The Biorefinery as a Pathway to Building Economic Complexity in the Post-Mine Landscape

By Juarez Amaral Filho, Haroon Bhorat, Sue Harrison, Robert Hill, Shilpa Rumjeet and Francois Steenkamp

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Abstract

There are currently over 6 000 derelict and ownerless mines in South Africa, which if left unrehabilitated, stand as a substantial risk to public health, the environment, and the economic wellbeing of surrounding mining communities. Building on research conducted by Harrison, Rumjeet, Mabasa and Verster (2019), Broadhurst, Chimbganda and Hangone (2019), and Allen, Bhorat, Hill, Rooney and Steenkamp (2019), we investigate the feasibility of the biorefinery concept as a method to facilitate both environmental and economic recovery of abandoned mine lands. Previous research undertook an analysis of the economic opportunities presented by using bast fibre from plants grown on abandoned mine lands to rehabilitate land, however, the production of lead fibre products leaves a substantial volume of plant biomass unprocessed. The biorefinery concept, investigated in this paper, assists in making use of residual biomass to build economic value and reduce materials waste. Using inter-disciplinary methods and the expertise of bio-process engineers, material scientists and development economists, we develop a novel inter-disciplinary micro industrial policy approach (IMIP) that makes use of economic complexity and relatedness metrics, and techno-feasibility studies. We find that lignocellulosic biomass can serve as feedstock to a wide array of products using different conventional and biorefinery technologies via different production platforms: namely, thermochemical, sugar and lignin, and seed oil. We identify 60 biorefinery products, which can be categorised into high-value platform chemical, low-value biomass products, energy products, and high-value bioplastics. Of these products, we identify 22 frontier biorefinery products that could drive economic development along multiple avenues, including inequality reduction, labour absorption, and positioning South Africa in growing global markets. Given the constraints of limited biomass availability, we further make use of pre-liminary techno-economic feasibility studies to identify and investigate three product clusters that lie within concomitant product value chains, to determine the technical readiness of these clusters, and the impact of these products on economic development outcomes. We do not find that any one cluster is strongly more advantageous than another, and the informed policymaker would have to assess the economic trade-offs in tandem with South Africa's technological readiness for various production processes before choosing which cluster of biorefinery products would best suit their needs and best cater to the end goals of the chosen micro-industrial policy.

JEL Codes: O10, O13, O14, O25, Q01, Q16

Keywords: economic complexity; smart specialisation; mine rehabilitation; biorefinery; industrial policy; fibrous plant economy

Contents

1 Introduction

Mining activities in South Africa date from the late 1800s. According to Statistics South Africa, in the fourth quarter of 2022 the mining sector employed 436 000 workers, and accounted for 4.5 percent of value added in the economy (Statistics South Africa, 2023a; Statistics South Africa, 2023b).[1] However, one of the adverse outcomes of an economy built off such intense and prolonged mining activity is that of abandoned mines and adjacent degraded lands.[2] The Auditor-General South Africa report on the rehabilitation of derelict and ownerless mines details the sheer scale of the challenge, stating that there are 6 100 abandoned mines in South Africa (Auditor-General South Africa, 2022). These abandoned mines are a serious source of risk to the environment, to public health and safety, and to the socio-economic stability of local communities proximate to these mines (Stacey, et al., 2010; Mhlongo & Amponsah-Dacosta, 2016). In particular, the adjacent land to these mines – to varying degrees of severity – is degraded and polluted. Surrounding communities are thus left in an economic vacuum, coupled with the related subsequent deleterious socio-economic impacts, as the primary driver of economic activity in their area ceases to be present.

Given the economic and environmental imperative to rehabilitate degraded mining land and build sustainable economies and communities in the localities nearby these abandoned mines, research was undertaken to investigate the feasibility and suitability of using fibrous plants (such as hemp, kenaf and bamboo) to both clean degraded mine lands through a process of mineral hyperaccumulation and phytoremediation, as well as build sustainable economies by producing economically viable products using these fibrous plants as feedstock for downstream industries.[3] In this paper, we build off this existing research to investigate the biorefinery concept as a method to further foster resource efficiency, economic resilience, and flexibility, through the fibrous plant industry. We investigate the extent to which this can be done by leveraging off existing industrial capabilities in such manner to drive industrial diversification and

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[1] In the fourth quarter of 2022, using constant 2015 prices, the mining sector accounted for 4.5 percent of total value added in the South African economy, down from 9.7 percent in 1994 (Statistics South Africa, 2023b), and 27.6 percent in 1960 (Timmer et al., 2015). The mining sector accounted for 2.7 percent of employment in the fourth quarter of 2022, down from 6.8 percent in 1994, and 8.8 percent in 1960 (Statistics South Africa, 2023a; Timmer et al., 2015).

[2] The Auditor-General South Africa refers to abandoned mines as derelict and ownerless (D&O) mines and defines them as "mines that are not operational, are not being maintained to manage their safety, and whose holders, as defined in the Act, have abandoned the mine and cannot be traced" (Auditor-General South Africa, 2022:6).

[3] This existing research forms part of the *Towards Resilient Futures Community of Practice* (CoP), and includes papers by Harrison, Rumjeet, Mabasa and Verster (2019), Broadhurst, Chimbganda and Hangone (2019) and Allen, Bhorat, Hill, Rooney and Steenkamp (2019).

build economic complexity. In particular, we aim to address the following questions: What technically feasible non-fibre-based materials – "biorefinery products" – can be produced using residual fibrous plant biomass by means of a biorefinery approach? Given current industrial capabilities, what biorefinery products are feasible for complexity building? What is the technical feasibility of proposing clusters of biorefinery products concomitantly?

An iterative inter-disciplinary research process which combines the research capabilities of bioprocess engineers and economists is used to address these research questions. By utilising both economic complexity metrics as well as engineering knowledge to identify product-level diversification opportunities, we develop a novel inter-disciplinary micro industrial policy approach (IMIP) aimed at comprehensive and inter-disciplinary policy making. In the first stage of the research process, the bioprocess engineers identify non-fibre-based materials, or biorefinery products, that can be made using residual lignocellulosic biomass. The second stage involves the mapping of these biorefinery products to the international product-level trade data nomenclature. Once mapped to the trade data, the third stage applies the frontier product approach: this approach uses industrial relatedness metrics to identify biorefinery products that are feasible to produce given current industrial capabilities, and economic complexity metrics to identify products that are desirable in terms of economic complexity gains. The frontier product approach draws from the smart specialisation literature, which has developed methods to inform regional industrial diversification policy strategies.[4] The final stage involves the selection of product clusters comprising these frontier biorefinery products and conducting a joint technical and economic analysis of these product clusters.

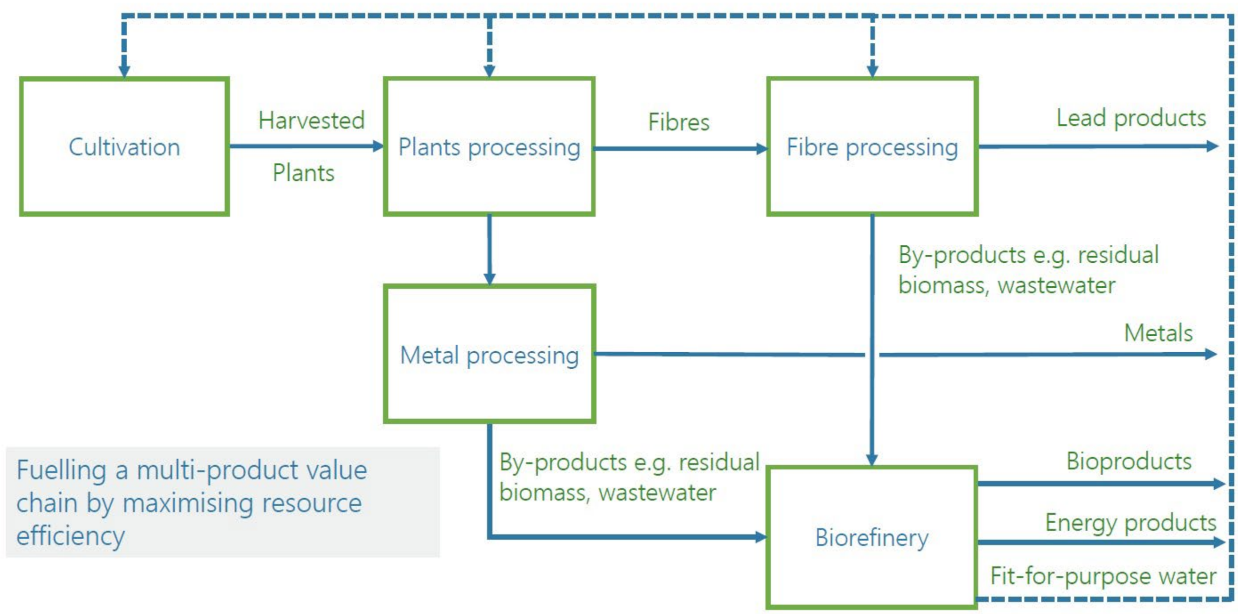
The development of a post-mining multi-product value chain centred around fibrous plants is an expansive system consisting of many different interconnected elements, a summary of which is presented in Figure 1. As alluded to above, the start of this multi-product value chain is centred around the use of fibrous plants as hyperaccumulators of residual trace metals in abandoned mine lands through the process of phytoremediation. These fibrous plants can be processed as feedstock to produce fibrous products, which

[4] The *smart specialisation* literature speaks to a methodological data-centric approach, which uses industrial relatedness and economic complexity metrics to identify industrial opportunities. For example, such an approach has been applied for Europe (Balland et al. 2019), and the United Kingdom (Mealy & Coyle, 2019).

can be used as a vehicle to drive economic complexity and economic development in the South African context.[5] This process is detailed in the top three blocks of Figure 1.

The biorefinery concept is a natural extension to exploring the potential to develop a fibrous plant economy in the post-mining context. This research allows one to ascertain whether further value creation and industrial diversification can be achieved through the efficient use of residual biomass post fibre extraction. Generally speaking, after fibre extraction, there will be some level of residual lignocellulosic material available for further processing, and a question arises as to whether further value can be extracted by the efficient use of this residual biomass in a biorefinery system – see the bottom block of Figure 1. As such, this research is motivated by the need to identify multi-product value chains and maximise resource efficiency, while minimising waste generation in line with circular economy principles.

Figure 1: Process Integration - The Biorefinery Concept detailing each step from cultivation to the production of several outputs. The process operates within a closed-loop system, adhering to the principles of the circular economy.



