



Operationalising the East African bioeconomy strategy: An assessment of industrial readiness of Uganda's banana fibre sector

Daphine Kamusingize^{a,c,*}, Esther Ronner^a, Godfrey Taulya^{b,1}, Rosa de Vos^a, Priver Namanya^c, Jerome Kubiriba^c, Katrien Descheemaeker^a

^a Plant Production Systems Group, Wageningen University & Research, P.O. Box 430, 6700AK Wageningen, the Netherlands

^b International Institute of Tropical Agriculture, P.O. Box 7878, Uganda

^c National Agricultural Research Organization, P.O. Box 7065, Uganda

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ABSTRACT

With SDG targets due in 2030, transitioning from a fossil-based to a green economy is urgent. Key to this transition is increased use of agricultural residues, e.g., banana pseudo-stems, as raw material for bio-based industries. However, a knowledge gap exists on the current level of Industrial Readiness (IR) of various bio-based value chains, beyond utilization options for such materials. We conducted a multi-dimensional sustainability assessment of the status of IR of Uganda's banana fibre sector and identified strategic requirements to sustainably upscale production and processing. Systematically, we collected and analysed data obtained through resource mapping, interviews and FGDs to: (i) map biomass flows; (ii) map relations among actors; (iii) assess readiness of farmers to supply raw material; and (iv) describe, from a stakeholders' perspective, the factors relevant in advancing the industry towards readiness. Results indicate that banana fibre biomass flows followed a complex pathway from pseudo-stem production to marketing and waste disposal, in which fibre processors were the most influential actors. Out of 102 farmers assessed, 40 % were ready (with *ability*) to sell pseudo-stems. Yet, over 70 % expressed interest to sell on condition of substantial price-increase. To achieve IR, various aspects were at nascent status of readiness but require attention: markets; actor partnerships; public awareness; human, technical and infrastructural capacity; and sustainability issues. Ultimately, sectoral transformation to industrial level is timely. However, it requires joint action to expand markets, targeted investment including policy implementation, and negotiation of trade-offs among actors. Also, enhancing methods developed for future evaluation of similar industries.

1. Introduction

With five years remaining to achieve the global Sustainable Development Goals (SDGs) by 2030, the urgency of finding solutions to transition from a fossil-based economy to a green economy due to growing environmental concerns and prospects of irreversible climate change is paramount (UN, 2023; Yang et al., 2021). A green economy is envisioned to improve the wellbeing of people, achieve social equity, and significantly reduce environmental impacts (UNEP, 2011). A key component of this transition is the increasing global demand for natural fibre for making bio-based materials (Kumar et al., 2019).

The total production potential of the global fibre industry is projected to reach about 150 million tonnes by 2030, of which 64 % is now

sourced from petroleum-based synthetic fibres, and 28 % from non-food plant-based fibres, such as cotton, hemp, sisal, and wood (TextileExchange, 2021). However, production and disposal of synthetic materials lead to negative environmental impacts, such as pollution, while non-food plant-based fibres compete for land and natural resources that are needed for food production and biodiversity conservation. The fibre industry, thus, needs bio-based solutions to transition to a more sustainable bioeconomy with minimum impact on the environment and food security. Afterall, a bioeconomy presents strong potential synergies with climate change mitigation and adaptation, especially for the agricultural sector (Oguntuase and Adu, 2020). Agricultural residues, for example, are a potential source of raw material for bio-based industries (Jayaprakash et al., 2022; Kumar Sarangi et al., 2022).

* Corresponding author.

E-mail address: daphine.kamusingize@wur.nl (D. Kamusingize).

¹ Makerere University, P.O. Box 7062, Kampala, Uganda.

These minimize competition for natural resources while providing an additional source of income for farmers (Adhia et al., 2021; Kremen, 2015).

Many countries have recently developed bioeconomy strategies to reduce dependency on finite natural resources (Gardossi et al., 2023; GermanyBioeconomyCouncil, 2015). For example, East Africa's regional bioeconomy strategy aims to develop bio-based industries to transform agriculture and energy sectors by using abundant, yet underutilized, natural resources to produce value-added products. This approach seeks to generate wealth and integrate smallholder farmers into new value chains (Virgin et al., 2022).

Research findings in the past decade show that fibres from banana pseudo-stems have superior qualities for industrial use, e.g. in the textile industry (Provin et al., 2024). The banana pseudo-stem is the cylindrical structure of tightly compacted elongated leaf stalks, called sheaths, that rise from the soil and carry the leaves upwards, while offering mechanical support to the plant (Speijer and De Waele, 1997). These sheaths contain fibres with properties such as low elongation, high tensile strength, and light weight, comparable to commonly preferred plant-based fibres like jute, abaca, cotton, and sisal. Yet, the potential to use these fibres remains grossly under-exploited as banana residues are commonly left on the field after harvest (Omotoso and Ogunsile, 2010; Ray et al., 2012; Silla et al., 2019).

The Great Lakes Region of East Africa is among the top five global producers of banana, with over 20 million metric tonnes produced in 2021, from an estimated acreage of 4 million hectares (FAO, 2021). This translates into a production of about 0.8–1.6 billion harvested pseudo-stems (Nalunga et al., 2015), and an estimated annual fibre production potential of 0.02 – 0.04 t ha⁻¹ (Muganga, 2022). This is 5 – 11 % of fibre produced from Abaca (*Musa textilis* Nee) in the Philippines (0.38 t ha⁻¹ in 2019²), the world's top *Musa* fibre producer. Abaca is the closest relative of banana, belonging to the same family, *Musaceae* (Kozłowski and Mackiewicz-Talarczyk, 2020). The banana fibre sector, therefore, presents an opportunity for the East African region to operationalize its bio-based industrial development agenda.

We used the banana industry in Uganda, the leading producer of banana in Africa and third globally (FAO, 2024), as a case study. Banana production systems in Uganda are characterized by high genetic diversity, minimal use of external inputs, and a strong reliance on recycling banana residues. In particular, farmers extensively use harvested pseudo-stem biomass as mulch to conserve soil and water (Kema and Drenth, 2018; Tinzaara et al., 2018). There is an existing banana fibre cottage industry producing mainly crafts, hair extensions, textiles, paper and bio-fuels for cooking (Eunice Gatonye, 2022; Gumisiriza et al., 2017; Voice of America, 2023).

So far, studies on banana fibre have mainly focused on widening the utilization scope of the fibre, e.g., for textiles (Balda et al., 2021; Ilyas et al., 2019; Provin et al., 2024; Ramdhoney and Jeetah, 2017). Yet, tapping into the increasing global fibre demand requires upscaling of the current small-scale fibre production and processing status to industrial scale. At the same time, increased utilization of banana fibre may have drawbacks, such as loss of biodiversity through expansion of production acreage, soil degradation if pseudo-stems are not retained for nutrient recycling, and food insecurity if pseudo-stems are harvested before fruiting. This is important since bio-based businesses need to operate within environmental and social limits while remaining economically viable (Pitkänen et al., 2016). Hence, the development of bio-based industries requires an understanding of various sustainability dimensions (Barra and Falcone, 2024). Therefore, this study conducts an in-depth, multi-dimensional sustainability analysis of challenges and opportunities for upscaling banana fibre production and processing in Uganda. Key enabling factors for upscaling include streamlining the value chain, addressing market barriers, strengthening partnerships

among actors, and creating an enabling policy environment for the industry to successfully introduce, adopt, and profit from innovations (Orozco and Grundmann, 2022; Poku et al., 2018; Salvador et al., 2022). Detailed information on such factors in Uganda's case is currently limited.

We assessed the level of preparedness to upscale production and processing of banana fibre in Uganda through the concept of Industrial Readiness (*IR*) (Pacchini et al., 2019). Most existing frameworks for *IR* have either assessed the technology (Clausing and Holmes, 2010; Mankins, 2009) or innovation (Orozco and Grundmann, 2022) as indicators of *IR*, and rarely considered societal readiness (Bruno et al., 2020). Yet, the readiness of an innovation for upscaling does not necessarily guarantee readiness of the actors involved (McCampbell et al., 2021). Additionally, a study by Falcone et al. (2019) emphasizes the need for new methodological frameworks in this area to incorporate social aspects encompassing viewpoints of diverse stakeholders. Therefore, it is crucial to assess *IR* from a multi-dimensional sustainability perspective to ascertain the status of preparedness of bio-based innovations in contributing towards a sustainable bioeconomy. To the best of our knowledge, there is no established index for holistically assessing *IR*.

In addition to assessing the overall readiness of the banana fibre sector, we focused specifically on the readiness of banana farmers as potential suppliers of raw material. Discussions of the bioeconomy often overlook readiness of the primary actors responsible for supplying bio-resources (Lima, 2022). In Uganda, stakeholders like fibre producers and processors often assume that banana farmers are always available, viewing their crop residues as a 'waste' product that can simply generate additional income. However, farmers are heterogeneous in their access to resources, production capacities and aspirations, as well as cultural norms and perceptions (Gambart et al., 2020; Mwijage et al., 2009; Ochola et al., 2013). Yet, *IR* needs a well-organised, sustainable production and supply chain of raw material, with sufficient benefits to the farmers.

