contributes to animal productivity and does not compete with human food uses. In Uganda, the women farmers are most likely to benefit from both supply of leafy green biomass and a local supply of high-quality dairy cow feedstuff, a population segment that typically experiences low salaries and lack of access to credit (**D5.1**). The introduction of green biorefinery thus has strong potential to contribute to the income diversification opportunities available to women farmers. In Ghana, the farmers most likely to benefit from the supply of ruminant feed are pastoralists, who experience high vulnerability to environmental change and can therefore experience greater resilience through the supply of local supplementary feedstuffs when grazing pasture is limited. In addition, the green biorefinery itself can introduce job opportunities for operating the machinery.

Technological and environmental aspects

The green biorefinery technology being utilised in the BIO4AFRICA project, corresponding to **no. 18** in **D1.3** (**Catalogue of small-scale bio-based technologies suitable for rural Africa**), is close to commercialisation in the EU, but is considered to have a Technology Readiness Level (TRL) of 5-7 in the African context, due to the very different type of feedstocks available. The green biorefinery technology is a relatively simple, mechanical process that uses a cascading extraction approach to produce the high-fibre presscake and green juice, from which protein is precipitated and dried, leaving the whey fraction. The addition of densification technology allows the protein concentrate to be used in feed pellets to feed smaller livestock, e.g. poultry and fish.

In addition to pasture forage, the BIO4AFRICA project will also examine the potential of "synergy forages", e.g. green, leafy residue from cassava and banana, to be used in the green biorefinery, which would add value to these feedstocks that might not otherwise be exploited, i.e. would be managed as a waste product. The local provision of high-protein animal feed has the potential to reduce the environmental impact of animal rearing, due to less dependence on high-cost, imported feedstuffs, e.g. soy. The small-scale systems being implemented in the BIO4AFRICA project enable co—location near feedstock producers, reducing environmental footprint and economic costs associated with transport and ensuring good feedstock quality due to transport distances being relatively short.

5.2 Income diversification potential of carbonisation technologies

Three carbonisation technologies are being implemented in the BIO4AFRICA project: locally constructed kilns and adapted Brazilian kilns, which take dry feedstock materials (**Fig. 9a-c**) and HTC, which takes wet feedstocks (**Fig. 9d**).

Figure 9: Carbonisation technologies in the BIO4AFRICA project using traditional kilns, e.g. kilns from a) Ghana and b) Côte d'Ivoire; adapted, pollution-reducing kilns, e.g. wood-burning kilns from Brazil (c); and hydrothermal carbonization technology, e.g. as adapted for use in Senegal (d).

Four main applications for the biochar produced will be examined:

- Soil amendment for crop production (Uganda, Ghana, and Côte d'Ivoire)
- Water filtration (Côte d'Ivoire)
- Biogas production additive (Senegal)
- Solid (cooking) fuel (Senegal, in combination with densification technology)

Biochar also has other potential applications, e.g. soil remediation, animal feed additive, but its use for these purposes are not explored in the BIO4AFRICA project. The income diversification opportunities associated with the green biorefinery technology and products being examined are described in **Fig. 10**.

Figure 10: Income diversification potential of carbonisation technology and products for rural households engaged in farming activities (dark green), farming organizations and food processors (dark purple), biochar producers (grey), fuel producers (brown), water treatment service providers (blue) and retailers involved in agri-supplies, food and fuel sales (red). Yellow circles represent products, dark blue parallelograms represent technological processes, black lines indicate movement of products without financial flows, lines of other colours represent product movement with trade potential (line colour indicates the value chain actors in receipt of income from product trade).