[5] For a more detailed exposition of the research underpinning this process, the interested reader is advised to consult Harrison, et al. (2019), Broadhurst, Chimbganda and Hangone (2019) and Allen et al. (2019).

A further motivation for this research into the biorefinery concept is that it aligns with the 2021 Draft National Mine Closure Strategy and is thus relevant to the current policy thrust in the sector. The Draft National Mine Closure Strategy adopts the concept of economic succession planning and the notion that every mine has the potential for some form of economic diversification both during the life of mine and beyond (Draft National Mine Closure Strategy, 2021:3). The draft policy proposes that the development of non-mining economic activities – e.g., both food and non-food agri-processing activities – on mining land be incorporated into mine closure programmes, thereby planning a transition toward a diverse post-mining economy.

Despite its resource-intensive nature, mining is essential for the operationalization of the UN Sustainable Development Goals (SDGs); specifically in emerging countries. Therefore, if the practice of mining is here to stay, it is key that the process be sustainable through effective mine rehabilitation. Mine rehabilitation in South Africa is driven by several laws and regulations, such as the National Environmental Act (NEMA) of 1998, and the Mineral and Petroleum Resources Development Act (MPRD) of 2002, which describe the responsibilities and requirements of mine operation with regards to mine closure. However, the current rehabilitation practices are focused on complying with the minimum legal requirements, and the opportunities for post-mine economic development are not considered. Abandoned mining land is an even graver issue, as old mining activities weren’t designed according to the current legal framework, and the onus of responsibility for abandoned sites’ rehabilitation is murky. The negative environmental footprint of such a lack of an integrated management system can be seen in several case studies worldwide (Bell et al. 2001; Gomes et al. 2011; Håkan Tarras-Wahlberg & Nguyen, 2008; Masindi et al., 2022). Through regenerative agriculture, and the associated value chain activities such as the biorefinery, it is possible to restore land capability in degraded areas, providing economic and environmental benefits that build sustainable communities and economic complexity in these localities.

The remainder of this paper is structured as follows: In Section 2 we introduce the biorefinery concept, detailing how a feedstock of lignocellulosic biomass can be processed through a biorefinery to produce a diverse range of energy and chemical products. Section 3 details the iterative inter-disciplinary methodology applied in this paper. Section 4 comprises three parts: first, we define a list of technically feasible biorefinery products. Second, we apply economic complexity and network relatedness metrics to identify biorefinery products that are both feasible given current industrial capabilities, and desirable in terms of economic complexity gains – namely, frontier biorefinery products. Third, we present a techno-feasibility assessment of biorefinery product clusters that comprise these frontier biorefinery products. Section 5 concludes.

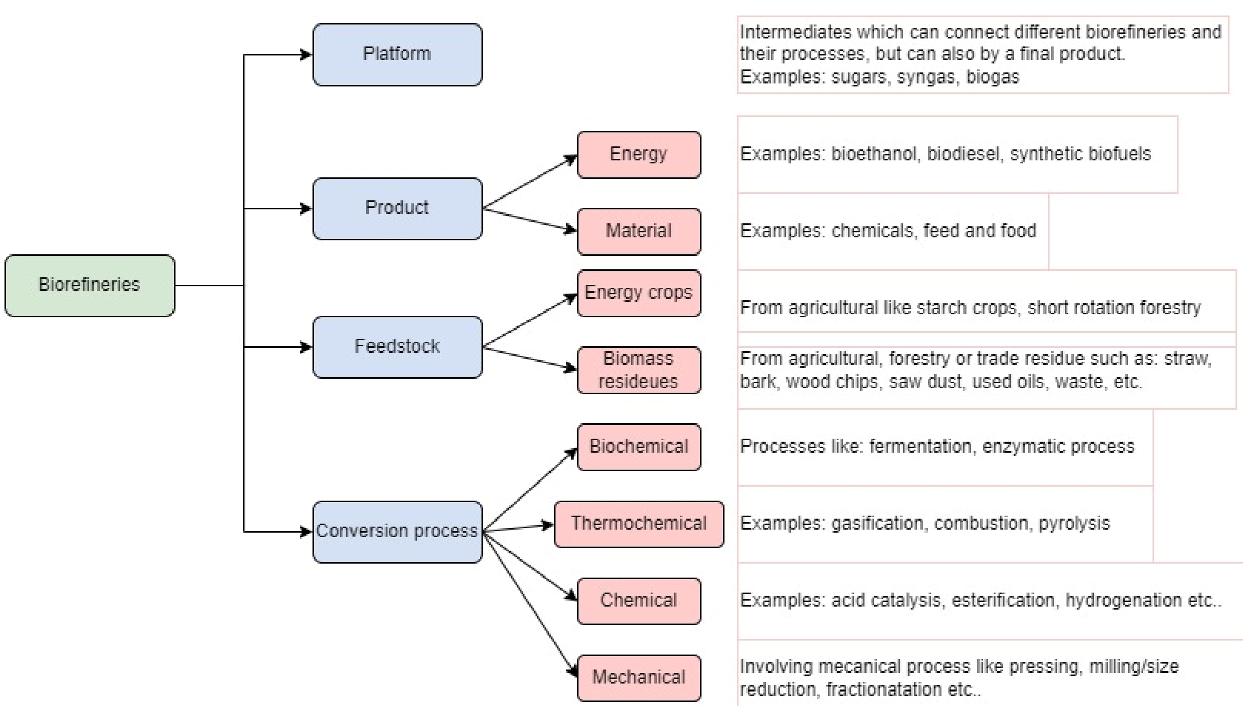
2 Moving towards a bio-based economy and the biorefinery concept

The move toward a bio-based economy can help address a number of concerns that impact economic development and performance, such as concerns surrounding the geopolitical and environmental implications of the traditional petroleum-based economy; price volatilities of oil and gas; and the need to transition to more sustainable production systems to boost economic growth while simultaneously preserving the integrity of our natural resources, maintaining ecosystem services and ensuring the well-being of the global population (de Jong et al., 2011; de Jong & Jungmeier, 2015). The bioeconomy includes sectors such as bioplastics, biopolymers, and biocomposites, which are gaining traction as alternatives to conventional materials (Niaounakis, 2015). Innovations in biochemistry are leading to the production of bio-based chemicals and pharmaceuticals, offering renewable and often less toxic options for various industries (Bozell & Petersen, 2010). The use of agricultural and forestry residues to create bioproducts contributes to waste valorization, reducing environmental impact and promoting circular economy practices (Ragauskas et al., 2006). Nevertheless, the International Energy Agency (IEA) predicts that the annual global demand for biofuels is estimated to grow by 28 percent by 2026, attaining a volume of 186 billion litres (IEA, 2022), indicating an increased appetite for bio-based economic activities.

According to European Directive 2009/28/EC, biomass is defined as the “biodegradable fraction of products, waste and residues from *[sic]* biological origin from agriculture (including plant and animal substances), forestry and related industries as well as the biodegradable fraction of industrial and municipal waste” (European Commission, 2009). Of particular interest is lignocellulosic biomass, which originates from plants or plant-based materials typically not used for food or feed. Lignocellulosic biomass is mainly composed of polysaccharides (cellulose and hemicellulose) and an aromatic polymer (lignin) (Zoghlami & Paës, 2019). Cellulose, which is the major component of lignocellulosic biomass, is an alternative to petroleum-based polymers (Ahn et al., 2012; Isikgor & Becer, 2015).

There is an estimated global production of 181.5 billion tonnes of lignocellulosic biomass across various industries, and this amounts to a substantial source of renewable feedstock which can be processed through biorefining processes (Paul and Dutta, 2018). Biorefining is defined, by the IEA, as the “sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)” (Cherubini et al., 2010). To some extent, biorefineries can be regarded as analogous to petroleum refineries, but with the following distinctive differences: In biorefineries, the variety of feedstock is notable; a larger range of processing technologies is required; and there is greater variability in quality and energy density (Clark & Deswarte, 2015; de Jong & Jungmeier, 2015; Wenger et al., 2018). The flexibility in processing technologies and products gives rise to different biorefinery systems, as seen in Figure 2. For example, an energy-based biorefinery is focused primarily on the production of liquid or gaseous biofuels, power or heat, along with producing additional value-added products from residues for improved economic and environmental gains. On the other hand, a product-based biorefinery aims for the highest economic benefit by fractionating and transforming biomass components into a portfolio of biobased products and closing the material loop by using residues for energy purposes (Wenger et al., 2018). Multi-product biorefineries also display a typical pattern correlating the product value and associated market volume – the higher the product value, the smaller the associated market volume (specialties) and vice versa (commodities). One fundamental roadblock to the large-scale implementation of biorefineries is the associated decentralized biomass supply, which is heavily dependent on the availability of feedstock in a specific area compared to the centralized supply of oil and gas, facilitated by oil fields and pipelines (Jack, 2009). As such, the scale of biorefining operations must reflect the ease of availability and logistics of the required feedstock in an area.

Figure 2: Biorefinery classification system diagram categorizing it based on four key components: Platform, Product, Feedstock, and Conversion Process.



Source: Adapted from de Jong and Jungmeier (2015) from Abdilla-Santes (2020).

2.1 Availability of residual lignocellulosic biomass in the context of regenerative agriculture on degraded mine land

As described in Figure 1 – and detailed by Allen et al. (2019) – using hemp, kenaf and bamboo plants as case studies, a number of promising fibre-based products have been identified as potential diversification pathways for the South African economy. The identified products are high- to medium-value plant-based composites (e.g., non-woven textiles) derived from the bast fibre plants (hemp and kenaf), and medium- to low-value wood-based product (e.g., flooring) derived from bamboo. Using the hemp plant as an example, Figure 3 illustrates the potential availability of residual plant biomass. It is important to note that on average only 30 percent of the hemp stem constitutes bast fibres (Thygesen et al., 2008), which can be re-directed towards the production of the lead composite product. This leaves behind a substantial amount of residual biomass in form of the woody fibres, bast fibre processing losses, leaves, and seeds, as illustrated in Figure 3 and Table 1. While this biomass can be crudely processed to yield bioenergy (Bian et al., 2020), there are various processing options that can be exploited to expand the product portfolio to a more dynamic and diversified one, which, in turn, can contribute towards the overall valorisation of plants grown on degraded mine land. This will be discussed further in Section 2.2. Whilst bast fibre and bamboo provide different lead products; the residual lignocellulosic plant biomass has similar composition and can be used as feedstock into a biorefinery process to produce chemicals and energy.