This study therefore aimed at assessing the multi-dimensional status of *IR* of Uganda's banana fibre sector and identifying strategic requirements necessary to sustainably upscale fibre production and processing. Specifically, we: (i) mapped the banana fibre biomass flows; (ii) mapped relations among actors in the value chain; (iii) assessed the status of readiness of banana farmers to supply raw material for the fibre industry; and (iv) described, from the stakeholders' perspective, the factors relevant in advancing the fibre industry towards readiness for commercial production and processing.

The rest of the paper is organized as follows: Section 2 describes the analytical framework that underlies the research procedure, and the methods used to collect and analyse data. In Section 3, we present the main findings of the study and discuss their implications in Section 4. Finally, Section 5 presents concluding remarks.

2. Materials and methods

2.1. Analytical framework

This study builds on a 'stage-gate' framework developed by Holden (2022), who assessed the level of readiness of new business innovations for a sustainable circular bioeconomy. This framework combines different dimensions of readiness - technological, innovation and societal - with a life cycle approach to obtain evidence-based understanding of readiness of an innovation. However, this framework is data demanding, time consuming, expensive, and impractical to implement for budding innovations, as readiness is achieved over time with incremental improvements. The use of Rapid Rural Appraisal (*RRA*) techniques, such as expert interviews (Chambers, 1992), offers a quicker and less expensive overview of the status of readiness necessary to guide stakeholders with initial decision-making and defining investment priorities. In this study, therefore, insights from Holden's framework and

² <https://www.philfida.da.gov.ph/index.php>

RRA techniques are combined into an overarching Situational Analysis (SA) framework (Clarke, 2021) to holistically assess the readiness of the banana fibre sector.

SA departs from the situation of inquiry, which, in this case, is the status of IR of Uganda's banana fibre sector. SA was used to explore the fundamental non-human and human elements (Clarke et al., 2015) and cross-cutting issues in the situation. Then spatial and temporal elements were integrated to understand the evolution of the sector. Non-human elements included the objects in the situation, such as resource flows and cultural practices related to pseudo-stem biomass (objective i). Human elements included the different actors in the situation, the activities they engaged in, and relationships among them (objective ii). Actor relationships were further explored through social network analysis (Scott, 2012). The element on cross-cutting issues included fibre-related aspects that encompassed both human and non-human elements facilitating or constraining production and processing (objective iv). Spatial elements included locations of different actors (human) and actants (non-human) while temporal elements included historic, current, and future expected events in the development of the sector. We considered 2022 as the baseline year for the current situation. The SA framework also emphasises the importance of understanding implicated actors to better appreciate power differences in the situation of inquiry. Clarke (2021) defines implicated actors as persons, whether present or absent, that are neither involved in actual negotiations of self-representation nor are their opinions sought out openly; hence, considered less powerful despite having agency. This study considered banana farmers as implicated actors.

In SA, findings about the situation of inquiry are analysed through three types of maps (Clarke et al., 2015), of which two were considered in this study: 1) a situational map that lays out the major elements in the situation of inquiry, and 2) a 'social worlds' map that shows actors and their relationships. Positional maps, meant to articulate a range of discursive positions, occupied or not, on key issues were not considered since they are independent of persons. Rather, we constructed a farmer readiness map to display the position of banana farmers along a standardized readiness scale developed for the purpose of this study (objective iii). This scale was based on a quantifiable parameter, *Farmer Readiness (FR)* as an integral part of IR. We define FR as the ability and willingness of a farmer to sustainably produce and supply pseudo-stems

for the fibre industry. For FR, we combined the generic sustainability tool for assessing agricultural systems, embedded in the *Principle, Criteria and Indicator (PC&I)* theory (van Bueren and Blom, 1997; van Cauwenbergh et al., 2007), with a farm typology approach (Alvarez et al., 2014) into a FR assessment framework.

To understand the major readiness factors in the banana fibre sector (objective iv), the dimensions of readiness from Holden (2022) were adopted as general themes for analysis of stakeholders' perspectives which were revealed through RRA. *Technological readiness* involved technical aspects associated with banana fibre production and processing i.e., the production of raw material (pseudo-stems and raw fibre) and the development of value-added fibre products. *Innovation readiness* encompassed aspects related to the fibre business such as resource flows, marketing systems, and support towards the investment. *Societal readiness* focused on actors' characteristics, including farm type, gender aspects, knowledge, and skills. As a proxy for *life cycle analysis*, we examined stakeholders' views on managing waste products from the fibre extraction process, competing farm-level uses of pseudo-stems, such as mulching or livestock feed, and the trade-offs with food production caused by early harvesting. Together, these readiness factors offer insights in opportunities and challenges for improving IR of the banana fibre sector in Uganda.

2.2. Data collection, processing, and analysis

Data, collected in 2022, were processed and analysed following a systematic mixed methods research procedure (Fig. 1) detailed below.

2.2.1. Steps 1–2: biomass flows, actor relations and readiness factors

Thirty-two in-depth key informant interviews were conducted to obtain data from two main stakeholder categories, i.e., *local knowledge experts* and *process professionals* (Table A.1). Participants were selected using both purposive and snowball sampling techniques. Audio recordings obtained were manually transcribed. Stakeholder perspectives were complemented with data obtained through field observations of fibre-related activities in the different geographical locations. Geo-referenced data of spatial elements, such as the location of fibre extraction machinery, were obtained. The social network analysis of actors was conducted with data obtained from key informant interview

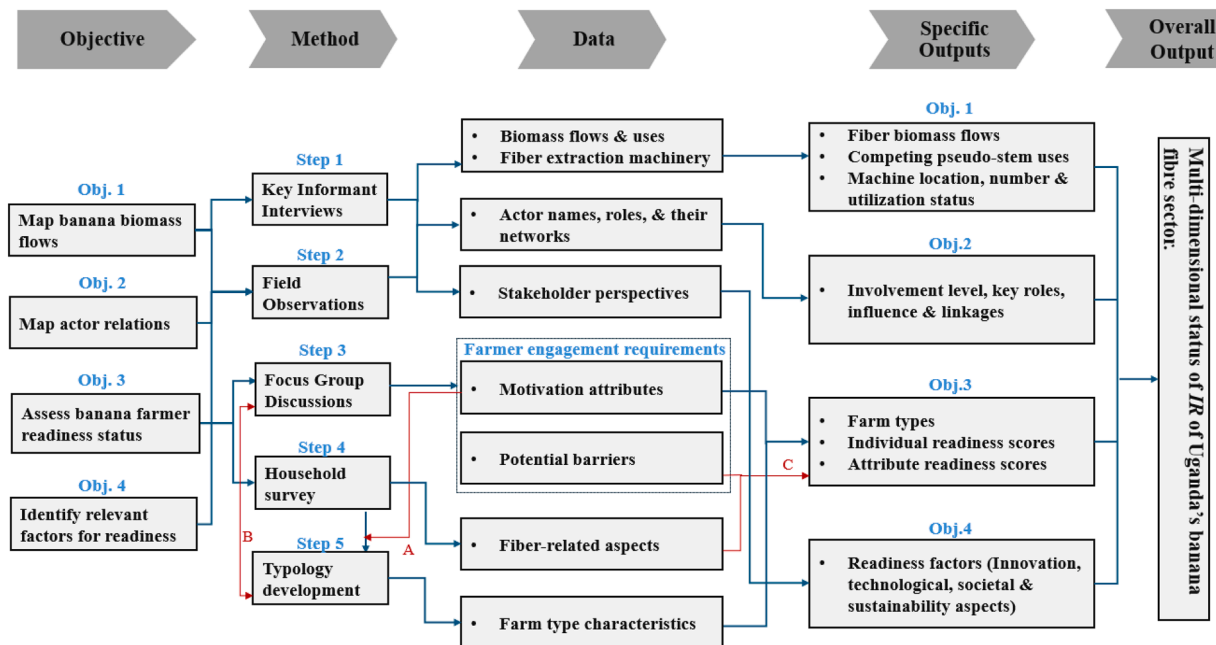


Fig. 1. Schematic diagram showing the research procedure. The blue lines indicate the general flow of the approach while the red lines indicate intermediary processes (i.e., A: indicator selection guide and B: validation of typology results) or complementary results (i.e., C) for a given objective.

transcripts, compiled into an 'edge-list' i.e. a tabular representation of the relationships between nodes in a network (Luke, 2015). Data obtained on banana fibre-related biomass flows was qualitatively constructed and graphically presented. Maps showing spatial elements were developed in an ArcGIS Pro environment. Actor relations were analysed using social network analysis packages in R (v4.3.2) software (Appendix A.1).