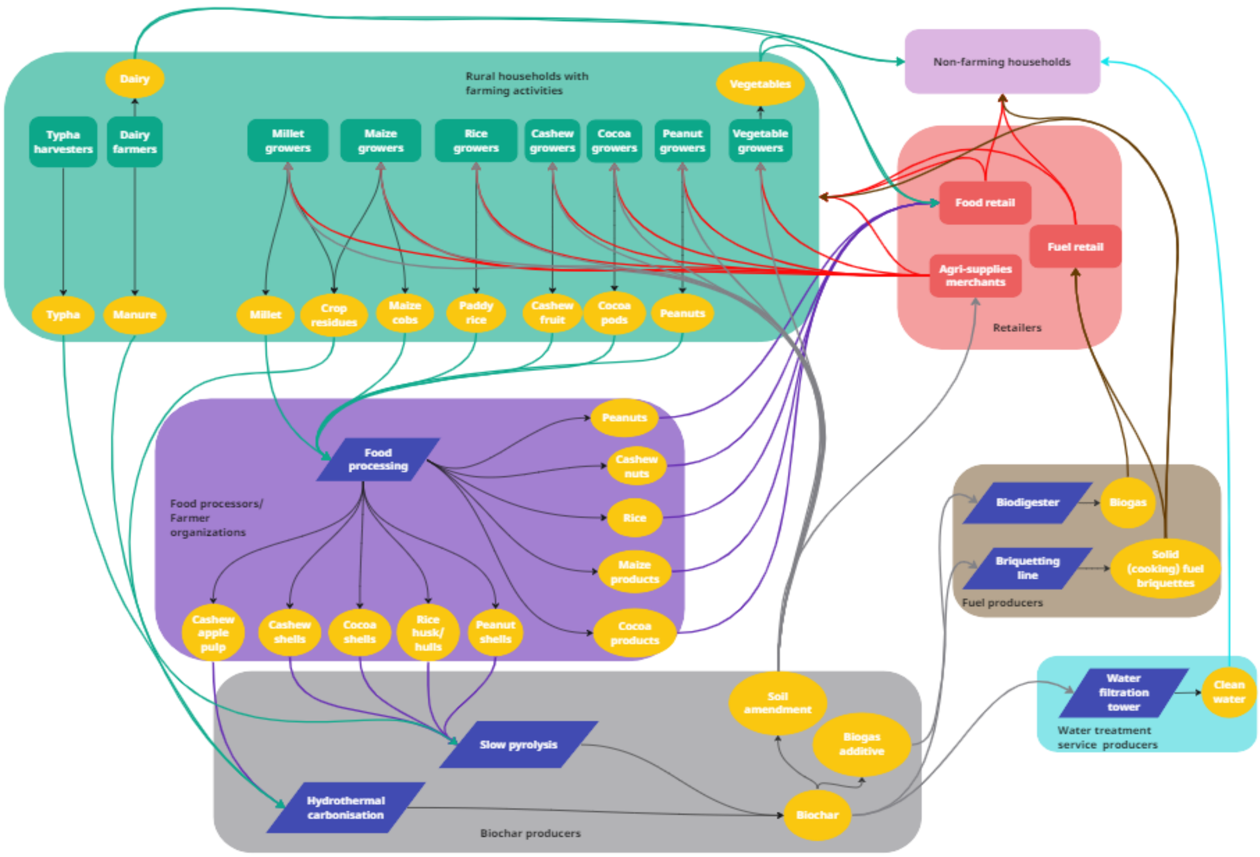


Figure 10 describes the main income generating activity of **rural households** engaging in farming activities relevant to carbonisation value chains, i.e. production of food, specifically vegetables, dairy milk, grains such as millet, maize, and rice, and commodity crops such as cashew, cocoa, and peanuts. While some food products may be consumed in the household, e.g. dairy and vegetables, these may also be traded with other households (with and without farming activities) either directly or through intermediary **food retailers**. Grain and commodity crops are sold to **food processors** (which may also be farmer organizations, e.g. cooperatives) for processing, which can sell these forward to **food retailers** for sale to households.

The introduction of pyrolysis and HTC technologies for biochar production adds additional revenue streams for rural households with farming activities and food processors/farmer organizations. **Biochar producers** can process post-harvest crop residues from rural households, e.g. millet and maize stalks, and post-processing residues from food processors, e.g. shells from cashew, cocoa, and peanuts, and rice husks/hulls, into **biochar** using **slow pyrolysis** technology. The introduction of **HTC** technology for **biochar** production from wet feedstocks creates the potential to add value to dairy production sidestreams (manure) and typha, an invasive species in Senegal, both of which can be sourced from rural households. Typha harvesting is therefore included as a potential income-generating activity relevant to rural households. **HTC** technology also enables value to be added to cashew apple pulp, a post-processing cashew residue, that can be sourced from food processors/farmer organizations.

Biochar producers can generate four revenue streams from the biochar produced. Biochar can be sold directly, or via intermediary **agri-supplies merchants**, to rural households with farming activities as a **soil amendment**. Biochar can also be sold to **fuel producers** as a **biogas additive** for improving biogas production, or as a primary component of **solid (cooking) fuel briquettes** that can be produced through **briquetting**. Both of these fuel products can be sold to farming and non-farming rural households directly or via intermediary **fuel retailers**. Biochar can also be used as a medium for **water filtration**, and sold to both public and private **water treatment service providers**, for supply of clean water to farming and non-farming rural households.

This map of income diversification opportunities across value chains associated with BIO4AFRICA carbonisation technologies and products suggests that food processors/farmer organizations, biochar producers, fuel producers, and even water treatment service providers may be distinct enterprises. However, the integration of some or all of these activities within one organization is also possible, and in the case of food processors/farmer organizations that integrates biochar production and processing with existing food processing activities this provides opportunities to transform waste products that are a business cost, into a revenue stream. An alternative approach to mobilising the value addition potential of these technologies is for the service of carbonisation to be provided to farming households or enterprises that bring feedstocks to be processed, and can then use or sell the resulting biochar in a similar way as the revenue streams described for biochar producers, above. In addition to income diversification potential there are other dividends for rural households from the carbonisation technologies and products, especially in the case where farmer organizations integrate these technologies in their activities. These include improving access to productivity-enhancing soil amendments for crop cultivation with the potential to reduce the need for mineral fertiliser and improve crop resilience to environmental change, e.g. drought; access to locally produced fuel that is sourced from agri-food residues and invasive species rather than forest; and improved access to clean water through a low-cost, locally produced water filtration medium.