Figure 3: Availability of residual lignocellulosic biomass for further processing to produce multiple biomass-derived products using hemp as example

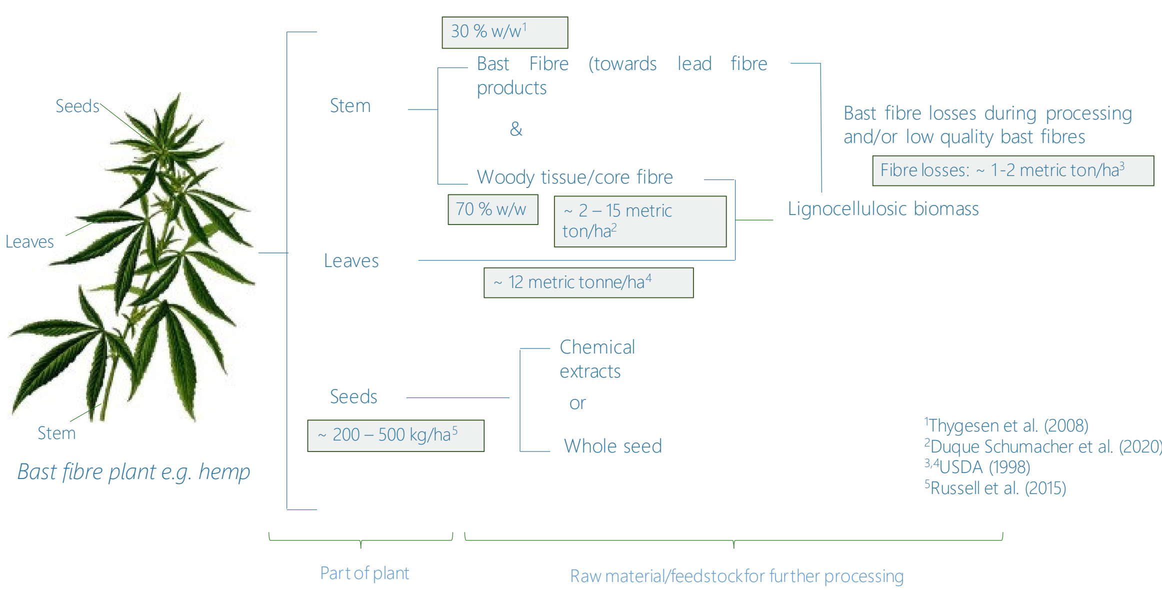


Table 1: Data used to estimate the amount of lignocellulosic biomass available for further processing after the production of lead bast fibre product

		Reference
Amount of hemp plants in one hectare of land (kg/ha)	40000	(USDA, 1998)
Amount of hemp leaves available for further processing (metric ton/ha)	12	
Bast fibre losses during retting available for further processing (metric ton/ha)	1 – 2	
Amount of dry matter extracted (metric ton/ha)	4 – 20	(Duque Schumacher et al., 2020)
Amount of extracted matter converted to bast fibre (%)	20 – 30	
Bast fibre content in hemp stem (%)	20 – 40	(Thygesen et al., 2008)
Hurds content in hemp step (%)	60 – 80	
Lignocellulosic content (%) (i) Bast fibre (ii) Hurd	 Cellulose: 57 – 77 Hemicellulose: 9 – 14 Lignin: 5 – 9 Cellulose: 40 – 48 Hemicellulose: 18 – 24 Lignin: 21 – 24	(Gümüşkaya et al., 2007)
Yield of hemp seeds (kg/ha)	200 – 500	(Russell et al., 2015)

2.2 Residual lignocellulosic biomass as a versatile feedstock

In the context of using fibrous plants as a vehicle to increase economic complexity on degraded and post-mine land, the biorefinery approach, introduced in Section 2.1, favours enhanced resource efficiency of the lignocellulosic biomass contained within fibrous plants. As mentioned previously, lignocellulosic biomass is composed of three main compounds – cellulose, hemi-cellulose and lignin, whose content vary according to species. The range is usually 30-50 percent cellulose, 20-40 percent hemicellulose, and 10-35 percent lignin. In more technical terms, cellulose is a linear polymer of linked glucose (C6 sugars) units. Hemicellulose is a combination of multiple C5 and C6 sugars (xylose, mannose, arabinose, galactose, glucose), and lignin is a complex polymer, responsible for maintaining the structural integrity of plants. (Zhu & Zhuang, 2012).

Lignocellulosic biomass can be either processed directly to bioproducts (e.g., biofuels and biochemicals) or converted to intermediary compounds by decomposing the lignocellulosic structure, before being further processed to a range of bioproducts.

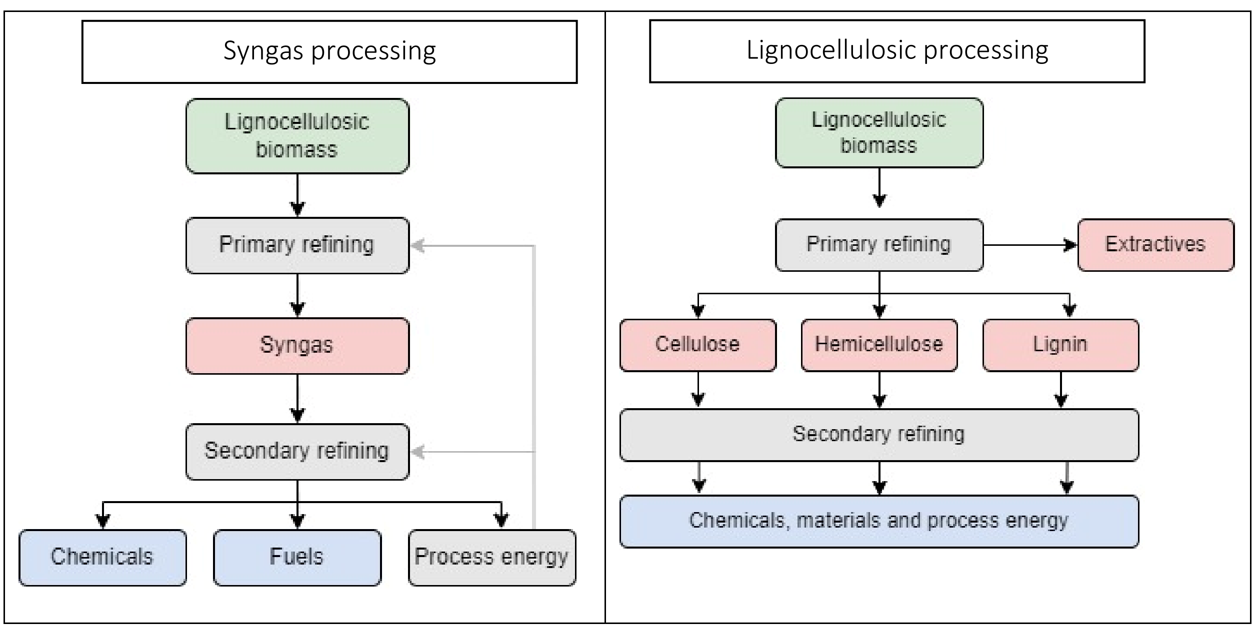
2.2.1 Direct processing of lignocellulosic biomass

Direct processing of lignocellulosic biomass usually happens via thermochemical or biological processes. Thermochemical processes yield heat, power and liquid fuels as products and usually proceed by commonly optimised processes like pyrolysis (Liu et al., 2020; Wang et al., 2020), liquefaction (Elliott et al., 2015; Patel et al., 2016), co-firing (Agbor et al., 2014; Patel et al., 2016a), carbonisation (Strezov et al., 2007) and combustion (Kumar et al., 2003). For direct processing using biological processes, processes such as solid-state and submerged fermentation can be used to produce single cell proteins, enzymes and organic acids (Kumar et al., 2016a).

2.2.2 Decomposing lignocellulosic biomass to intermediary compounds for further processing

The decomposition method of processing lignocellulosic biomass yields a plethora of products, in much greater quantity and diversity than through the direct processing route. Fundamentally, lignocellulosic biomass can be decomposed in two main ways, as depicted in Figure 4: i) by gasification, using high temperatures to synthesise gas (syngas), which acts as the intermediary compound that can be further transformed to fuels and chemicals (Dahmen et al., 2017); and ii) by separating the cellulose, hemicellulose and lignin fractions, which can be either separately or jointly converted to biofuels, bio-based chemicals, and bio-based materials (Harmsen & Hackmann, 2014; Brodin et al., 2017; Lask et al., 2019).

Figure 4: Processing routes for lignocellulosic biomass using intermediary compounds



Source: adapted from Dahmen et al. (2018).

The successful decomposition and conversion of lignocellulosic fractions to bioenergy and biochemicals, however, necessitates the addition of a pre-treatment step before the lignocellulosic biomass can be decomposed and processed, owing to its recalcitrant nature (Moreno & Olsson, 2017). For an in-depth overview of various types of pre-treatment technologies for lignocellulosic biomass together with their advantages and disadvantages, the works of E4tech, RE-CORD and WUR (2015) and Abdilla-Santes (2020) are recommended.