The *Line-of-Argument* (LoA) synthesis approach (Noblit and Hare, 1988) was used to elucidate major readiness factors. ATLAS.ti (v.22) software was used to code and analyse data from the key informant interview transcripts and field notes to reveal these factors. Dimensions of *IR* were adopted from Holden (2022) and inductive coding used to identify the most important factors raised by stakeholders (third order codes, Table A.2) (Corbin and Strauss, 2013). The readiness factors obtained were finally assigned a qualitative score to show status of readiness using a Likert scale, i.e., *Not ready, Infancy, Nascent, and Ready*. The score considered developments made to date and limitations.

2.2.2. Steps 3–5: status of readiness of banana farmers to engage in the fibre sector

A situation is best understood by those who live it. This study explored banana farmers' perspectives to understand underlying socio-economic factors that could motivate or constrain them from actively engaging in the banana fibre sector as raw material producers. We considered banana farming households in two ecologically contrasting banana growing districts, namely Isingiro (south-western) and Bunyangabu (western) in Birere and Rwimi sub-counties respectively (Fig. A.1) (UBOS, 2010). The banana cropping systems in Isingiro are predominantly monoculture stands with patches of scattered banana-coffee plantations. Those in Bunyangabu were diverse mixed perennial-annual systems characterized by the banana-cereal system. Banana fiber production activities in both sites were characterized by a few isolated groups engaged in craft making for the tourism industry. In addition, Lwamata subcounty, located in Kiboga district (central), was selected as a reference site to compare focus group discussion (FGD) results with those of the target sites. Kiboga has active ongoing banana fibre-related activities, such as pseudo-stem trade and fibre extraction. The banana cropping system in Kiboga is dominated by coffee-banana intercropping (further details in Appendix A.2.1).

We used a three-step approach to assess *FR*. First, we conducted three FGDs, one per site, to identify key motivation attributes and barriers for farmer engagement. The term 'fibre' was new to most participants. Therefore, all farmer-related discussions were held from the perspective of 'removing pseudo-stems in large quantities from the banana fields'. Consolidated preliminary findings from the three sites resulted in 8 motivation attributes and 10 potential barriers ranked in order of importance (Tables A.3 and A.4).

Second, using farmer motivation attributes only (the '*ability*' aspect of *FR*), we developed a farmer typology to characterize farmers into relatively homogenous groups of readiness. We used data from 102 households [Isingiro ($n = 53$) and Bunyangabu ($n = 49$)] from the NARO Banana Agronomy Project endline survey database (conducted in April/May 2021), to obtain indicators for each motivation attribute. A total of eleven indicators were selected (Table A.5). Missing data on indicators were obtained from the same households through a supplementary household survey conducted in May 2022. The typology was developed using multivariate analysis techniques (Alvarez et al., 2018) in R software (Appendix A.2.3). We also asked farmers about their level of fibre awareness, willingness to participate in fibre production, and the lowest price for which they would be willing to sell their pseudo-stems for fibre extraction (the '*willingness*' aspect of *FR*). Answers to these questions were not included in the typology development process but used to better understand farmers' position in fibre-related aspects not raised by other stakeholders.

Third, we quantified *FR* (*ability*) using an index developed in this study (Appendix A.2.3). To assess readiness with indicators in different

units, a standardized scale of 0 (not ready) to 1 (ready) was used. Quantitative indicators were scaled using the min-max normalization technique (Duda and Hart, 1973), and qualitative indicators were assigned meaningful scores, i.e., 0 and 1 for binary variables, and 0, 0.5 and 1 for ordinal variables. An inverted score was used for the indicator on market access since the nearer the farmer is to the market the better (Bagamba, 2007). Finally, we computed *FR* as the sum of the product of readiness score and weight across attributes (Eq. A.2). Descriptive statistics were used to describe mean readiness scores and other characteristics per farm type.

3. Results

3.1. General overview of Uganda's banana fibre sector

The banana fibre sector in Uganda was characterised by non-human elements, human elements, and cross-cutting issues (Fig. 2). In addition to banana farmers as implicated actors, we also identified consumers of fibre products at the end of the value chain. Their product preferences were commonly assumed by players in processing and marketing. Unfortunately, efforts to establish contact with consumer representatives were in vain as some actors withheld such information to safeguard business interests.

The development of the sector actively started in 2010 in the central region around the capital city, Kampala, pioneered by TEXTFAD, a private company engaged in fibre processing and value addition. By 2022, fibre production and processing activities had spread out to several banana growing areas. Despite increasing awareness of the potential of the sector, most stakeholders were uncertain about how the sector would develop in space and time. A few stakeholders, however, predicted sectoral growth beyond national level to regional and global levels. The following sections present details of the components under each element while integrating spatial and temporal trends.

3.2. Non-human element: resource flows and cultural practices

3.2.1. Banana fibre biomass flows

The major, minor, and desirable flows of pseudo-stems, raw fibre, fibre products and waste products accruing from fibre extraction followed a complex pathway (Fig. 3).

Pseudo-stems were taken to facilities for fibre extraction and, in some cases, subsequent value addition. The raw fibre was either taken to facilities engaged in value addition or traded directly in local and export markets. All fibre products were marketed whereas fibre waste was commonly left at the extraction facility for disposal. Only a small proportion of the waste was channelled to secondary industries producing biofuels, e.g. briquettes, mostly in the central region. In some cases, in western and southwestern regions, farmers who extracted fibre close to their fields recycled fibre waste into the banana fields as a source of mulch and manure.

The current (2022) spatial extent of banana fibre biomass flows included regions within and beyond Uganda (Fig. 4).

In all regions visited, pseudo-stems were sourced within the neighboring villages close to the location of the fibre extraction machines. Raw fibre was mainly transported from major banana growing regions to the capital city, Kampala, where most of it was either utilized locally or sold to other regions, and or exported to international markets. Most of the fibre produced around the Mt. Rwenzori region in western Uganda was marketed within the area. Stakeholders proposed a relatively linear, traceable, and more organized flow of bioresources in future, characterized by specialized activities along the value chain. To sustain banana fields, stakeholders recommended that fibre waste material, post extraction, is returned to farms where the pseudo-stems were sourced for recycling.

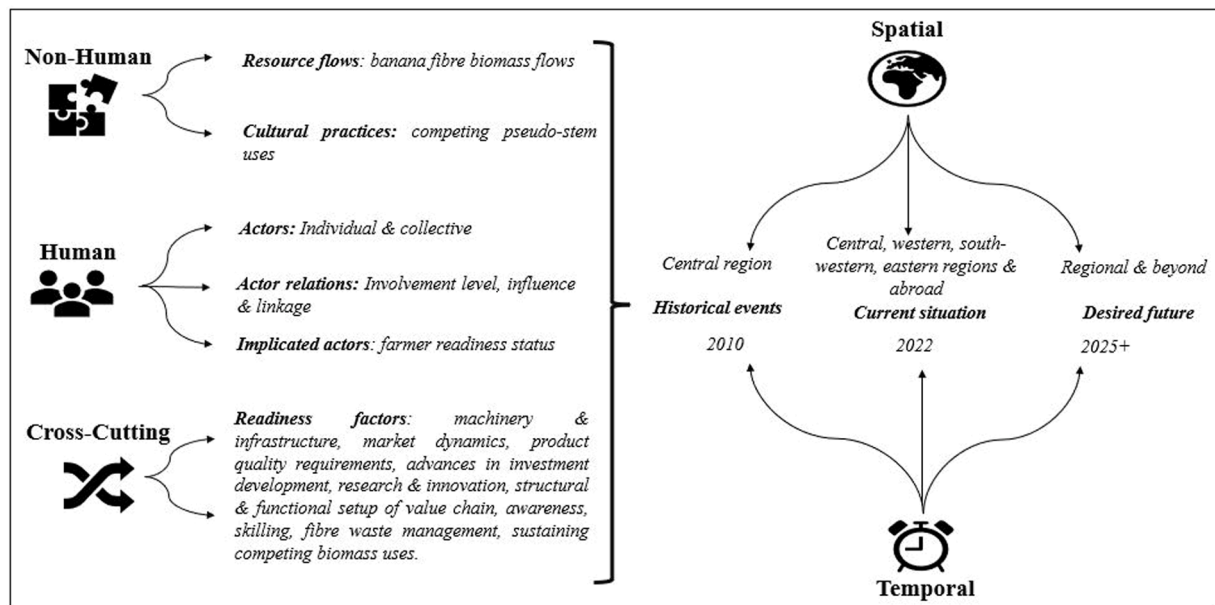


Fig. 2. Situational map of Uganda's banana fibre sector showing elements assessed.