5.2.1 PESTLE analysis of carbonisation technologies and products

Political and legal aspects

No direct or indirect incentives concerning carbonisation technologies were identified in the respective countries. However, there is very strong social acceptance within Côte d'Ivoire for the use of biochar, especially among farmers. In Senegal, there are national initiatives to support bio-based fuel production, e.g. the Senegal National Biogas Programme which aims to deploy more than 52,000 biogas digesters between 2021 and 2030. Moreover, Through the use of agri-food residues from commodity crops in particular, these technologies can support political ambition to improve the viability of cassava and cashew sectors in Côte d'Ivoire and rice and peanuts in Senegal (**D5.1**).

HTC technology requires a lengthy certification process (at least six months) to ensure that it can be operated safely, which is a challenge that can be mitigated through advance planning for this delay. In Côte d'Ivoire, biochar requires certification in order to enter the marketplace, e.g. for sale by agri-supply merchants as a soil amendment. However, no certification is required to provide the pyrolysis service to farmers for production of biochar from their own agri-food residues, for farmers or farming organizations to implement pyrolysis kilns to produce biochar for their own use, or for sale of biochar in bulk from INP-HB to farmers. The BIO4AFRICA project will contribute to a proposal for a change in legislation regarding biochar certification in Côte d'Ivoire.

Social and economic aspects

As in the case of green biorefinery activities in Uganda and Ghana (**section 5.1.1**), the utilisation of agri-food residues in particular can benefit rural women, who are primarily involved in farming activities in Uganda, Ghana and Senegal. Biochar applied as a soil amendment can also benefit rural households, and therefore farming women, due to the benefits it can generate for fertility, water holding capacity, and nutrient retention, and consequently crop yield (Kamali et al., 2022). Biochar also has the capacity to adsorb pollutants, a characteristic which has been applied for soil remediation (Brassard et al., 2019; Kamali et al., 2022). In the BIO4AFRICA project, this characteristic will be exploited for the purification of water in Côte d'Ivoire, with implications for human health and wellbeing. Biochar as a water filtration system has the capacity to remove heavy metal, suspended organic matter and reduce microbial content. As more than a third of the population of Côte D' Ivoire do not have reliable access to clean water, requiring women and girls to walk long distances to fetch water, reducing their capacity to engage in economic or educational activities, respectively.

While there are construction costs associated with introduction of Brazilian kiln and HTC technologies, in Ghana, Côte d'Ivoire, and Senegal, locally developed kilns are also in operation, which are typically cheaper to construct. Cross-case comparison of trial results will inform the cost-benefit assessment of producing biochar form locally developed kilns or novel carbonisation technologies. The carbonisation technologies, and associated processes in the value chains for biochar-based soil amendment, water filtration, solid fuel and biogas additives, all have the capacity to generate employment. This is especially the case where one or more of these activities is vertically integrated, creating the possibility of end-to-end localised production. In the case of solid fuel and biodigestion in Senegal this has implications for access to clean energy, and therefore health and wellbeing of rural households but especially women and children, who are often most exposed to the health risks associated with use of firewood and charcoal.

Technological and environmental aspects

The Brazilian kiln technology has been designed to combust woody material. The kiln comprises four circular ovens, where the feedstock is carbonized to create biochar, in a process lasting 6-7 days. The ovens are connected to a brick furnace with a 3.5m chimney to collect gases released during slow pyrolysis. Brazilian kiln pyrolysis has been evaluated as having a TRL of 5-7, with an aim to improve the TRL through adaptation to local feedstocks derived from agri-food sidestreams.

The HTC technology to be used in the BIO4AFRICA project is based on the design of Robbiani ((2013)). This is a highly prospective technology in the African context and is considered to have a TRL of 3-5. The suitability of the technology to wet biomass, e.g. cashew apple and livestock manure, and affordability of implementation make this technology particularly suitable for pilot locations with wet agri-food sidestreams, e.g. cashew production in Senegal and livestock-rearing in Uganda.