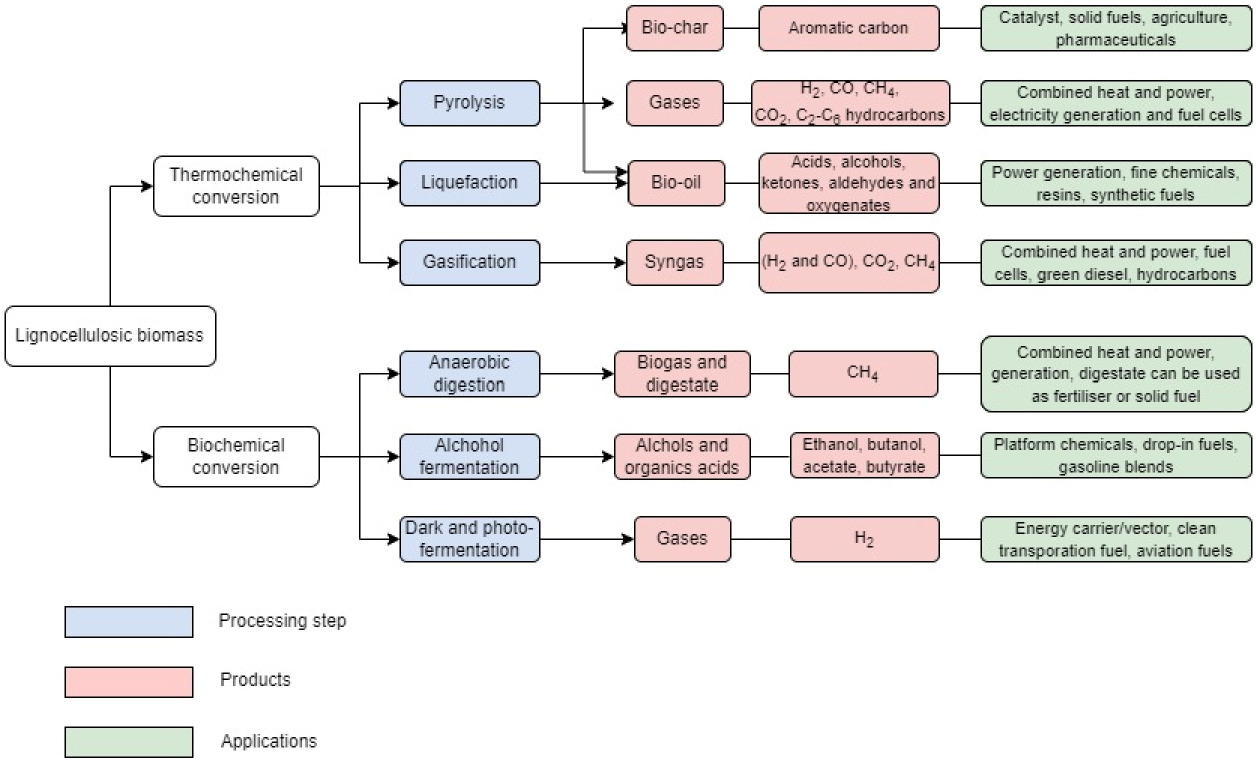
2.2.3 Overview of products and their production platforms

As highlighted in Section 2.2, lignocellulosic biomass can serve as feedstock to a wide array of products using different conventional and biorefinery technologies. Broadly speaking, lignocellulosic-derived products can be classified into the following categories (Okolie et al., 2021):

i) Biofuels
ii) Biochemicals
iii) Bioplastics and biocomposites
iv) Speciality materials from cellulose
v) Speciality materials from lignin
vi) Multifunctional carbons

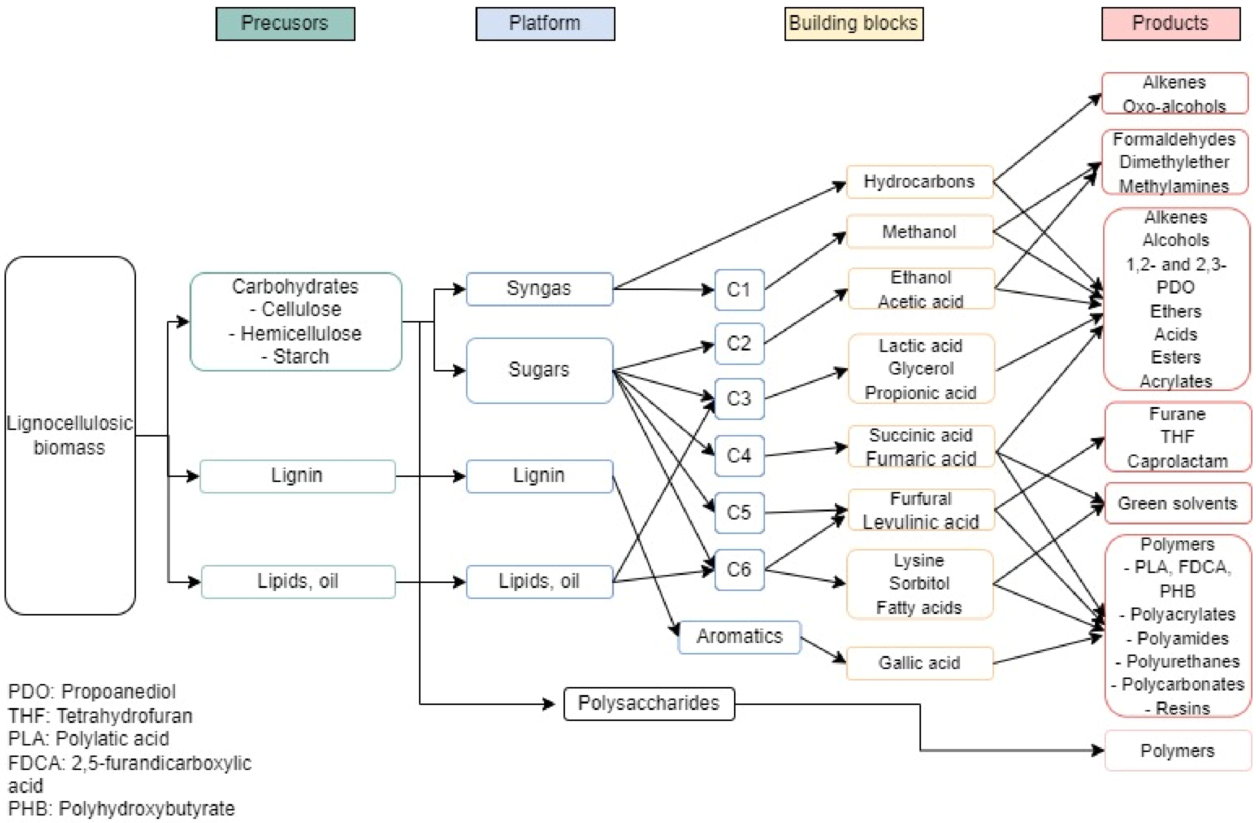
Figure 5 shows common biofuel production pathways from lignocellulosic biomass, highlighting the wide range of applications of lignocellulosic biomass-derived fuels in various industries. The versatility of lignocellulosic biomass-derived products is further highlighted in Figure 6, demonstrating the additional production potential of biochemicals and biopolymers.

Figure 5: Common biofuels production pathways from lignocellulosic biomass



Source: Adapted from Okolie et al. (2021)

Figure 6: Biochemicals and biopolymers from biomass



Source: Adapted from Abdilla-Santes (2020) and based on Kamm and Kamm (2005).

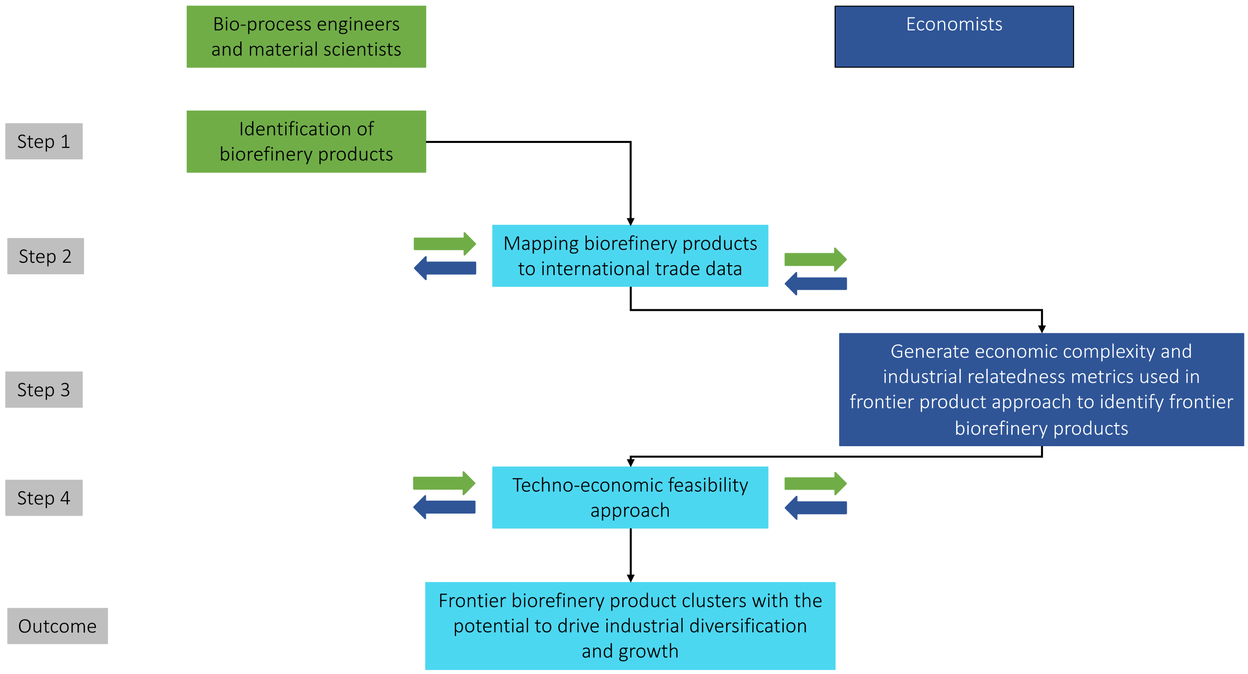
3 Methodology

Section 3 details the iterative inter-disciplinary methodology employed to identify clusters of frontier biorefinery products with the potential to foster resource efficiency, economic resilience, and flexibility in the fibrous plant industry, by leveraging off existing industrial capabilities in such manner to drive industrial diversification and build economic complexity. We start by providing an overview of the broader inter-disciplinary approach. We then detail each of the more specialised discipline-specific methodologies that fit within the broader iterative inter-disciplinary methodology. This commences with a description of the approach behind the identification of non-fibre-based biorefinery products, and the compiling of analytically relevant characteristics of these products. We then provide a discussion on the iterative inter-disciplinary process of mapping these products to international trade data nomenclature. This mapping enables one to generate metrics of economic complexity and industrial relatedness, and thereby, in line with methods applied in the smart specialisation literature, apply a frontier product approach to identify frontier biorefinery products. We describe this method. Finally, we make note of the technical and economic feasibility approach applied in identifying clusters of biorefinery products, which present industrial opportunities in the post-mine South African landscape.

3.1 Iterative inter-disciplinary approach

The inter-disciplinary methodological approach, depicted in Figure 7, is one that is iterative and sequential. This inter-disciplinary method forms the basis of the inter-disciplinary micro industrial policy approach (IMIP) we develop in this paper. The inter-disciplinary research team comprises engineering expertise (on the left and denoted as green) – in the form of material scientists and bio-process engineers – and economic expertise (on the right and denoted as blue). Using a holistic problem-solving approach, the research process involves discipline specific research, such as in step 1, where the material scientists and bio-process engineers identify a spectrum of products that can be manufactured from residual biomass in a biorefinery. Similarly, step 3 involves the economics team applying economic complexity and industrial relatedness metrics to determine frontier biorefinery products that present as industrial diversification opportunities. Step 3 is enabled by step 2: a collaborative and iterative inter-disciplinary process (denoted by the green and blue arrows) where the two research teams combine discipline-specific skills to map the biorefinery products identified in step 1 to the international trade data that is used in step 3. Step 4, which builds on the outcomes of step 3, is again an iterative inter-disciplinary element in the research process where the two disciplines combine technical and economic expertise to identify clusters of biorefinery products that present industrial opportunities in the given context.