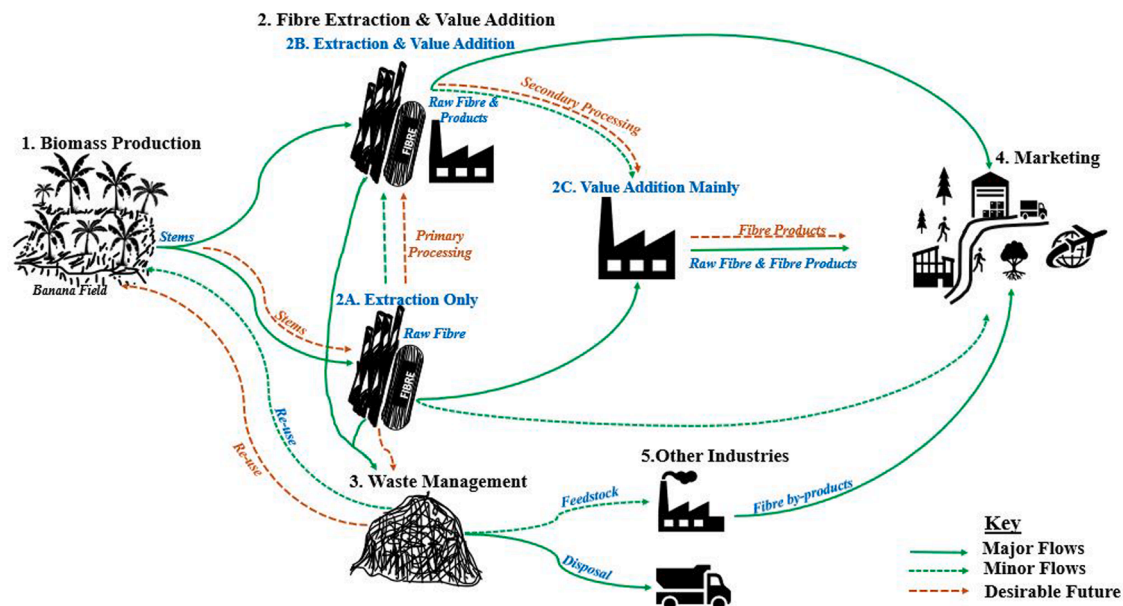


Fig. 3. A generalized map showing banana fibre biomass flows in Uganda.

3.2.2. Competing uses of banana pseudo-stem biomass

The use of pseudo-stem biomass in Uganda has evolved over time. In the 20th century, for example, after de-trashing, the dry fibre sheaths were commonly used as roofing material during construction, to make local crafts like mats and ropes for use within households, and as mulch for banana plantations. In the 21st century, the pseudo-stems, especially those freshly harvested, have gained more value as a supplementary feed for livestock, packaging material for banana traders, and a major source of mulch and organic matter in banana cropping systems (Fig. 5).

3.3. Human element: the actors and their relations

3.3.1. The actors

The banana fibre sector in Uganda included fifteen actor categories, i.e., eight primary and seven secondary actors (Table 1). Primary actors

were those directly involved in the fibre value chain including production, marketing and consumption of goods and services. Secondary actors offered support services to primary actors.

3.3.2. Actor relations

Across both primary and secondary levels of involvement, the top four most influential actor categories, i.e., those facilitating the highest number of linkages to other categories, were the fibre processors, followed by fibre producers, research and training, and civil society (Fig. 6).

Overall, TEXTFAD, a fibre processor, and Uganda Industrial Research Institute (UIRI) in the research and training category were the most influential individual actors. TEXTFAD played an important role in organizing and building capacity of fibre producer groups within banana producing communities, creating market linkages and partnerships, and

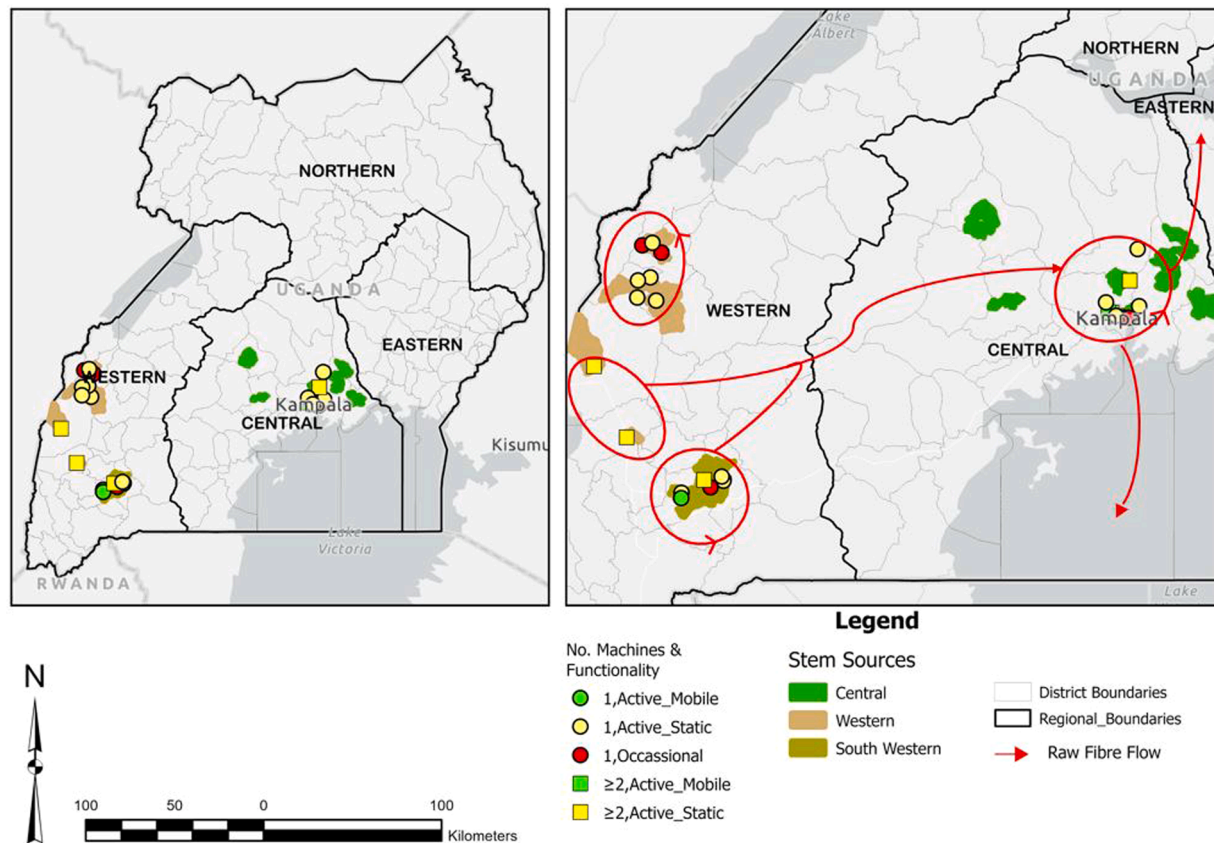


Fig. 4. Current spatial arrangements of banana fibre extraction activities and flows in Uganda. The downward arrow directed from Kampala to Lake Victoria denotes fibre export to other countries within and beyond the East African region.



Fig. 5. Current competing uses of banana pseudo-stem biomass in Uganda as (a) organic matter, (b) livestock feed, and (c) packaging material.

co-facilitating discourses which contributed to research and policy development. UIRI is a government parastatal, with state-of-the-art research facilities tasked to conduct industrial scientific research. A number of actors in the fibre sector had interfaced with UIRI staff who supported them in product development and incubation activities, use of machinery, and awareness creation.

Primary actors showed the strongest inter-actor linkages (Fig. 6) facilitating market linkages and the exchange of production resources, such as raw material, machinery, mobility services and information. The strongest connections were observed between fibre processors and research and training actors, and between fibre producers and civil society actors, especially in Mt. Rwenzori region. Civil society actors included the local NGO called Kabarole Research and Resource Centre (KRC) that spearheaded a certified, donor-funded youth capacity

building program on fibre-related operations in 2022. KRC also provided a marketing platform through which youth groups marketed their fibre-related products. Weaker inter-actor linkages also existed, e.g. between quality assurance and fibre processor categories. Media was the least influential actor category with one weak linkage to fibre processors only. Other key linkages were missing between product consumers and quality assurance actors, and actors involved in research and training.

3.3.3. Implicated actors: status of readiness of banana farmers to engage in fibre production

In general, only 40 % of all farmers assessed had a readiness score of ≥ 0.5 , which we considered as a fair readiness level (Fig. 7a). We identified three farm types, hereafter referred to as FT_1, FT_2 and FT_3 (Fig. B.2b). Despite varying scores within farm types and across attributes, FT_3 farmers were the readiest (Fig. 7b).

Farmers' readiness scores were highest for access to market and lowest for capital for re-investment. Though the overall readiness score for FT_1 and FT_2 did not differ significantly, FT_1 performed better in agronomic management and FT_2 in growing preferred varieties (Table B.1). Most farmers in these two groups had average attribute readiness scores below 0.5 for agronomic management, social group affiliation, alternative nutrient sources, and plantation acreage. Despite being the readiest group, farmers in FT_3 were limited in plantation acreage and growing of preferred varieties. Across sites, Isingiro farmers performed best in terms of awareness, and Bunyangabu farmers performed best in terms of market access, social group affiliation and alternative nutrient sources. The other attributes were similar across sites.