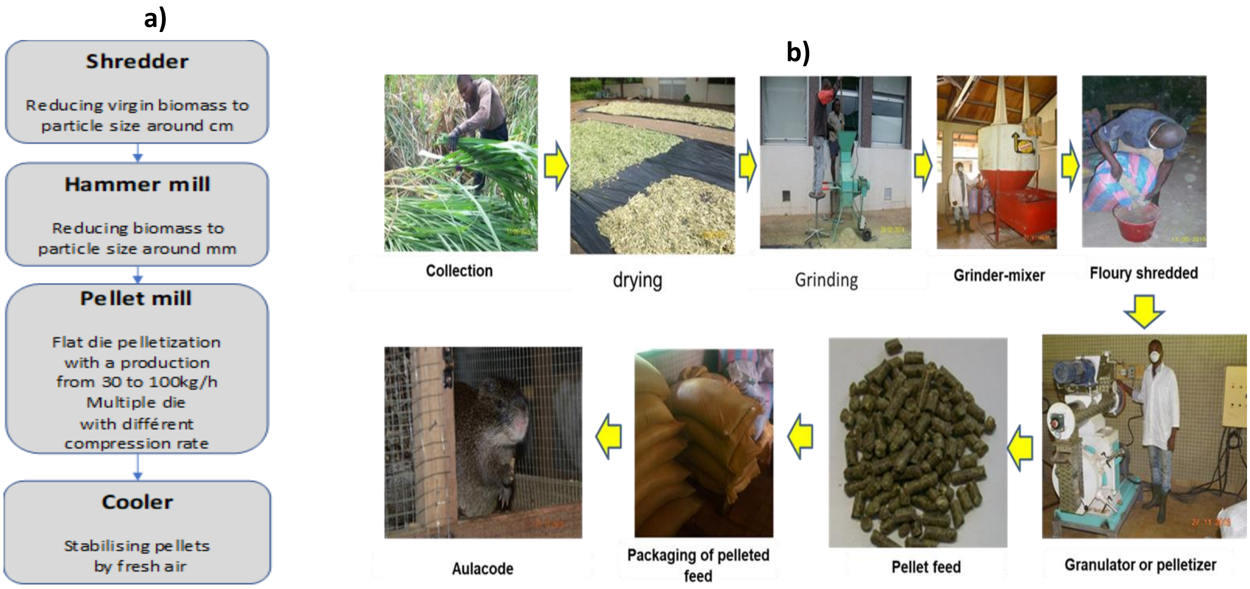
Biochar as a soil amendment can improve soil nutrient retention, which can reduce fertilizer requirements for crop productivity. In addition, through improving soil water retention, biochar can reduce the need for irrigation during the “shoulders” of dry season, and thus reduce general water demand. Biochar characteristics can vary substantially depending on the feedstock and pyrolysis conditions such as temperature, time and pressure. For application of biochar as a soil amendment, It is therefore important to characterise the biochar, and also evaluate the soil and agronomic conditions of the crops being produced by farmers in order to appropriately match the biochar type and application rate to the needs and production context of purchasing farmers.

Most of Senegal’s energy needs are met by biomass in the form of non-renewable firewood and charcoal, followed by fossil fuel, although there is good Government support for domestic biogas production. The stability and efficiency of biogas production, and calorific value of the resulting biogas, can be enhanced through biochar addition, as biochar can mitigate the inhibitive effect of compounds arising in the anaerobic digestion feedstock, e.g. heavy metals, antibiotics, and compounds generated during the anaerobic digestion process, e.g. volatile fatty acids (Zhao et al., 2021). The potential for biochar derived from carbonisation (including HTC) of local agri-food sidestreams to enhance anaerobic digestion efficiency and improve the purity of the resulting biogas can contribute to the green energy transition in Senegal, and provide a more ecologically sustainable alternative to firewood harvesting.

5.3 Income diversification potential of densification technologies

Densification uses biomass with small particle size (achieved through shredding or pulverisation in a hammer mill (**Fig. 11**)) and converts it to a dense, storable product that is often easier to transport and handle than the bulky raw materials.

Figure 11: a) schematic description of densification stages (RAGT, 2022) and b) pelletising process for animal feed pellets in Côte d'Ivoire



Five main applications for densification technology will be examined:

- Sheep feed pellets (Côte d'Ivoire)
- Rabbit feed pellets (Côte d'Ivoire)
- Poultry feed pellets (Côte d'Ivoire)
- Fish feed pellets (Uganda, also in combination with green biorefinery technology, **section 5.1**)
- Solid (cooking) fuel briquettes (Senegal, in combination with carbonisation technology, **section 5.2**)

The income diversification opportunities associated with the densification technology and products being examined are described in **Fig. 12**, with the exception of fish feed pellets incorporating protein concentrate derived from green biorefinery and solid (cooking) fuel briquettes which are already included in **Figures 8** and **10** respectively.

Figure 12: Income diversification potential of densification technology and products for rural households engaged in farming activities (dark green), food processors and farming organizations involved in food processing (dark purple), feed processors and farming organizations involved in feed processing (bright green), and retailers involved in food and feed sales (red). Yellow circles represent products, dark blue parallelograms represent processing by technologies, black lines indicate movement of products without financial flows, lines of other colours represent product movement with trade potential (line colour indicates the value chain actors in receipt of income from product trade).