Figure 7: Diagram presenting the Inter-disciplinary research approach and steps used in this study to demonstrated the feasibility of biorefinery as a pathway to building economic complexity in the post-mine landscape.

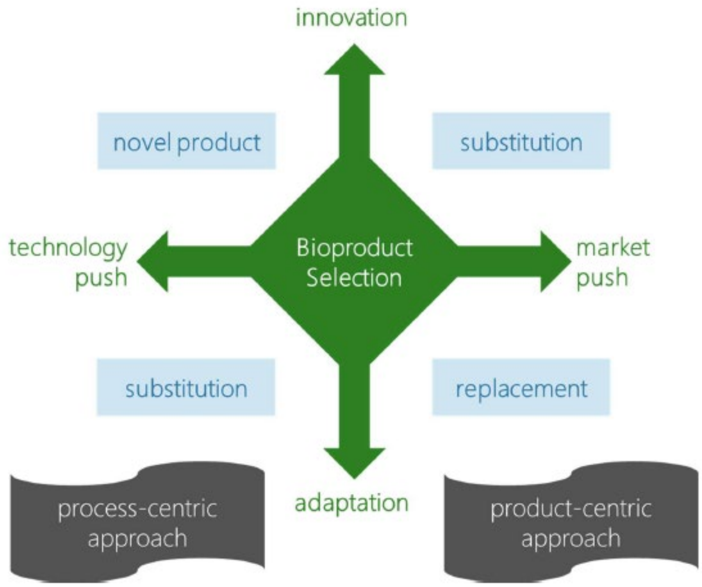


The remainder of this section details the methodological approaches that fit within each of these steps of the overall inter-disciplinary research process, and outlines the steps required to operationalise our proposed IMIP methodology.

3.2 Identification of biorefinery products

As seen in Section 2.2.3, there is a wide range of possible products which can be manufactured from lignocellulosic biomass, ranging from biofuels to specialty chemicals, targeting various industries. While there exist various methodologies and approaches to select promising biomass-derived products, Batsy et al. (2013) postulated two fundamental orientations: i) a process-centric design approach which uses innovative technology to deliver or "push" products, or ii) a product-centric approach which selects products with a known market "pull" (Figure 8).

Figure 8: Process-centric and product-centric approaches for the selection of products



Source: Based on Batsy et al. (2013).

It is important to contextualise the purpose of product selection in this particular study to decide on which of the two approaches to use. Firstly, referring to Figure 1, there is residual lignocellulosic biomass after the production of lead fibre-based products from bast fibre and bamboo plants, grown on degraded mine land in regions characterised by limited water and nutrient availability. Secondly, there is a need to support alternate economies and supply chains to provide consequent livelihoods for derelict mining communities. Thirdly, circular practices in developing a plant-based economy need to be anchored in sound economic, technical, and environmental feasibility. Given these considerations, the product-centric approach is deemed to be the most suitable approach in this study to ensure market uptake. This can be done by targeting products which have both a high market interest and a high technology readiness level (TRL). TRL is a term coined by NASA, referring to the maturity of a technology, aimed at supporting decision making processes in several industries related to science and engineering (Armstrong, 2015). Table 2 illustrates the definitions of the different TRLs for science and engineering, described by the Research Contracts and Innovation Department at the University of Cape Town.

Table 2: Technology readiness level (TRLs) for science and engineering

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Basic idea	Concept developed	Experimental proof of concept	Lab demonstration	Lab scale validation (early prototype)	Prototype demonstration	Pilot system demonstrated	System incorporated in commercial design	Proven system ready for full deployment

Source: Research Contracts and Innovation at the University of Cape Town (2024).

Products of interest were initially identified based on a number of studies and reviews, as detailed in Table 3. Subsequently, a method of product selection and classification was devised to allow for the successful screening and product mapping required for complexity analysis using the following steps:

1) Three main biorefinery production platforms (refer to Figure 6) were identified to investigate the full product potential of lignocellulosic biomass: namely, the thermochemical platform using syngas; the sugar and lignin platform; and the seed oil platform, chosen especially for investigating hemp and kenaf seed oil product formation potential.
2) High market interest (both internationally and locally) was chosen as the main criterion of selection to shortlist promising bioproducts. Thereafter, a TRL of 8 was used to select lignocellulose bioproducts for the sugar and lignin platform.
3) Chosen products were further classified as intermediary or final products. Additionally, they were broadly grouped in four main categories – a) energy products, b) platform chemicals, c) bioplastics/biopolymers, d) low-value biomass products. [6]

[6] A platform chemical, also known as a chemical building block, is described as a chemical which can serve as a substrate to produce various other higher value-added products (Takkellapati et al., 2018).

Table 3: Overview of studies and reviews consulted for identifying relevant and promising lignocellulosic biomass-derived bioproducts for South Africa

Study Title, Author, Year	Chemicals listed	Notes
Biorefinery approaches for the production of fuels and chemicals from lignocellulosic and algal feedstocks (Naira et al., 2020)	Furfural, hydroxymethyl furfural, 2,5-furandicarboxylic acid, levulinic acid, formic acid, 2,5-dimethyl furan, itaconic acid, 1,3-butadiene, 1,4 -butanediol, adipic acid, cyclohexane, lignosulphonates, ferulic acid, vanillin, acetic acid, bioethanol, biobutanol, acetone, organic acids, enzymes, biopolymers, bio-oil, syngas, charcoal, syngas, methane, hydrogen, biodiesel, fatty acids, glycopeptides, proteins, pigments, vitamins, polypeptides, lipids, residual biomass, crude glycerol, nutritional supplements, pharmaceuticals.	This study focussed on exploring the biorefinery potential of lignocellulosic and algal feedstocks for co-producing biofuels and biochemicals using various thermochemical and biological conversion routes.
Syngas derived from lignocellulosic biomass gasification as an alternative resource for innovative bioprocesses (Ciliberti et al., 2020)	Syngas (mixture of H_2, CO and CO_2) and its derivatives.	This study explored biomass gasification opportunities integrated with syngas fermentation to support second-generation biorefineries and replace fossil-based processes.
A review on commercial-scale high-value products that can be produced alongside cellulosic ethanol(Rosales-Calderon & Arantes, 2019)	1,2-butanediol, 1,3-popoanediol, 1,4-butanediol, 2, 3-butanediol, acetone-butanol-ethanol, furfural, furfuryl alcohol, glutamic acid, isobutanol, itaconic acid, lactic acid, lactide, lysine, polylactic acid, polytrimethylene terephthalate, propylene glycol, sorbitol squalene, succinic acid, terpenes, xylitol and microfibrillated cellulose.	The authors investigated an integrated cellulosic ethanol biorefinery with the production of high value chemicals to improve the economics of cellulosic ethanol production. Their products of choice were presented as a list of chemicals and materials with a minimum TRL of 8, thus having already attained commercial scale production.
Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review (Patel et al., 2016b)	Methanol, ethanol, dimethyl ether, ethylene, propylene, ammonia, bio-oil, bio-char, Fischer-Tropsch fuel, hydrogen, gasoline, liquefied petroleum gas (LPG), gasoline & diesel, naphtha & diesel.	The authors investigated the thermochemical conversion of biomass to energy via pyrolysis, gasification, combustion, co-firing, liquefaction, and carbonization. They used techno-economics and life cycle assessment to compare the various process options.
Biotechnological transformation of lignocellulosic biomass into industrial products (Kumar et al., 2016b)	Industrial enzymes, bioethanol, biomethane, bio-hydrogen, citric acid, succinic acid, lactic acid, acetic acid, polysaccharides, single-cell proteins, xylitol.	This review discussed the chemical and physical properties of lignocellulosic biomass and how it can be converted to industrial products.

Study Title, Author, Year	Chemicals listed	Notes
Feasibility study: Bio-based chemicals landscape of South Africa (Harrison et al., 2016)	Top 20 chemicals for South Africa: Citric acid, lactic acid, iso-butanol, n-butanol, ethanol, isoprene, glutamic acid, acetic acid, algal lipids, ethylene, furfural, adipic acid, polylatcic acid, succinic acid, lactate esters, farnesene, levunilic acid, polyhydroxyalkanoates, malic acid.	This feasibility study ranked product potential (not limited to lignocellulosic biomass feedstock) in South Africa based on market demand in South Africa and globally, current use and future applications, complexity of production routes, technology readiness, and barriers to market. A combination of technology review, market literature, import–export data, application analysis, and expert opinion was used.
Lignocellulosic biomass: A sustainable platform for production of bio-based chemicals and polymers (Isikgor & Becer, 2015)	Undertook detailed product mapping for 15 C5/C6 derived platform chemicals: 1,4-diacid, 5-HMF & FDCA, 3-HPA, aspartic acid, glutamic acid, glucaric acid, itaconic acid, glycerol, sorbitol, levulinic acid, 3-HBL, lactic acid, xylose-furfural-arabinitol, acetone-butanol-ethanol (ABE).	This study reviewed over 200 value-added chemicals which can produced from lignocellulosic biomass. The authors further conducted detailed mapping for specific chemicals and their associated polymers.
From the sugar platform to biofuels and biochemicals E4tech, RE-CORD and WUR (2015)	The report investigated 94 sugar-based products and shortlisted 25 products of interest. The authors further undertook detailed cases studies for 10 products, selected based on having a TRL of at least 5, having at least one EU developer and demonstrating significant potential for market expansion. The products were acrylic acid, adipic acid, 1,4 butanediol, farnesene, 2,5 furan-dicarboxylic acid, isobutene, polyhydroxyalkanoates, polyethylene, polylactic acid, succinic acid.	This study mapped value chains for the sugar platform and assessed them based on their development status, economic competitiveness, environmental sustainability and market potential.

3.3 Mapping biorefinery products to international trade data

As shown in Figure 7, step 2 of our inter-disciplinary methodology involves mapping the biorefinery products identified in step 1 to international trade data. A total of 60 biorefinery products classified into energy, low-value biomass, platform chemical, and bioplastic/biopolymer product groupings, are mapped at the 6-digit level to the 1992 revision of the Harmonised System (HS) classification.