Across all farm types, over 70 % of households expressed interest to engage in the fibre business and were willing to give out their pseudo-stems for fibre extraction (Table B.1). However, the smallest

Table 1
Actor categories and their roles in Uganda’s banana fibre sector.

Involvement level	Actor category	Description and key role
Primary	Pseudo-stem producers	Banana farmers (potentially) supplying pseudo-stems as raw material for fibre extraction.
	Pseudo-stem brokers	Persons involved in sourcing and selling pseudo-stems from banana farmers to fibre producers or processors. Also, commonly responsible for sourcing and negotiating labour and transport costs.
	Pseudo-stem loaders	Casual labour providers during pseudo-stem sourcing and transportation.
	Pseudo-stem transporters	Motorists that offer transportation services for those involved in pseudo-stem movement from source to the extraction facility.
	Fibre producers	Individuals or groups involved in fibre extraction business and marketing of raw fibre. Also, often source pseudo-stems directly from farmers.
	Fibre processors	Individuals or groups involved in the utilization of raw fibre to make finished products and marketing them. Also, mobilise interested groups to produce raw fibre with the aim of sourcing it from them.
	Fibre product consumers	Individuals or groups who purchase raw fibre and fibre products traded in local or export markets.
	Machine fabricators	Local artisans of key machinery used in the banana fibre industry, such as fibre extractors. Also, offer maintenance services, continuous improvement of machine prototypes, and occasionally, create fibre market linkages for producers and processors.
	Agro-input suppliers	Mineral fertilizer producers, manure dealers, banana seed breeders and agricultural extension providers offering agro-inputs and or information related to good agronomic practices to banana producing communities.
Secondary	Civil society	Non-profit oriented organizations supporting initiatives related to banana fibre production through capacity building and establishing market linkages.
	Research & training	Locally available research-oriented organizations, both academic and non-academic, involved in diverse kinds of banana fibre-related research and capacity building.
	Quality assurance	Government bodies at different regulatory levels, i.e., line ministries, local governments and autonomous agencies responsible for developing and implementing government programs and legal frameworks related to production, processing and marketing of products.
	Donors	Development partners that offer financial support to facilitate initiatives within the banana fibre sector.
	Media	Licensed private companies offering communication services promoting the sector, i.e., print, television and radio.
	Others	Includes: producer cooperatives, incubation and manufacturing platforms and community-based groups. These are associated with some of the above actors in fibre-related activities., e.g. trainings.

acceptable price per pseudo-stem across all farm types was US\$ 0.84, six times higher than the prevailing average market price of US\$ 0.14. Also, farmers’ interest strongly differed between sites as farmers in Bunyangabu showed greater interest to engage (100 %) and willingness to give out their pseudo-stems (96 %) compared to Isingiro farmers at 68 % and

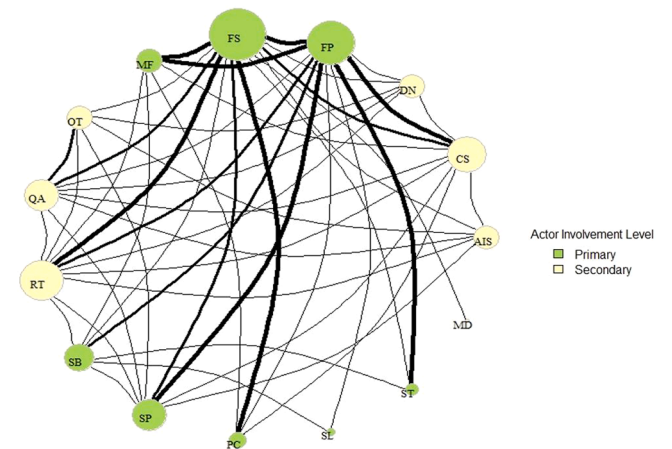


Fig. 6. A Netmap of relations among actor categories. Actor influence was visualised by the size of the node/circle; i.e., the bigger the size, the more influential the actor was in facilitating linkages among other actors within the network. Actor linkages were visualized by the thickness of the line; i.e., the thicker the line, the larger the number of connections, grouped into classes: thinnest (1–5 connections), thickest >10 connections and the intermediary, 6–10 connections. The letters denote: **FS** (Fibre Processors), **FP** (Fibre Producers), **SP** (Pseudo-stem producers), **PC** (Fibre product consumers), **SB** (Pseudo-stem Brokers), **SL** (Pseudo-stem loaders), **ST** (Pseudo-stem Transporters), **AIS** (Agro-Input Suppliers), **MF** (Machine Fabricators), **MD** (Media), **RT** (Research & Training), **QA** (Quality Assurance), **DN** (Donors), **CS** (Civil Society) and **OT** (Others).

55 % respectively (Table B.2). The smallest acceptable pseudo-stem price in Isingiro was more than double (US\$ 1.4) that in Bunyangabu (US\$ 0.56).

3.4. Cross-cutting element: factors relevant in advancing the fibre sector towards industrial readiness

Factors related to innovation readiness, especially market dynamics, were the most reported and those on sustainability, the least (Fig. B.3 and B.4). Most factors were either at the infancy or nascent status of readiness and associated with considerable limitations and recommendations for improvement (Table 2). Under innovation readiness, market dynamics encompassed aspects on demand and supply, profitability and market availability for the fibre assessed from different perspectives. The structural and functional setup of the value chain assessed started in 2012 facilitated by funding through the Afri-Banana consortium.³

Under technological readiness, the tools and equipment used to extract banana fibre evolved over time, but still required considerable investment to reach readiness. For research and innovation, evidence-based information in critical aspects was urgently needed to inform investment, and future research programmes. A lack of standardized protocols for quality assurance was diagnosed, though generic undocumented considerations existed. These were developed over a decade of experience by fibre processors and producers actively engaged in the business.

Through the Afri-Banana consortium, societal readiness was advanced focused on skilling and awareness creation, including exposure visits to other fibre-producing countries like India. Finally, farm-level sustainability aspects, particularly those associated with soil fertility management, food security and livestock feed were also identified.

A more detailed narrative of factors related to all dimensions, integrating spatial and temporal extents, is documented in Appendix B.3.

³ <https://www.kcca.go.ug/kabd/listings/afri-banana-products-ltd/>

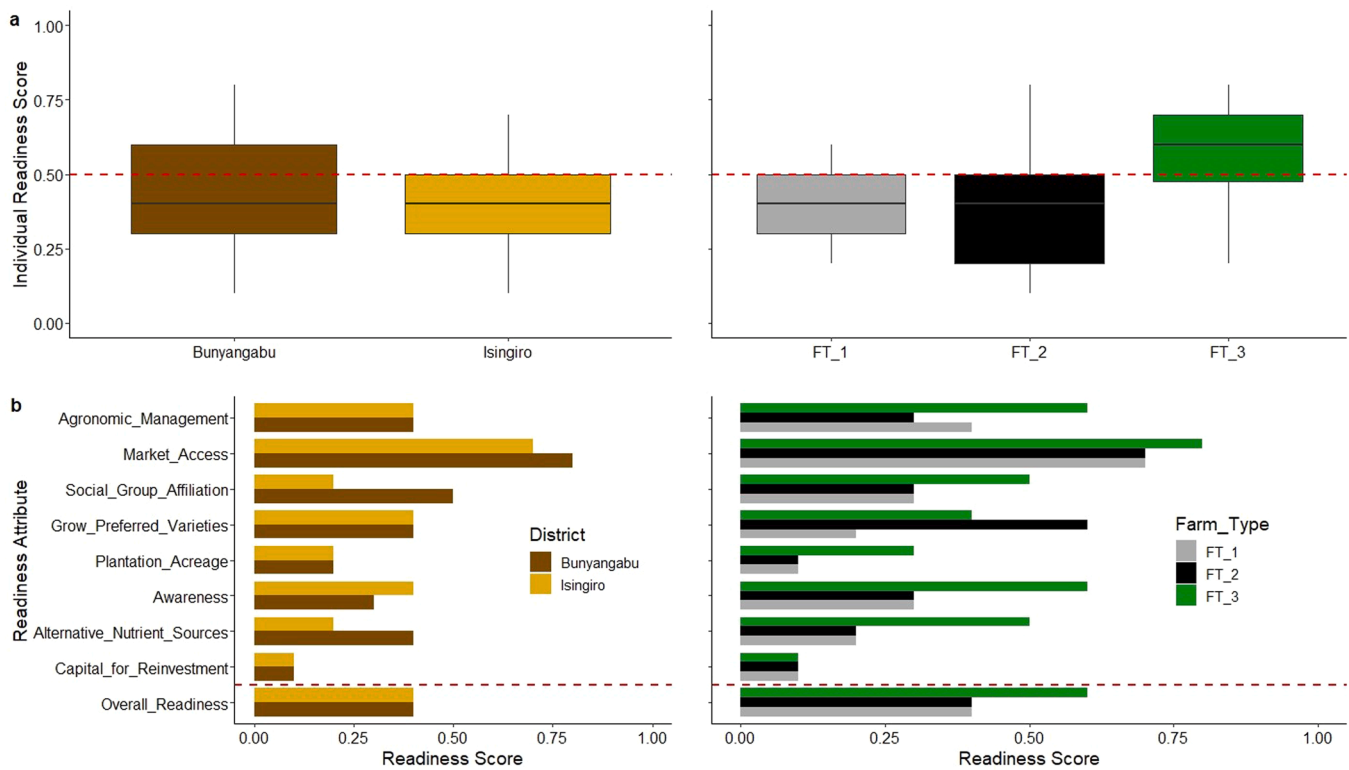


Fig. 7. The standardized status of readiness at individual (a) and attribute level (b) across sites and farm types. The readiness attributes are arranged in order of importance from top to bottom.