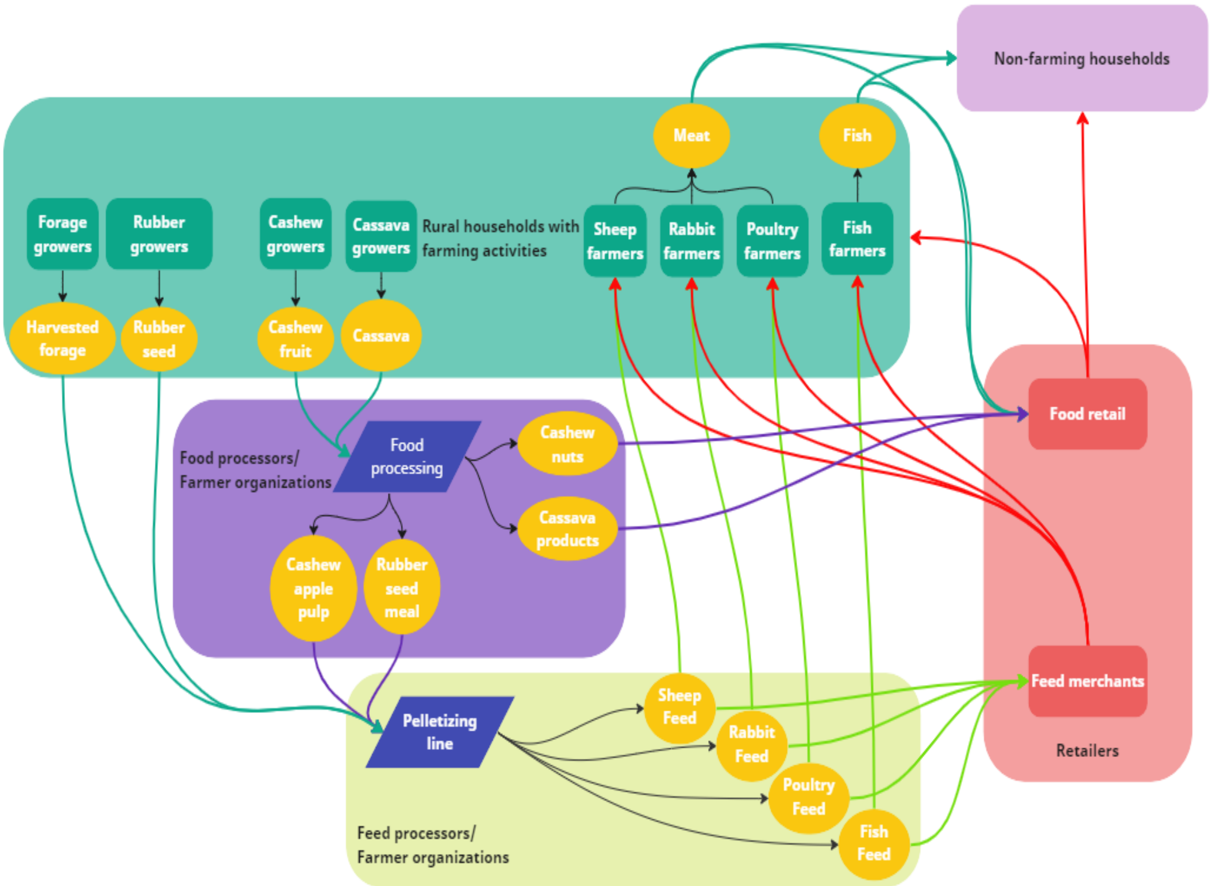


Figure 12 describes the main income generating activity of **rural households** engaging in farming activities relevant to densification value chains, i.e. production of food, specifically meat and fish, and commodity crops such as cashew, cassava, and agro-industrial crops such as rubber seed. While some food products may be consumed in the household, e.g. meat, these may also be traded with other households (with and without farming activities) either directly or through intermediary **food retailers**. Commodity crops are sold to **food processors** for processing, and these products can be sold forward to **food retailers** for sale to households.

Four main product lines for **feed processors/farmer organizations** with **pelletizing technology** are described in Fig. 12. Rubber seed can be sold to feed processors/farmer organizations for production of poultry feed pellets using pelletizing technology. While rubber seed can be applied for other uses, e.g. soap manufacture, only the application as animal feed is explored in the BIO4AFRICA project, and thus only this aspect of the rubber seed value chain is shown in this diagram. Rural households may also have access to pasture for harvesting of forage species which can be processed by **feed processors/farmer organizations** into **sheep** and **rabbit feed pellets**. Food processors can also mobilise post-processing residues as an income stream through sale to feed processors for production of **sheep, fish** and **rabbit feed pellets**. These animal feed pellets can be sold directly to rural households with farming activities or via an intermediary **feed merchant**. Feed merchants/farmer organizations with pelletizing technology can also offer the service of pelletizing to rural households or food processors with a supply of forage crops, rubber seed, or agri-food residues, to produce feed pellets for their own use (rural households) or for sale to farmers or feed merchants. **Protein concentrate** produced by **green biorefinery technology** can also be used by feed processors with pelletizing technology to produce protein-enriched **fish feed pellets**. However, the income diversification opportunities associated with the combination of green biorefinery and pelletizing technology are described in detail in **Fig. 8** and **section 5.1** and so are not included in this diagram.