The mapping is an iterative inter-disciplinary process that involves the following stages: First, the economics team determines which of the 96 aggregated 2-digit chapters within the HS classification contain biorefinery products. This reduces the number of disaggregated 4-digit and 6-digit product codes that the material scientists and bio-process engineers must search through to locate and identify biorefinery products.[7] Second, the material scientists and bio-process engineers systematically sifted through the 4- and 6-digit codes that fell within the initial subset of 2-digit codes, and matched biorefinery products identified in step 1 to the relevant product codes. An advantage of this matching process was the discovery of additional biorefinery products that were not initially identified in step 1. Third, the economists checked these matches and assisted in matching biorefinery products that could not be matched as easily. This final stage in the mapping was a back-and-forth process that iterated until the two research teams were satisfied with what became the final mapping.

The iterative inter-disciplinary mapping process has both advantages and limitations. An advantage of this mapping process is that the material scientists and bio-process engineers possess the relevant knowledge to reliably inform the mapping. This is particularly apparent in the mapping of, for example, organic chemicals, such as xylene, ethylene, methanol, and acetic acid. This is not a subject matter that is typically found in an economist's toolbox, and thus limits their ability to reliably perform such a mapping exercise. A key limitation of the mapping approach is that the HS system does not distinguish between product production processes. The implication being that a product code could contain both products that are made using bioprocesses and/or synthetic processes. For example, ethanol can be manufactured from petroleum via the chemical transformation of ethylene, or via biological processes, through the fermentation of sugars from biomass.

3.4 Using economic complexity and industrial relatedness metrics to identify frontier biorefinery products

Once the biorefinery products are mapped to the international trade data, we use economic complexity and industrial relatedness theory and metrics – as per the frontier product approach – to identify industrial

[7] The HS classification contains 1224 Headings at the 4-digit level and 5205 Sub-headings at the 6-digit level. Large subsets of these Headings and Sub-headings are not likely to contain biorefinery products. We use the 2-digit Chapters of the HS classification to refine the search and mapping process. For example, HS Chapter 01 'Live animals' is clearly not relevant and can be removed from the mapping process, while HS Chapter 29 'Organic chemicals' is relevant and may contain biorefinery products that can be mapped.

diversification opportunities in the biorefinery space. In this section we detail this economic discipline-specific methodological approach.

3.4.1 Economic complexity: Identifying a desirable set of industrial diversification opportunities

The theory of economic complexity is based on the notion that the development of products or services not only requires the standard factors of production, such as raw materials, labour, and machinery, but also the tacit productive knowhow on how to put all these inputs together in a business operation. This productive knowhow – or capabilities – is typically a key constraint to diversifying economic activities because, given its tacit nature, it is not easily transferable and tends to be spread across many individuals who need to coordinate across teams and organisations (Hausmann et al., 2014; Hausmann et al., 2022). As such, countries (or places) that have accumulated a wide and sophisticated set of productive capabilities are able to produce a diverse range of complex products. The most complex economies produce a diverse range of products, many of which other countries are unable to produce given the specialised nature of the capabilities and knowhow required, whereas the least complex economies produce a small range of ubiquitous products.

A particular challenge faced in the application of this theory is that productive knowhow is not directly measurable. Drawing on the assumption that, ultimately, countries develop the products (or services) enabled by their capabilities and knowhow, Hidalgo and Hausmann (2009) address this challenge by indirectly inferring measures of productive knowhow – economic complexity – by examining what countries (places) are able to produce. Two logical extensions emerge from this observation: Firstly, countries that have a larger knowledge base are able to produce a greater diversity of products. Secondly, if a particular product requires a large volume of knowledge in order to produce it, this product can only be produced in those few countries in possession of the wide variety of capabilities needed. These two observations provide the notions underlying two key components that are used in building up a measure of economic complexity: diversity and ubiquity.

Diversity and ubiquity together provide a starting point for developing the notion of economic complexity. Since diversity relates to the number of products present in a country's export basket, and ubiquity refers to the number of countries that produce a particular product, one can categorise complex economies as those countries with a large diversity of products with low ubiquity. Put simply, if a country produces a wide variety of products that are not produced by many other countries, then this economy is likely to be more complex. Analogously, complex products are those that are not produced by many other countries – i.e., not ubiquitous – and, further, produced by countries with diverse export structures – i.e., countries with many capabilities.

Following Hausmann et al. (2014) and using methods related to dimensionality reduction, we manipulate product-level export data from the BACI International Trade Database and construct an economic complexity index (ECI) and a product complexity index (PCI).[8] We define a binary country-product matrix M, with elements M_{cp} which are equal to 1 if country c exports product p with revealed comparative advantage (i.e., RCA≥1) and 0 otherwise. RCA is calculated using the Balassa (1965) index shown in equation (1):

$$RCA_{c,p} = \frac{X_{c,p}/\sum_c X_{c,p}}{\sum_p X_{c,p}/\sum_{c,p} X_{c,p}} \tag{1}$$

where $X_{c,p}$ is country c's exports of product p.[9] Diversity and ubiquity can be calculated by summing along the rows and columns of the matrix, M, respectively. Formally, we can define these concepts as:

$$Diversity = d_{c,0} = \sum_p M_{c,p} \tag{2}$$

$$Ubiquity = u_{p,0} = \sum_c M_{c,p} \tag{3}$$

To capture how similar one country's export basket is to another, we calculate a new matrix $\widetilde{M}$, which is given by

$$\widetilde{M} = D^{-1} M U^{-1} M' \tag{4}$$

Where D is a diagonal matrix with the entries along the main diagonal being the diversity measures for each country as defined in equation (2), and U is the diagonal matrix with diagonal entries equal to product ubiquities, as per equation (3).

The vector of ECI values for all countries is then defined by the eigenvector corresponding to the second-largest right-eigenvalue of the matrix $\widetilde{M}$. It is common practice to standardise this ECI vector by subtracting

[8] We use export data at the 6-digit level of the Harmonised System 1992 revision. All economic complexity measures, and the other metrics detailed below, are 5-year aggregates. Five-year aggregates allow for the minimizing of trade fluctuation noise in the data.

[9] A product is classified as being exported competitively if $RCA \geq 1$, while a product is classified as not being exported competitively if $RCA < 1$.

the mean and dividing by the standard deviation of the vector's entries. As a result, one can define the ECI mathematically as:

$$ECI = \frac{\vec{D} - < \vec{D} >}{sd(\vec{D})} \tag{5}$$

where $\vec{D}$ is the eigenvector associated with the second-largest right-eigenvalue of $\widetilde{M}$, $<\cdot>$ represents the mean of the vector, and $\mathrm{sd}(\cdot)$ represents the standard deviation. The PCI, which is the equivalent complexity index for products, can be defined as

$$PCI = \frac{\vec{U} - < \vec{U} >}{\mathrm{sd}(\vec{U})} \tag{6}$$

where $\vec{U}$ is simply the eigenvector associated with the second-largest right eigenvalue of the matrix $\widehat{M} = U^{-1}M'D^{-1}M$ (Mealy & Coyle, 2019).

The resulting economic complexity measures are useful for our purposes of identifying biorefinery products that can bring about industrial growth, and thereby shift South Africa to higher levels of economic development. The empirical basis for this result emerges from work by, amongst others, Hidalgo and Hausmann (2009) and Hausmann et al. (2014), who show that economic complexity is positively correlated with economic development and predictive of future economic growth. Further, it has been shown that countries which have experienced industrialisation, or manufacturing-led structural transformation, are more complex (Bhorat, Steenkamp & Rooney, 2017). Thus, from an industrial policy standpoint, accumulating productive capabilities and knowhow, and diversifying into increasingly complex products – thereby building economic complexity – is a desirable endeavour given the potential economic development outcomes. As an example for the biorefinery case, this could mean prioritising the development of technical knowhow to produce highly complex products such as carboxylic acids in the future, rather than diversifying production into less complex products such as wood charcoal. The theory of economic complexity would suggest that the process of diversifying into the production of carboxylic acids would be more beneficial for overall economic development in the long term, than the diversification into the production of wood charcoal.

3.4.2 Industrial relatedness: Identifying a feasible set of industrial diversification opportunities

While building economic complexity is a desirable industrial policy objective, it is not always clear which diversification opportunities represent feasible industrial pathways to follow. The industrial relatedness literature provides the conceptual and empirical basis for determining feasible industrial pathways.

Hausmann et al. (2014) argue that building economic complexity is contingent on developing the requisite productive capabilities. However, the accumulation of productive capabilities in order to grow economic complexity suffers from the ‘chicken and egg’ problem: countries cannot create products for which they do not have the capabilities. However, in the same breath, countries are unlikely to want to accumulate new capabilities if the production processes that demand these capabilities do not exist (Hausmann et al., 2014).

A potential solution to this circular problem is for economies to develop new capabilities that are similar to the capabilities that are needed for goods produced within the current industrial structure, and this is where the notion of relatedness emerges. The theory of relatedness states that the success of a country (place) entering an economic activity depends on the cognitive and technological proximity between the new activity and a location’s prior activities (Hidalgo, 2021). Put differently, the feasibility of diversifying into a new product is dependent on how related – in terms of capabilities – the product is to the country’s (place’s) current production structure. Big jumps to “distant” unrelated products require substantial capability investment, while small jumps to “nearby” related products require fewer new capabilities and thus present feasible diversification pathways. This is evidenced empirically by research showing that the probability that a country (place) enters an economic activity is correlated with the presence of related “nearby” activities (Hidalgo et al., 2007; Neffke & Henning, 2013).

Therefore, to identify feasible industrial diversification opportunities within the biorefinery space, we calculate relatedness measures, and in particular, the distance index. Using international trade data from the BACI International Trade Database, we estimate how related these traded products are in terms of underlying production capabilities, by drawing on the measure of product proximity ($\phi_{i,j}$) proposed by Hidalgo et al. (2007). The proximity measure is increasing in the likelihood that two products i and j are exported by the same country, where proximity can be defined as follows:

$$\phi_{i,j} = \min \{\mathrm{P}\big(RCA_i \geq 1 | RCA_j \geq 1\big); \mathrm{P}\big(RCA_j \geq 1 | RCA_i \geq 1\big)\} \tag{7}$$

where $\mathrm{P}(RCA_i \geq 1 | RCA_j \geq 1)$ is the probability that a country exports product i competitively (i.e., with RCA≥1), conditional on the fact that it already exports product j competitively, and vice versa for $\mathrm{P}(RCA_j \geq 1 | RCA_i \geq 1)$. Given that the proximity measure is conceptually related to distance and given that a distance function defined on any metric space must be symmetric[10] (Khamsi & Kirk, 2001), the minimum of these two conditional probabilities is used in order to satisfy this property.