4. Discussion

This study aimed at assessing the multi-dimensional status of *IR* of Uganda's banana fibre sector and identifying strategic requirements to sustainably upscale production and processing. Over the past decade, significant developments have occurred in the sector that increased *IR*. Key developments include a growing network of actors and technological advancement in fibre-related machinery. Despite these developments, however, we found that overall *IR* was limited due to several challenges, in particular the ability and willingness of farmers to supply pseudo-stems given current prices, limited collaboration among actors in the value chain, and the lack of supporting policies to enhance marketing of banana fibre products for industrial use. In the following discussion, we reflect on these developments and challenges, comparing the specifics of Uganda's banana fibre sector to bio-based sectors in general. Finally, we formulate recommendations to policy makers to further enhance *IR* of the banana fibre sector.

4.1. Cross-cutting assessment of industrial readiness of the banana fibre sector

4.1.1. Biomass availability and flows

Stakeholders stated that Uganda has sufficient feedstock to sustain the fibre industry, even at a projected commercial scale. A similar notion is shared at the East African regional level regarding huge volumes of under-utilized biological resources (Virgin et al., 2022). Contrastingly, in parts of Asia, e.g. India, the world's largest producer of bananas, a study by Adhia et al. (2021) highlighted the low availability of banana residue as a key limitation to advance its commercial use for textile. Hence, even in East Africa, where volumes are assumed to be sufficient, issues such as cost of and access to the biomass, farmers' willingness to sell it, and stability of supply, need to be addressed for the industry to advance. Notably, high prices for biomass remain a key limitation to the economic sustainability of the bio-based industry even in developed

bio-economies of Europe (Nattrass et al., 2016). To ensure sustainable supply, for example, knowing the spatial-temporal distribution of biomass stocks and flows of different types is also important (Yang et al., 2021).

Our findings underscore the above-mentioned limitations. For example, Isingiro district is the leading producer of bananas in Uganda (UBOS, 2020), thus it might be assumed to generate large amounts of biomass. However, almost 50 % of farmers assessed in this district were not willing to offer their pseudo-stems (Table B.2), because they needed them as mulch for their banana fields, and farmers considered the prices for the pseudo-stems to be too low. Moreover, the pseudo-stem requirements, such as varietal preferences, and proposed production strategies (e.g., increased plantation acreage), render the sustainable supply of pseudo-stems uncertain. The expansion of the production acreage, to satisfy biomass demand, within and beyond banana production zones presents additional challenges (Bennich and Belyazid, 2017). These include biodiversity loss due to conversion of natural ecosystems to farmland, and food insecurity arising from re-allocation of land grown with other food crops to banana production for fibre.

Furthermore, biomass production is significantly affected by agronomic management, including nutrient and water management (Bande et al., 2013). This is a key challenge for farmers (Table A.4), because intensifying these agronomic practices requires high annual investment costs (Ronner et al., 2023), while farmers generally lack capital (Fig 7b). Importantly, the intensification of biomass production requires energy and material costs from other sectors, such as the fertilizer industry (Sherwood, 2020), which is likely to increase the carbon footprint of the fibre products.

Our study also highlights the complexity of banana fibre biomass flows. This complexity is partly attributed to the multi-tasking nature of the actors aiming to maximize returns from the business (Fig B.5). Moreover, the scarcity of raw material drives actors to search for alternative sources to sustain a steady flow of biomass (Nattrass et al., 2016; Popp et al., 2021). In Uganda, our findings show that this scarcity

Table 2

A summary of key factors relevant in shaping the fibre industry towards readiness.

Readiness dimension	Relevant factor	Readiness status	Key characteristics / limitations	Recommendations towards readiness
Innovation	Market dynamics	Nascent	<i>Pseudo-stem sourcing:</i> - Availability hindered by urbanization, high logistical costs and biotic stresses. - Average unit prices vary between USD 0.08 to 0.54, determined by field accessibility, plant girth and genotype, seasonality, operational costs, bargaining power, and access to market information. - The market is occasional and non-contractual with low price offers, and dependent on buyers dominated by brokers. <i>Fibre extraction and value addition:</i> - Commonly traded products: crafts, paper and home interiors. - Product demand and supply growing rapidly but based on mutual relations with no binding agreements. - Few actors producing little due to high capital requirements and with few product portfolios. - Average raw fibre prices increased from USD 1.4 in 2018 to currently 4.1 per kg, sometimes dependent on sheath location. - Raw fibre prices are low and volatile, yet value-added products are expensive and of low quality. - Contrasting opinions on market availability among actors.	- Increase banana production e.g. through expansion of acreage within and beyond current production zones. - Organize farmers into producer cooperatives for raw material supply with contractual arrangements and an agreed pricing system. - Assess cost-benefit of the pseudo-stem business from farmers' perspective. - Prioritize production and marketing of raw fibre, crafts, home interiors and sanitary ware in the short term, then hair extensions, textiles and paper for long term investment. - Improve market access and product visibility through advanced marketing strategies.
	Structural and functional setup of the value chain	Nascent	- The value chain is disintegrated and disorganized with actors working in isolated groups. - Growing initiatives to streamline operations in major banana producing communities to minimize logistical costs.	- Invest in a public-private partnership business model spearheaded by government. - Harness existing farmer organizational structures to mobilize raw material suppliers. - Harness a multi-layered approach with production and supply of quality raw material at grassroot level, and off-takers for value addition and marketing at processing facilities.
	Advancements in investment development	Nascent	- A taskforce set up to consolidate developments of the whole banana value chain including fibre. - Diverse projects and legal frameworks exist but limited in implementation, and not specific to agricultural residues. - Fibre-related initiatives financed through short-term donor-funded projects. - Limited access to business financing, credit facilities and unfavourable economic policies, e.g. high interest rates and heavy taxation on imported equipment.	- Attract the right financing and facilitate intra and inter trade linkages spearheaded by government. - Develop favourable policies which promote affirmative action against unfair trade competition.
Technological	Machinery and infrastructure	Nascent	- Decorticating machines for fibre extraction inefficient, bulky, costly and require intensive manual labour. - Poor state of road network and electricity shortage hinder timely supply of raw material.	- Establishment of multi-locational fibre production and processing facilities. - Investment in efficient simple-to-use mechanized systems.
	Research and innovation	Infancy	- A few studies, focused mainly on product development, conducted. - Little research outcomes taken up for commercialization or used to guide policy development. - No access to research information by the public including actors. - Government-aided facilities available to conduct fibre-related research, but costly to use.	- Involve technocrats in product development for different clientele. - Integrate research findings into the national industrialization agenda. - Generate information on: available biomass stocks; product quality; market potential; re-usability of waste; attainable fibre yield; sustainability impact, and return on investment for business viability.
	Product quality requirements	Nascent	- A fibre grading system based on raw fibre colour and sheath location along the pseudo-stem developing. - Pseudo-stem preferences: height, girth, health, growth stage and freshness. Most preferred genotypes: <i>Kayinja</i>, <i>Sukali ndizi</i>, <i>Gonja</i>, and <i>Bogoya</i> due to high fibre quality and yield. Matooke genotypes least preferred. - Lack of a standard code of practice for product development and sourcing of raw material. - Harvesting the bunch without damaging the pseudo-stem for fibre is laborious.	- Develop a standard code of practice with minimum requirements for production. - Facilitate collaboration among actors to minimize risks of adulterated products. - Harness fibre sourced from readily available genotypes rather than pushing farmers to produce what the industry prefers. - Ensure consistency in production and quality assurance.
Societal	Skilling	Nascent	- A growing critical mass of unskilled and semi-skilled labour-force trained in various fibre-related operations. - Skills transferred through incubation programs targeting youth and women groups.	Establish multi-locational skilling centres to train a critical mass of specialised skilled labour force.