Another densification technology, **briquetting**, provides additional income generation opportunities for rural households with farming activities and food and feed processors/farmer organizations with food and feed processing activities, e.g. through the production of **biochar briquettes** for **solid (cooking) fuel** from agri-food residues. The income diversification opportunities associated with the combination of carbonisation and briquetting technology are described in detail in **Fig. 10** and **section 5.2** and are therefore not included in this diagram.

The use of densification technologies alone or in combination with green biorefinery or carbonisation technologies can create income diversification opportunities through the addition of value to agri-food residues, agro-industrial crops such as rubber seed, and forage crops. In addition, the local production of animal feed pellets through pelletizing can: 1) enhance rural household resilience to economic and climate shocks, by extending shelf-life compared with the raw materials and providing an easily storable source of nutritious animal feed from seasonal products such as forage; and 2) contribute to animal health through the targeted inclusion of health-promoting ingredients, e.g. forage species with anthelminthic effects as trialled by Côte d'Ivoire with sheep feed pellets. In the case of farmer organizations integration of pelletizing within other food and feed processing activities, alone or in combination with green biorefinery and briquetting technologies, can enhance capacity to promote collective revenue generation capacity and resilience.

5.3.1 PESTLE analysis of densification technologies and products

Political and legal aspects

While no political incentives for densification value chains in Ghana, Côte d'Ivoire or Senegal were identified, these value chains are also without any significant political or legal barriers. Through the use of agri-food residues from commodity crops in particular, these technologies can support political ambition to improve the viability of cassava and cashew sectors in Côte d'Ivoire and rice and peanuts in Senegal (**D5.1**).

Social and economic aspects

Densification allows different raw materials to be combined according to specific "recipes", e.g. containing biochar and protein concentrate, and adapted to consumer needs. In the case of livestock feed especially, this can make the target feed more ingestible and attractive to animals. The feed pellets and biochar briquettes developed in the BIO4AFRICA project are largely produced using agri-food residues or forage plants harvested when seasonally available. This is an economic opportunity for farmers with forage or post-harvest residues and food and feed processors with post-processing residues. However, pelletizing equipment can involve high operating costs, which may be difficult to recoup if using higher cost materials (as opposed to agri-food residues), especially in a competitive market such as that of fish feed pellets in Ghana. Including novel ingredients to achieve additional benefits for farmers and their animals can help distinguish pellets from their competitors. Forage species with anthelminthic effect, *Cajanus cajan* and *Leucaena leucocephala*, have been trialled as added ingredients in sheep pellets in Côte d'Ivoire. The trial results indicate a positive impact, including 80% reduction in parasite load, reduced lamb mortality and improved weight gain. The improvements in lamb performance suggest a 15% increase in farmer income compared with the control diet, indicating added advantage for the farmer from using the pellets as well as added value for the pellet producer. Trials with biochar briquettes in Senegal are at too early a stage to indicate the likely economic implications for briquette producers and users.

The use of densification technologies for producing feed pellets and biochar briquettes can generate employment opportunities in relation to equipment operation, and collection of feedstocks (in the case of feed pellet production from agri-food residues and forage species). The local production of nutritious, high-quality animal feed and cooking fuel can also support greater resilience to economic and environmental change among rural households, including those not engaged in farming activities.

Biochar briquettes will be trialled using improved "Jambar" stoves that produce less smoke and are typically more efficient in fuel use than traditional stoves, when using traditional fuels (wood and charcoal) (Sow, 2022). The results will thus illustrate the viability of biochar briquettes compared with traditional fuels, but also using improved cookstove technology, which has benefits to women and children, both of whom are more exposed to indoor air pollution and negative health impacts associated with wood and charcoal fuels (Chidumayo & Gumbo, 2013; Sow, 2022).

Technological and environmental aspects

In BIO4AFRICA, briquetting and pelletising processes will be enlarged to 150-200kg/h, to accommodate the local feedstocks with greater efficiency than that offered in existing systems, allowing better value chain development. Novel feedstocks, in both raw form and transformed through carbonisation or green biorefinery, will also be employed to explore value addition potential for these biomass types. These are described in **sections 5.1** and **5.2** respectively. Enlarged densification systems to accommodate raw biomass (Côte d'Ivoire), biorefinery protein concentrate (Ghana) and biochar (Senegal), are perceived to have TRL of 5-7, with biochar briquetting in particular being less mature, with TRL of 3-6.