To estimate how related a given product – and in our case, a biorefinery product – is to a country's current set of production capabilities, we employ the density measure developed by Hidalgo et al. (2007). Density calculates the average proximity between a given product j and all the products that a country c currently exports competitively (i.e., with RCA≥1). This is given by

$$\delta_{j,c} = \left(\frac{\sum_i M_{c,i}\phi_{i,j}}{\sum_i \phi_{i,j}}\right) for\ i \neq j \tag{8}$$

where $M_{c,i}$ is a binary variable equal to unity if country c has RCA≥1 in product i and zero otherwise. To obtain a measure for distance, one calculates the additive inverse of density as follows:

$$\Delta_{j,c} = 1 - \delta_{j,c} \tag{9}$$

We can now generate a measure of the distance – in terms of capabilities – between a given biorefinery product and South Africa's existing productive structure.

We also generate an additional measure that combines economic complexity and relatedness measures, called the complexity outlook gain (COG) index. This measure combines product complexity and distance indices to quantify the extent to which adding a new product to the current production structure opens up subsequent diversification opportunities into more complex products. This index captures the strategic value of a potential diversification opportunity based on the new paths to diversification into more complex sectors that it opens up. This complexity outlook gain index is defined as follows:

$$COG_{j,c} = \left[\sum_i \frac{\phi_{i,j}}{\sum_k \phi_{k,i}}(1 - M_{c,i})PCI_i\right] \tag{10}$$

Therefore, the distance index speaks to industrial feasibility while the product complexity and complexity outlook gain indices speak to economic desirability, which means one can identify both desirable and feasible biorefinery products for South African firms to diversify toward. This is formalised in the frontier product approach, which is detailed below.

[10] This is the notion that a valid distance function, d, defined between the points x and y should satisfy the property that $d(x,y) = d(y,x)$.

3.4.3 The frontier product approach

The frontier product approach, which falls within the smart specialisation literature, is used to identify industrial diversification opportunities in a data-centric manner, and thereby provide a quantitative basis for industrial policy interventions.[11] The frontier product approach draws on the two key ideas discussed above, and their accompanying metrics: firstly the notion of relatedness, which speaks to the feasibility of diversifying into a product; and secondly, economic complexity, which speaks to the desirability to diversify into a product. These two ideas form the foundation of the frontier product approach.

We draw on the approach developed by Hausmann et al. (2014), where we apply the following steps: First, frontier products should promote industrial diversification, and we, thus, restrict the set of candidate products under investigation to only those that are not currently exported competitively ($RCA < 1$).[12] Second, frontier products should build economic complexity. We thus restrict the set of candidate products under investigation to those whose PCI value is strictly higher than the country's ECI ($PCI_i > ECI_c$). Third, frontier products should offer strategic value in terms of a potential diversification opportunity affording subsequent diversification opportunities into other more complex sectors. As such, frontier products should have an opportunity gain index greater than zero ($COG_{j,c} > 0$).

Fourth, after taking into account the complexity and opportunity gain desirability criterion, we now consider the distance feasibility criterion. Ideally, one would want product-level diversification opportunities to be both complex and related in terms of requisite productive capabilities, and thus lie in the top left corner of the product complexity-distance space (i.e., have low relative distance from the current productive structure, while also having high relative complexity). However, there exists a trade-off where more complex products are generally more distant and thus more difficult to develop. To identify a set of frontier products, we thus impose the condition that diversification into a more complex product is only feasible if the corresponding complexity gain from said product is sufficiently high. In other words, the gain in complexity must compensate for the substantial investment in productive capabilities needed to

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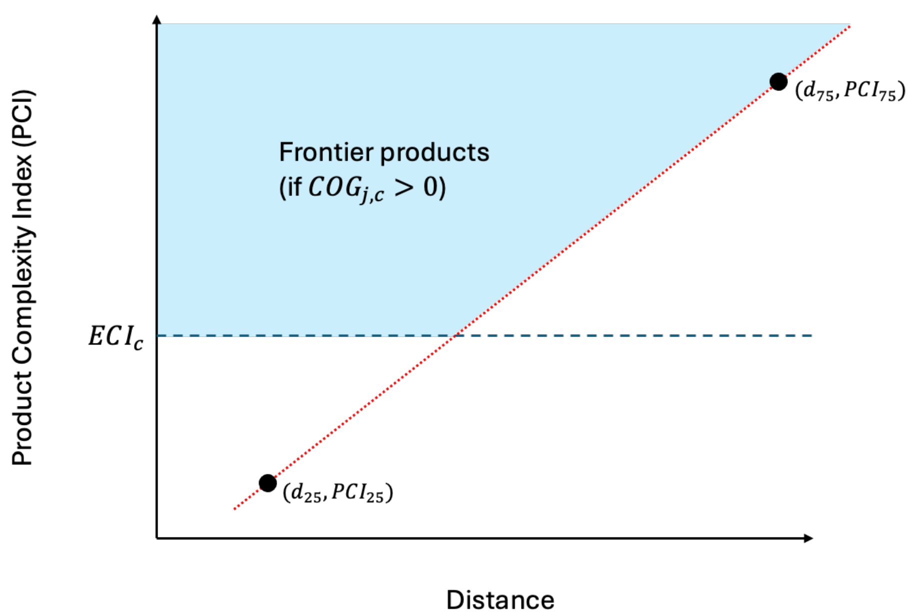
[11] We draw on studies emerging from the Centre for International Development at Harvard University, such as those by Hausmann et al. (2014) and Hausmann and Chauvin (2014), which apply the notion of identifying industrial opportunities at a country's technological *frontier* – hence the *frontier product approach*. The methodological approach applied in these studies is housed within the *smart specialisation* literature, which uses industrial relatedness and economic complexity metrics to identify industrial opportunities in, for example, Europe (Balland et al., 2019), and the United Kingdom (Mealy & Coyle, 2019).

[12] However, it is important to note that when we consider various clusters of biorefinery products, while focusing on mainly including frontier biorefinery products into these clusters, we also allow for the limited inclusion of biorefinery products that are currently exported competitively. As such, the cluster approach exploits existing productive capabilities to include these existing products and builds off these industrial capabilities to diversify into nearby products.

overcome the distance gap. To represent this constraint, we create a diagonal cut-off line that joins the points representing the joint 25th and 75th percentiles of complexity and distance, respectively.[13] We classify products lying above this boundary line as those that balance the objectives of higher complexity (desirability) with lower distance (feasibility). We thus only consider distant products if they are correspondingly complex. A notional depiction of this methodology is presented in Figure 9, where products in the blue shaded area would be classified as frontier products under the assumption that they exhibit positive opportunity gain indices ($COG_{j,c} > 0$).[14]

Figure 9: Illustration of the frontier product approach methodology



Source: Authors' depiction based on Hausman et al. (2014).

Note: (d_{25}, PCI_{25}) and (d_{75}, PCI_{75}) refer to the points in the distance-complexity space representing the 25th percentile of distance and complexity, and the 75th percentile of distance and complexity, respectively.

Finally, given the focus of this study, we narrow our focus to biorefinery products that meet the criteria detailed in the four preceding steps. We do this by identifying the subset of all frontier products that were identified as biorefinery products in the inter-disciplinary mapping procedure. These we refer to as *frontier*

[13] In other words, we create this line to join up the points (d_{25}, PCI_{25}) and (d_{75}, PCI_{75}) in the distance-complexity space.

[14] When applying this methodology to the South African economy, 1 703 products meet all of the described criteria and are thus classified as frontier products.

biorefinery products. These are a subset of the products identified in Section 3.2. We detail these findings in more detail in Section 4.2.

3.4.4 Secondary Criteria

Over and above the economic complexity and relatedness criteria used in the frontier product approach to identify frontier biorefinery products, we also consider a set of secondary criteria. These secondary criteria are not used to determine the set of frontier products, but rather provide additional policy lenses from which to inform the policymaker when deciding on industrial policy interventions.

Product Gini Index: (In)equality

We use the product Gini Index (PGI) developed by Hartmann et al. (2017) to provide an income inequality lens when considering product-level industrial diversification opportunities. Hartmann et al. (2017) show that complex economies are more inclusive and, ultimately, structural shifts toward a more complex productive structure are set to be equality-inducing. They, in turn, develop product-level Gini Index measures. The PGI associates a product to a level of income inequality equal to the average Gini Index of the countries exporting that product. Formally, the PGI for product p is defined as follows:

$$PGI_p = \frac{1}{N_p}\sum_c M_{cp} s_{cp} Gini_c \tag{11}$$

where $Gini_c$ is the Gini coefficient for country c, M_{cp} is equal to unity if country c exports product p with a revealed comparative advantage, and zero otherwise, and s_{cp} is the share of country c's exports represented by p. N_p is the normalizing factor that ensures that the PGIs are the weighted average of the Ginis. N_p and s_{cp} are calculated as follows:

$$N_p = \sum\nolimits_c M_{cp} s_{cp} \tag{12}$$

$$s_{cp} = \frac{X_{cp}}{\sum_{p'} X_{cp'}} \tag{13}$$

Where X_{cp} is the total export of product p by country c.[15]

[15] We generate PGI indices using export data from the BACI International Trade Database as the 6-digit level of the Harmonised System 1992 revision. Gini coefficient data is taken from the World Income Inequality Database (UNU-WIDER, 2021). We average out data over five year periods and use the 2015 to 2019 period in our analysis.

Revealed capital intensity index: Labour absorption

We also generate revealed capital intensity indices, along the lines of Shirotori, Tumurchudur and Cadot (2010), to provide a labour absorptive lens when considering product-level industrial diversification opportunities. To generate a revealed capital intensity index (RCI), we follow a method analogous to that detailed for the PGI above – simply replacing a country-level capital-to-labour ratio for the Gini coefficient in equation (11).[16] Given the focus on labour-absorption, we opt to invert our final measure of RCI so as to obtain a direct measure of revealed labour intensity (RLI), which will be more useful for our interpretation later in this paper.