(continued on next page)

Table 2 (continued)

Readiness dimension	Relevant factor	Readiness status	Key characteristics / limitations	Recommendations towards readiness
Sustainability aspects	Awareness	Nascent	• Insufficient skilled labour-force and organizational structures to absorb the high influx of interested persons. • Fibre-related activities are labour-intensive • Information dissemination, largely personal-driven, through traditional channels by actively involved actors. • Information is unreliable, inconsistent and irregular even among actors. • Limited public awareness.	• Deliberate investment in public awareness, e.g. through use of existing grassroots extension systems to disseminate information. • Establish a centre of excellency with an incubation hub offering information and facilitating learning. • Facilitate open information sharing to ensure innovative developmental research. • Returning fibre waste products to biomass source farms, e.g. by extracting on or close to the farm.
	Management of fibre waste	Infancy	• Huge volumes of waste at extraction facilities hardly put to beneficial use. • High logistical costs limit recycling waste products at biomass source farms.	None
	Sustaining competing pseudo-stem uses	Not ready	• Concerns over sustaining the ecological function of pseudo-stems in the cropping system. • Removal of pseudo-stems presents an opportunity for increased demand of agro-inputs, though their supply is limited by increasing scarcity and prices. • Food security risk due to harvesting pre-mature pseudo-stems or growing non-food, fibre-preferred genotypes. • Impact on livestock feed not significant.	

is driven by urbanization, high logistical costs and biotic stresses. Although structures to streamline biomass flows are underdeveloped, the on-going efforts by fibre producers and processors to set up structures for mobilizing biomass within banana growing areas are commendable. If developed further, e.g. into local biorefineries, more benefits could be realised including valuable returns for multiple actors involved along the value chain (Kumar and Verma, 2021).

4.1.2. The actors

Uganda's banana fibre sector is dominated by a growing private sector, with strong linkages between fibre processors and research and training on the one hand, and fibre producers and civil society actors on the other hand. Such linkages have the potential to advance IR, e.g., through developing a concrete bio-based research program, and strengthening community-based farmer networks to supply raw material. In a different context, the Brazilian sugarcane sector has greatly thrived on strong linkages between multi-national companies and research institutes to become the world's leading bioethanol industry (Scheiterle et al., 2018). Such linkages, therefore, point in the right direction for Uganda's banana fibre sector.

However, minimal linkages observed between actors in the quality assurance category and other categories, such as fibre producers, is worrisome. These actors, who play a key role in advancing institutional quality pillars, such as quality regulation, government effectiveness and control of corruption, are found to positively impact the bioeconomy sector in Europe (Barra and Falcone, 2024). However, similar to our findings, López Hernández & Schanz (2019) show that most bio-based actor networks lack involvement of quality assurance actors. Furthermore, stakeholders in other bio-based sectors, for example in Ireland, said that a lack of integration across government institutions and limited awareness negatively affected the coherence in bioeconomy policies (Pender et al., 2024). Similarly, such barriers could also deter inter-actor linkages in developing bioeconomies. It, therefore, remains crucial to further explore why useful but weak linkages still exist, and how stronger partnerships can be harnessed for developing bioeconomies like in Uganda.

Growth in skills and increased awareness among actors, especially fibre producers and processors, expand the horizon of opportunities for IR. Personal initiatives such as word-of-mouth and multi-media channels proved effective in raising awareness among actors. Indeed, using such information dissemination channels was considered a good practice in

business models for bio-based companies in Europe that used them to raise awareness about their products and services among customers (Hatvani et al., 2022). However, reliance on dominant actors, such as processors, reluctance to engage in collaborations by policy players, and information sabotage by brokers (Appendix B.3.3.2) continue to limit overall awareness of bio-based products, and skills development. Related barriers, particularly the lack of awareness and collaboration among consumers and actors, and workforce challenges still limit progress of circular bioeconomy systems in Africa (Salvador et al., 2022).

Furthermore, the insignificant role of media observed through minimal and weak linkages requires attention. In the current fourth industrial revolution, economic growth is driven partly by information dissemination through diverse digital platforms (Caruso, 2018). The bio-based economy is no exception. In recent years, the global forest-based bioeconomy chain, in general, has taken big steps towards digital solutions, e.g. e-commerce advancement to eliminate the distance between upstream and downstream value chain segments (Watanabe et al., 2018). Yet, even with the existence of traditional information dissemination techniques (Katungi et al., 2008), the majority of farmers we assessed lacked basic information about the fibre business (Table B.1). Nevertheless, with increasing access to mobile phones among smallholder farmers, broadening information dissemination through farmer-friendly ICT tools could offer better results (Ayesiga, 2023).

Stakeholders suggested that harnessing a public-private partnership business model, spearheaded by government, could promote fair participation of all actors and significantly boost the industry. The success story of Petrobras Biofuels, a public company created by the Brazilian government to engage smallholder farmers in the biodiesel sector, registered remarkable growth for both farmers and industries (Gomes et al., 2010; Lima, 2022). A similar arrangement in Uganda's case could enhance active participation of banana farmers in the fibre sector which is currently limited. However, the effectiveness of such business models within African agricultural value chains remains a challenge (Poulton and Macartney, 2012).

4.1.3. Other readiness aspects

Innovation readiness was dominated by market aspects (Fig B.4). Despite temporal and spatial market developments (Appendix B.3), a number of limitations remain, including contrasting views among

actors, and high volatility of product prices.

First, actors expressed contrasting views on market prospects: processors perceived a huge market to satisfy, while farmers and fibre producers perceived a lack of market opportunities. Such disparities are attributed to limited access to market information, non-contractual arrangements, lack of standards to ease trade, and deliberate exploitation by brokers. Similar observations are presented in studies on barriers and challenges to transitioning to circular bio-economies (Dace et al., 2024; Salvador et al., 2022). Furthermore, we observed market share dominance and distortion, especially by fibre processors. Such tendencies resulted in overly priced raw fibre on the local market with some processors trading it at double the price bought from producers (USD 8.1).

Second, there was high price volatility for pseudo-stems and value-added fibre products. This was partly attributed to price-related challenges and system complexity of biological resources linked to quality variations, seasonality and production costs in line with findings from other studies (Dace et al., 2024; Gontard et al., 2018; Lewandowski, 2015; Salvador et al., 2022). Such weather and price uncertainties pose risks to those interested in investing in long-term strategies to supply products to the industry. Overall, access to reliable and sustainable markets remains a general limitation to the success of the bio-based industry (Nattrass et al., 2016).

Technologically, significant efforts to put in place fibre extractor machines have yielded great results, such as improved turnover of biomass into fibre. This technology is quick, easy to use, less technically demanding and easily transferable (Provin et al., 2024; Ray et al., 2012). However, current machinery suffers from limitations of low fibre recovery, bulkiness, labour requirements, initial high cost and insufficient amounts. Also, other infrastructural requirements, such as the poor state of roads, need consideration because they affect accessibility and transaction costs for goods and services (Lewandowski, 2015; Poku et al., 2018). Furthermore, the observed long time lag between pseudo-stem harvest and fibre extraction, coupled with the lack of drying and storage facilities affect the quantity and quality of fibre obtained. A study by Dace et al. (2024) confirms that limited technological development and infrastructural capacity present major technical barriers to a bioeconomy transition.

Finally, related to sustainability aspects, it was surprising to see huge amounts of fibre waste at extraction facilities without any utilization mechanisms in place. This presents sustainability concerns (Popp et al., 2021), such as fibre extraction effluents causing eutrophication of nearby water streams, poor quality of air, and breeding sites of disease-causing vectors like mosquitoes as observed in the field. Simultaneously, soil fertility management is currently of major concern due to increasing scarcity and cost of inputs such as manure and mulch (den Braber et al., 2021; Ronner et al., 2023). Therefore, a plausible mechanism for managing fibre waste is returning them to the source farms for recycling (Fig. 3), a principle of the circular bioeconomy (Freeman et al., 2022; Provin et al., 2024). However, the inherent logistical costs and associated risks, such as waste apportioning dynamics among farmers and the potential spread of pathogens, make this approach complex. In addition, recycling for use on farms would negate potential benefits of such waste to secondary industries which would otherwise increase the value proposition of the industry. For example, a review by Provin et al. (2024) showed that banana waste by-products, such as pseudo-stem sap is used in India as a substitute for synthetic chemicals during dyeing processes to reduce effluent loads in the textile industry.

4.2. How to achieve industrial readiness?

A first prerequisite is to organize and streamline biomass production and supply chains (Sherwood, 2020). This necessitates finding suitable alternatives to current competing uses of pseudo-stems (Lewandowski, 2015), managing varietal preferences, addressing production constraints like crop diseases, and access to affordable inputs. Offering

subsidies on quality agricultural inputs to banana farmers, for example, would be a potential option to ensure sustainable crop nutrient management by compensating nutrient losses when biomass is removed from the field (Lima, 2022; Sherwood, 2020). Unfortunately, in Uganda, subsidy regimes are often ignored by those in authority (US Department of State, 2023).

On varietal preferences, our findings show that the most demanded genotypes for fibre, especially those in AAB and ABB genome groups, are the most threatened, mainly by fusarium wilt disease (Kema and Drenth, 2018; van Westerhoven et al., 2022). Contrastingly, the most widely grown cooking-type bananas are least attractive for fibre production due to their poor workability during extraction, i.e., they break easily and contain too much liquid extract resulting in low fibre recovery. Therefore, exploring potential valorisation pathways for the latter is commendable to avoid food insecurity risks associated with prioritising non-food-producing genotypes to meet industrial demands. The expanding scope of research on banana fibres, focusing on various genotypes and their industrial applications, (Provin et al., 2024) is expected to address such limitations.