Briquettes for solid (cooking) fuel use need to be of an appropriate size to easily add to cooking stoves. Oval-shaped briquettes were selected as the preferred briquette type for biochar briquettes in Senegal. A balanced composition, e.g. in terms of ash, binders, etc. is important to achieve in order to produce a good-quality briquette. The pelletizing equipment being implemented in the BIO4AFRICA project has been adapted to local needs (e.g. throughput of processing line) but also the target animal(s). While larger sized pellets are suitable for sheep, smaller pellets are required for smaller animals like rabbits, poultry and fish. In Côte d'Ivoire a ring-die press with three different size holes is being implemented to allow the press to be adjusted to the needs of the target livestock. Fish feed pellets not only need to be a suitable size but also need to float without disintegrating, requiring a pelletizing mill with a specialised extruder and capacity to coat the pellets during manufacture. The balance of nutritional composition, durability (to ensure low levels of dust) and density is important to achieve for all animal types.

The capacity to produce competitive animal feed pellets locally from agri-food residues and forage reduces the need to import animal feed or feed ingredients, while also managing agri-food sidestreams that can otherwise become waste, e.g. cashew apples left to decompose in fields (**D5.1**). In Senegal, where biochar briquettes are being trialled as solid (cooking) fuel, firewood and charcoal are the main sources of cooking fuel, and even in urban areas where LPG stoves are prevalent, charcoal is used as a back-up fuel to provide fuel security when LPG supply is unreliable. Ecologically, extractive deforestation can result in species decline and degrade soil and ecosystem integrity, leaving habitats and local communities more vulnerable to destructive environmental shocks, e.g. flooding and landslides due to heavy rainfall on exposed soil. Biochar from agri—food residue has the potential to provide a more sustainable alternative to wood-derived charcoal, while also generating value for feedstock producers.

6. Conclusions and Next Steps

This report describes the framework for cross-case comparison of bio-based products trialled in Uganda, Ghana, Côte d'Ivoire and Senegal as part of the BIO4AFRICA project, and for the evaluation of income diversification potential associated with these products and the value chains in which they are embedded.

The report provides an initial exploration of within and between country trial comparisons, based on trial designs, including identification of parameters that will be compared within and between countries. From this initial exploration, **nine trial cases were identified which are suitable for within country comparison**, i.e. are being undertaken using a combination of one or more locally developed and novel technologies implemented through the BIO4AFRICA project. These trial cases involve fish feed pellet trials and biochar-based soil amendment trials in Ghana (two), sheep and rabbit feed pellet trials and biochar-based soil amendment trials in Côte d'Ivoire (four), and biochar-based biogas production additive and biochar solid (cooking) fuel briquettes in Senegal (three). **Twelve trial cases were identified which are suitable for between country comparison**, i.e. are being undertaken in one or more countries. These trial cases involve green biorefinery products in Uganda and Ghana (eight product trials) and pyrolysis products in Uganda, Ghana and Côte d'Ivoire (four product trials). As few trials have been completed to a point where results are comparable, the analysis in this report was limited to that of trial designs/protocols.

The report also provides an initial analysis of income diversification potential, based on literature review including BIO4AFRICA deliverables published to date, and peer-reviewed and grey literature; product trial designs and early product trial results; and interviews and consultation with project partners involved in technology adaptation and implementation and product trials. On this basis, the **income diversification opportunities for rural households and businesses have been mapped across the value chains** in which the small-scale bio-based technologies and their products are being deployed. An **initial PESTLE analysis** has also been conducted, scoping the opportunities and challenges associated with the technologies and products with regard to political, economic, social, legal, technological and environmental aspects.

The final cross-case comparison and evaluation of income diversification potential (**D4.5**) will be completed by **M44**. The next steps for cross-case comparison includes the **compilation of all product trial results**, which will enable cross-case comparison of trial outcomes, and more informed evaluation of income diversification potential. The next steps for evaluation of income diversification potential includes expanding and updating the preliminary analysis based on engagement with a wider network of project stakeholders, including beneficiaries of the project (e.g. farmers and women's groups trialling biochar briquettes for cooking). This will be supported by more extensive project results and project partner knowledge from the completion of technology adaptation and deployment, and product trials (including trial results), and the results of other activities being undertaken in the BIO4AFRICA project, e.g. life cycle assessment (**Work Package 5**) and business accelerator programmes (**Work Package 6**).

7. References

Abdul-Nasser Salifu, G. (2019). The Political Economy Dynamics of Rural Household Income Diversification: A Review of the International Literature. *Research in World Economy*, *10*(3), 273–290.

Achinas, S., Horjus, J., Achinas, V., & Euverink, G. J. W. (2019). A PESTLE Analysis of Biofuels Energy Industry in Europe. *Sustainability 2019, Vol. 11, Page 5981*, *11*(21), 5981. https://doi.org/10.3390/SU11215981

Brassard, P., Godbout, S., Lévesque, V., Palacios, J. H., Raghavan, V., Ahmed, A., Hogue, R., Jeanne, T., & Verma, M. (2019). Biochar for soil amendment. *Char and Carbon Materials Derived from Biomass: Production, Characterization and Applications*, 109–146. https://doi.org/10.1016/B978-0-12-814893-8.00004-3

Chidumayo, E. N., & Gumbo, D. J. (2013). The environmental impacts of charcoal production in tropical ecosystems of the world: A synthesis. *Energy for Sustainable Development*, *17*(2), 86–94. https://doi.org/10.1016/J.ESD.2012.07.004

Davis, B., Di Giuseppe, S., Zezza, A., & Zezza, A. (2014). *Income Diversification Patterns in Rural Sub-Saharan Africa: Reassessing the Evidence*. https://papers.ssrn.com/abstract=2524162

Jørgensen, U., Jensen, S. K., & Ambye-Jensen, M. (2022). Coupling the benefits of grassland crops and green biorefining to produce protein, materials and services for the green transition. *Grass and Forage Science*, *77*(4), 295–306. https://doi.org/10.1111/GFS.12594

Kamali, M., Sweygers, N., Al-Salem, S., Appels, L., Aminabhavi, T. M., & Dewil, R. (2022). Biochar for soil applications-sustainability aspects, challenges and future prospects. *Chemical Engineering Journal*, *428*, 131189. https://doi.org/10.1016/J.CEJ.2021.131189

Laghari, M., Naidu, R., Xiao, B., Hu, Z., Mirjat, M. S., Hu, M., Kandhro, M. N., Chen, Z., Guo, D., Jogi, Q., Abudi, Z. N., & Fazal, S. (2016). Recent developments in biochar as an effective tool for agricultural soil management: a review. *Journal of the Science of Food and Agriculture*, *96*(15), 4840–4849. https://doi.org/10.1002/JSFA.7753

Lee, G., Kim, D., & Lee, C. (2020). A sequential pattern mining approach to identifying potential areas for business diversification. *Asian Journal of Technology Innovation*, *28*(1), 21–41. https://doi.org/10.1080/19761597.2019.1693900

Niehof, A. (2004). The significance of diversification for rural livelihood systems. *Food Policy*, *29*(4), 321–338. https://doi.org/10.1016/J.FOODPOL.2004.07.009

Ravindran, R., Donkor, K., Gottumukkala, L., Menon, A., Guneratnam, A. J., McMahon, H., Koopmans, S., Sanders, J. P. M., & Gaffey, J. (2022). Biogas, Biomethane and Digestate Potential of By-Products from Green Biorefinery Systems. *Clean Technologies 2022, Vol. 4, Pages 35-50*, *4*(1), 35–50. https://doi.org/10.3390/CLEANTECHNOL4010003

Robbiani, Z. (2013). *Hydrothermal carbonization of biowaste/fecal sludge: Conception and construction of a HTC prototype research unit for developing countries* [MSc]. Swiss Federal Institute of Technology.

Singh, B., Singh, B. P., & Cowie, A. L. (2010). Characterisation and evaluation of biochars for their application as a soil amendment. *Soil Research*, *48*(7), 516–525. https://doi.org/10.1071/SR10058

Sow, S. (2022). Cookinations: Mechanisms to Decouple Wood Production and Food Preparation in Sub-Urban Areas. *Sustainable Energy Access for Communities*, 139–146. https://doi.org/10.1007/978-3-030-68410-5_13

Windeatt, J. H., Ross, A. B., Williams, P. T., Forster, P. M., Nahil, M. A., & Singh, S. (2014). Characteristics of biochars from crop residues: Potential for carbon sequestration and soil amendment. *Journal of Environmental Management*, *146*, 189–197. https://doi.org/10.1016/J.JENVMAN.2014.08.003

Zhang, Y., Cui, Y., Chen, P., Liu, S., Zhou, N., Ding, K., Fan, L., Peng, P., Min, M., Cheng, Y., Wang, Y., Wan, Y., Liu, Y., Li, B., & Ruan, R. (2019). Gasification Technologies and Their Energy Potentials. *Sustainable Resource Recovery and Zero Waste Approaches*, 193–206. https://doi.org/10.1016/B978-0-444-64200-4.00014-1

Zhao, W., Yang, H., He, S., Zhao, Q., & Wei, L. (2021). A review of biochar in anaerobic digestion to improve biogas production: Performances, mechanisms and economic assessments. *Bioresource Technology*, *341*, 125797. https://doi.org/10.1016/J.BIORTECH.2021.125797