Additionally, farmer organizational structures, such as producer cooperatives, facilitate efficient production and supply mechanisms of raw material while farmers benefit from economies of scale associated with such collective arrangements. However, the functioning and members' negative perceptions of such entities could prevent interested farmers from joining them (Grashuis and Su, 2019). We found that only 50 % of households in the readiest farm type (FT_3, Table B.1) were affiliated to a farmer group.

Secondly, it is important to address market limitations, strengthen regulatory frameworks and increase public awareness of bio-based products and processes. Market issues require a multi-faceted approach, including addressing unfair competition faced by such niche products due to liberalized open trade policies (Ggoobi et al., 2017; GoU, 2007). Also, improving the quality of products, especially durability, requires attention. This is necessary to address the current competition from conventional products which are of high quality and cheap (Dammer et al., 2013), whereas production costs for bio-based products are high (Nattrass et al., 2016) and most consumers are not willing to pay a premium price for them. Therefore, it is important to match quality expectations and product cost from the stakeholders' perspective (Falcone et al., 2019).

Important too, is the need for standardized protocols stipulating minimum requirements for basic product quality control (van Dam et al., 2005). Such quality assurance measures have contributed significantly to the growth of the bioeconomy sector in Europe (Robert et al., 2020; Singh et al., 2021). Globally, the lack of conducive regulatory frameworks limits readiness of many bio-based industries (Poku et al., 2018; Salvador et al., 2022). Stakeholders in this study, however, said that in Uganda regulatory instruments are adequate. In fact, in addition to the policy frameworks documented here (Appendix B.3.2.3), bioeconomy-related activities are further embedded in other frameworks (Oguntuase and Adu, 2020); the latest being the Uganda national bioeconomy policy framework under development (Virgin et al., 2022). However, implementation of these regulations on the ground is limited, mainly, by rampant corruption (Ggoobi et al., 2017) and lengthy bureaucratic operational processes as raised by stakeholders.

To increase public awareness, e.g. among farmers and consumers, stakeholders proposed building onto existing local institutions like the government extension system to facilitate information flow. Though promising, such institutions are faced with multiple constraints, especially limited funding, characteristic of Africa's agricultural sectors (Moyo and Salawu, 2018). The proposed approach of utilising digital platforms to increase visibility of the industry, and establishing a strong coalition of willing actors, could offer greater success.

Third, deliberate investment in technical, infrastructural, and human capacity is key. Stakeholders in this study considered access to favourable financing regimes the main stimulant for such investments.

However, access to financial resources to invest in bio-based economies remains a big challenge, even globally (Nattrass et al., 2016; Poku et al., 2018; Salvador et al., 2022). Perhaps, bioeconomy investments can benefit from global climate financing initiatives targeting low-carbon and climate-resilient strategies (Buchner et al., 2014). But currently, Africa faces an annual climate financing gap of USD 242.4 billion further hindering sustainable industrialization (Nchofoung et al., 2024). Nevertheless, there is growing global commitment to invest in green finance targeting bioeconomy businesses, e.g. in Italy (Falcone and Sica, 2019). In Uganda, opportunities for green financing exist through local and international funding mechanisms, such as the National Environment Fund and the global Green Climate Fund (Bakiika et al., 2020). Most recently, the Uganda Development Bank, among the frontiers of green financing in Africa (The Independent, 2024), established a Climate Finance Facility dedicated to mobilizing capital to finance low carbon and climate resilient investments⁴. Benefiting from such opportunities, however, requires addressing challenges of rising inflation and high bank lending rates (Ggoobi et al., 2017; GoU, 2007).

Additionally, technical investment is largely dependent on continuous research and innovation because bioeconomies are knowledge-based economies (Birmer, 2018). Therefore, issues of intellectual property rights require consideration to safeguard interests of participating actors where a private-public partnership business model is proposed (Aguilar et al., 2019; Krauss et al., 2021). Furthermore, investment in human capacity development is required to spearhead technology development and knowledge generation for the industry. In addition, the current manual-based nature of most industry operations puts the industry at risk of shortages in semi-skilled workers despite Africa's increasing youthful population, majority unemployed (Sumberg et al., 2021). Today's youth are attracted to less labour-demanding jobs that require soft skills, thus, remain trapped in a 'missing jobs crisis' in search for decent work (Metu et al., 2020). Therefore, successful readiness will greatly depend on how creative such labour needs, both skilled and unskilled, are met with interests of potential service providers. An attractive option could be to deliberately fit youth-friendly skilling techniques to the different value chain segments.

4.3. Methodological reflections

Our multi-dimensional sustainability approach, combining qualitative and quantitative methods, provided a broad understanding of various dimensions of readiness, though not exhaustively. Future studies could consider more aspects, such as financial sustainability and social impact of bio-based products to enhance innovation and societal readiness, respectively. Particular to societal readiness, for example, assessing aspects like feedback mechanisms, transparency and product benefits, helps to understand the social acceptability of bio-based products (Falcone et al., 2019).

Using a quantifiable index to assess *IR* can facilitate comparison across bio-based industries at different stages of development, guide decision making to target investment, and facilitate continuous evaluation of performance. To contribute towards such integrated indices, we developed the *FR* assessment index. Besides providing a general understanding of the status of *FR* at farm type level, the index provided diagnostic information at individual level. Additionally, information on the lowest scoring attributes could aid targeting interventions to improve the status of readiness. While using the *FR* framework, however, we recognize some limitations. First, we left the identification of priority attributes for farmer engagement to the discretion of stakeholders leading to different sets of prioritized attributes across sites (Table A.3). In future, we propose a two-step approach, i.e., obtain relevant attributes across sites first, and then their rankings in specific

sites in round two. Second, deficiencies in one or more indicators could be masked in the overall outcome when results are aggregated (Fig. 7b) (Marinus et al., 2018). Future assessments should also explore the contribution of each indicator individually. Third, we used the min-max scaling technique (Duda and Hart, 1973) for standardization due to lack of reference values for readiness. A shift in these boundaries could lead to different outcomes. Lastly, the index is entirely based on motivation attributes, while a robust readiness framework should also integrate the 'willingness' aspects of *FR*, and the reducing effect of potential barriers (Table A.4).

Importantly, this study recognises the active involvement of diverse stakeholders in assessing *IR*, especially implicated actors. The stakeholders identified and prioritized key aspects for success of the assessment that could otherwise be overlooked.

5. Conclusion

Successful operationalization of the East African bioeconomy strategy requires bridging the current knowledge gap on the status of industrial readiness (*IR*) of plausible bio-based industries like Uganda's banana fibre sector. This study provides a multi-dimensional sustainability outlook of *IR* to guide upscaling of production and processing of banana fibre in Uganda. Specifically, we assessed current biomass flows, actor relations including farmer readiness to supply raw material, and factors relevant in advancing the industry towards readiness. Biomass from banana pseudo-stems is a potential source of natural fibre for the growing bio-based industry, which presents great opportunities for Uganda, and the East African region, to develop its bio-based industrial agenda. Upscaling fibre production and processing to industrial level is therefore timely, but still limited across all dimensions of readiness, i.e., innovation, technological and societal readiness, and several sustainability issues exist. Partly, these barriers are associated with the current nascent stage of development of the industry.

Going forward, if actors jointly facilitate the expansion of markets for fibre products, increase public awareness, improve actor collaborations, negotiate trade-offs with farmers, and if responsible authorities improve regulations and access to financing to invest in technical, infrastructural and human capacity, then the sector will keep growing. Additionally, development of supportive policy frameworks is not enough to realize the desired bioeconomy transition. It is important for such frameworks to shift towards mission-oriented innovation policies with clear practical targets and financial instruments to deliver them.

Importantly, our study is the first to generate an in-depth multi-dimensional sustainability outlook of a plausible bio-based industry using novel methodological approaches. The farmer readiness (*FR*) framework, developed as part of *IR* assessment, offers initial steps towards development of robust tools for conducting similar studies in future. Specifically, the framework allows exploring the integral role of smallholder farmers to sustainably support a bioeconomy transition, as raw material producers, which turned out to be a critical perspective. Furthermore, beyond Uganda's banana fibre sector, future research could explore *IR* of other bio-based industries to generate empirical data necessary to guide a holistic transformation of the regional bio-based industrial development agenda.

CRedit authorship contribution statement

Daphne Kamusingize: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Esther Ronner:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Godfrey Taulya:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Rosa de Vos:** Writing – review & editing, Validation, Supervision, Resources, Methodology. **Priver Namanya:** Writing – review & editing, Supervision, Project administration, Funding acquisition,

⁴ UDB Climate Finance Facility: <https://www.udbl.co.ug/service/combating-climate-change-through-sustainable-financing/>

Conceptualization. **Jerome Kubiriba**: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Katrien Descheemaeker**: Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Supplementary materials

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Data availability

Data will be made available on request.

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