Demand

A final secondary factor that we include in our analysis is a variable capturing global demand for a given product. Ideally, when tailoring industrial policy to foster industrial diversification, it is desirable to slant toward growing global markets. We adopt a relatively crude measure by calculating annualised global growth rates for each product, with positive annualised growth rates pointing to growing global markets. In particular, we focus on the period following the Global Financial Crisis (GFC), and as such, we make use of annualised global growth rates for products specifically between 2010 and 2019 for our analysis.[17]

3.5 Technical feasibility analysis

After the selection of frontier biorefinery products detailed in Section 3.4, a technical feasibility analysis is conducted to propose different product clusters which can be produced from the residual lignocellulosic biomass left over in the post-mining regenerative agriculture endeavour. One limit of the frontier product approach is that it is agnostic to the synergies, complementarities, and trade-offs between products as regards their use of biomass as feedstock. For example, both carboxylic acid and glycerol are identified as frontier biorefinery products, and according to economic complexity metrics both present desirable diversification opportunities for the South African economy. However, these two products are not part of the same multi-product value chain, meaning that in practice – given limited availability of feedstock for production – one would need to choose between these two frontier biorefinery products, and one could not produce both. As a result, it is critical to understand the full multi-product value chain to identify

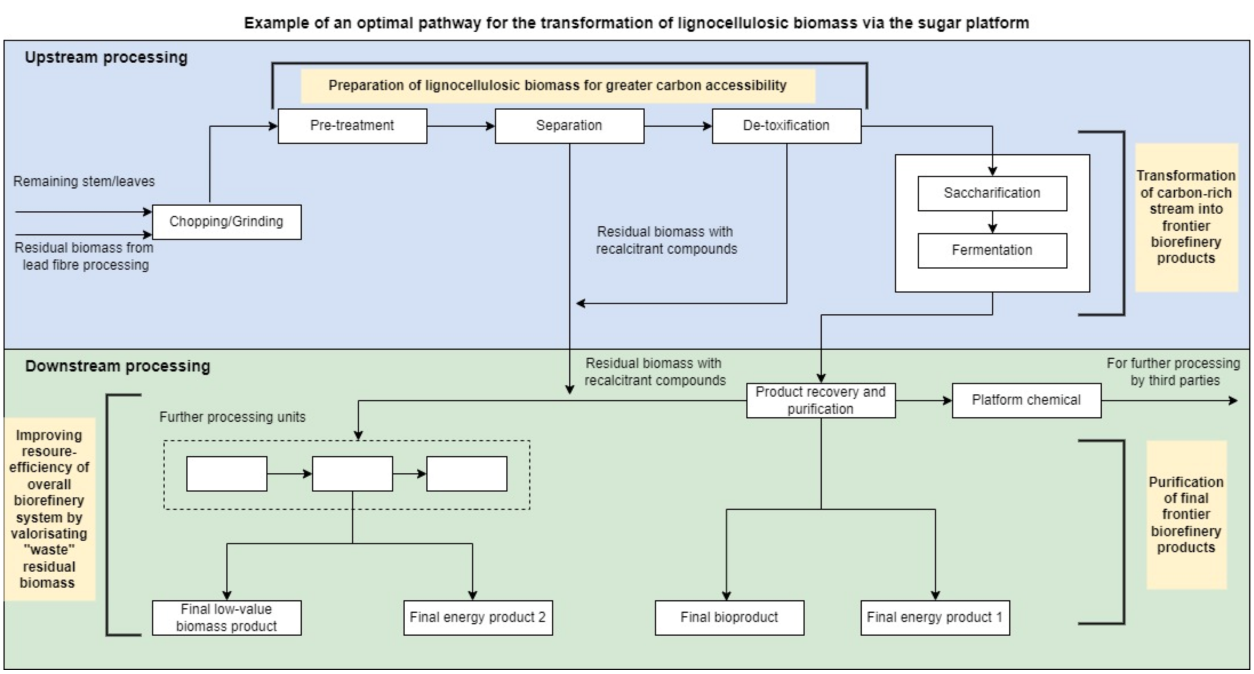
[16] We generate RCI indices using export data from the BACI International Trade Database as the 6-digit level of the Harmonised System 1992 revision. Country-level capital-to-labour ratio data is taken from the Penn World Table version 10.01 (Feenstra, Inklaar & Timmer, 2015). We average out data over five-year periods and use the 2015 to 2019 period in our analysis.

[17] One could choose any other period to proxy for global growth, however, we believe this is most appropriate given that the growth in biorefinery products is likely to be more recent, and so we utilize the most recent decade of growth data available to us.

clusters of related products that can be co-produced given a limited supply of biomass feedstock. Product clusters are also proposed instead of single products to fully support biorefining operations, which are anchored in a multi-product production system that aims to maximise resource efficiency – as highlighted in Section 2. As an example, Figure 10 provides a visual representation of an ideal biorefinery set-up for the sugar production platform.

The blue portion of the diagram consists of upstream processing and transformation steps to: i) prepare and fractionate the residual lignocellulosic biomass after the production of lead fibre-based products; and ii) to transform the carbon contained within the lignocellulosic biomass into frontier biorefinery products. The green portion of the diagram captures the various downstream processing steps to extract and purify frontier biorefinery products, either as a platform chemical or a final high value product coupled with an energy product. Any residual biomass which still contains valuable carbon resources can be re-directed to additional processing units to produce more products of lower economic value (e.g., fertilisers, biogas etc.). This approach can realise a cascade of products with varying economic value, ranging from high-value platform chemicals to the medium-value bioenergy products, and finally, to low-value biomass products.

Figure 10: Example of an optimal biorefinery production system for the transformation of lignocellulosic biomass via the sugar production platform



For the context of this study, three product clusters are proposed, each containing one or more frontier biorefinery products, and an extra medium or low value product to close the material loop as much as possible. In choosing the frontier biorefinery products in each cluster, various reviews and techno-economics studies were consulted to select the most technically feasible products in terms of market potential, product volume, and yield. Further details on these results are provided in Section 4.3, based on established medium to large operations.

Following the identification of these clusters of biorefinery products, we are able to further analyse them through the lenses of economic complexity, or the secondary indicators outlined previously. In short, for each cluster, we assume that the constituent products reach $RCA \geq 1$ (i.e., they are produced and exported competitively on a substantial scale) and we then analyse how the values of our various indices – economic complexity (ECI), inequality (XGini), labour intensity (RLI), complexity outlook gain (COG), and global demand – change as a result of these new products entering the export basket. This economic analysis then allows for policy-relevant insights to be drawn regarding the various diversification options available.

4 Main results

4.1 Biorefinery product list

Using the approach detailed in Section 3.2, three product maps were generated to investigate the product potential of lignocellulosic biomass in the context of post-mine development. These will be discussed in the sections that follow.

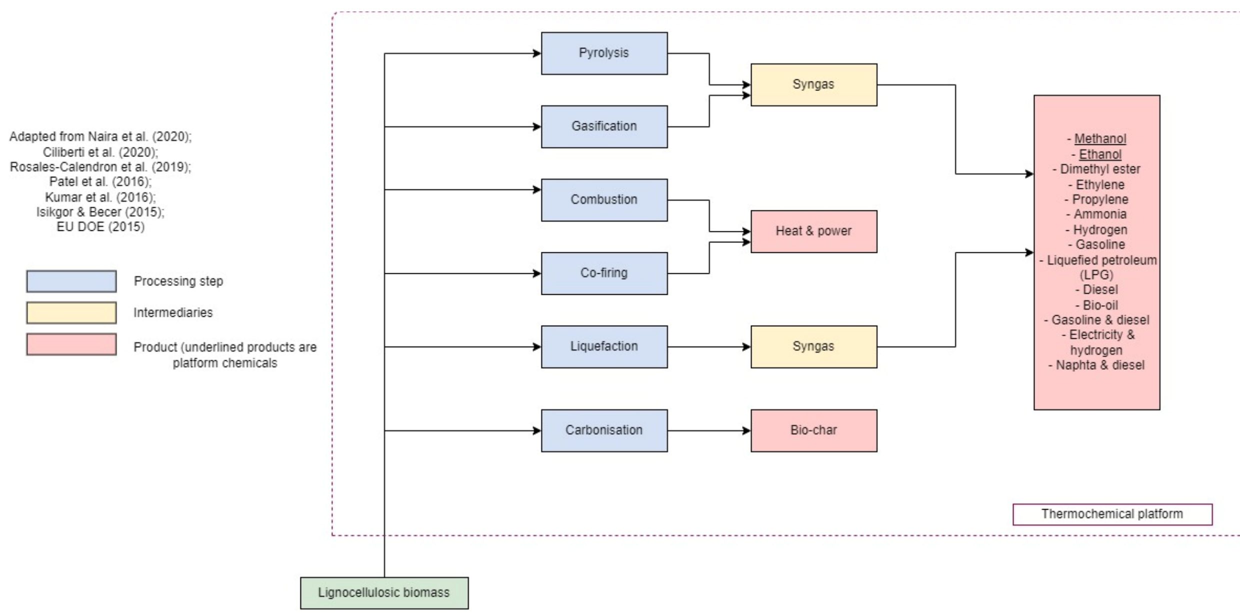
4.1.1 General overview of the thermochemical production platform

The thermochemical platform (Figure 11) illustrates the high potential of using thermochemical technologies to transform lignocellulosic biomass to products, which are traditionally synthesised from petrochemicals such as syngas, heat and power. Syngas (a mixture H_2, CO and CO_2) can serve as a valuable intermediate for further processing to important chemicals such as methanol, ethylene and LPG. Biomass-derived syngas is a highly sought after intermediate product to drive the global decarbonisation of the fuel industry by decreasing the dependence on fossil fuels and address the rising climate change challenges (Bolívar Caballero et al., 2022).

Fundamentally, thermochemical processing of biomass requires heat and a catalyst to generate products, with the main types of processing being gasification and pyrolysis. Gasification involves the thermal decomposition of organic matter (including lignin) into flammable gases through an equilibrium process at high temperatures and with long residence times. This process yields tar, char and other contaminants, which need to be removed before further processing of the intermediate gases (e.g., syngas). Since each contaminant requires their own catalyst, the gasification process is a costly process that is only economically feasible at large scale. Another common thermochemical process is fast pyrolysis, with low residence time and high temperature, which rapidly heats biomass in the absence of oxygen to produce syngas, charcoal (bio-char), and a liquid mixture of organic compounds and water (bio-oil). The chemistry of pyrolysis is poorly understood, and this is a major challenge for scale-up processes (National Research Council (US) Chemical Sciences, 2012).

The processing of syngas to platform chemicals and end-products can be done either chemically or biologically (Molino et al., 2016). Based on the product selection criteria established in Section 3.2, chemical processing of syngas proved to be more beneficial for this study, especially products used in transportation fuel production, such as Fischer-Tropsch, liquid fuels, hydrogen, methanol and dimethyl ether (DME) as there are already established markets for these products (Rauch et al., 2014).

Figure 11: Short-listed products of interest for the thermochemical platform using lignocellulosic biomass as feedstock



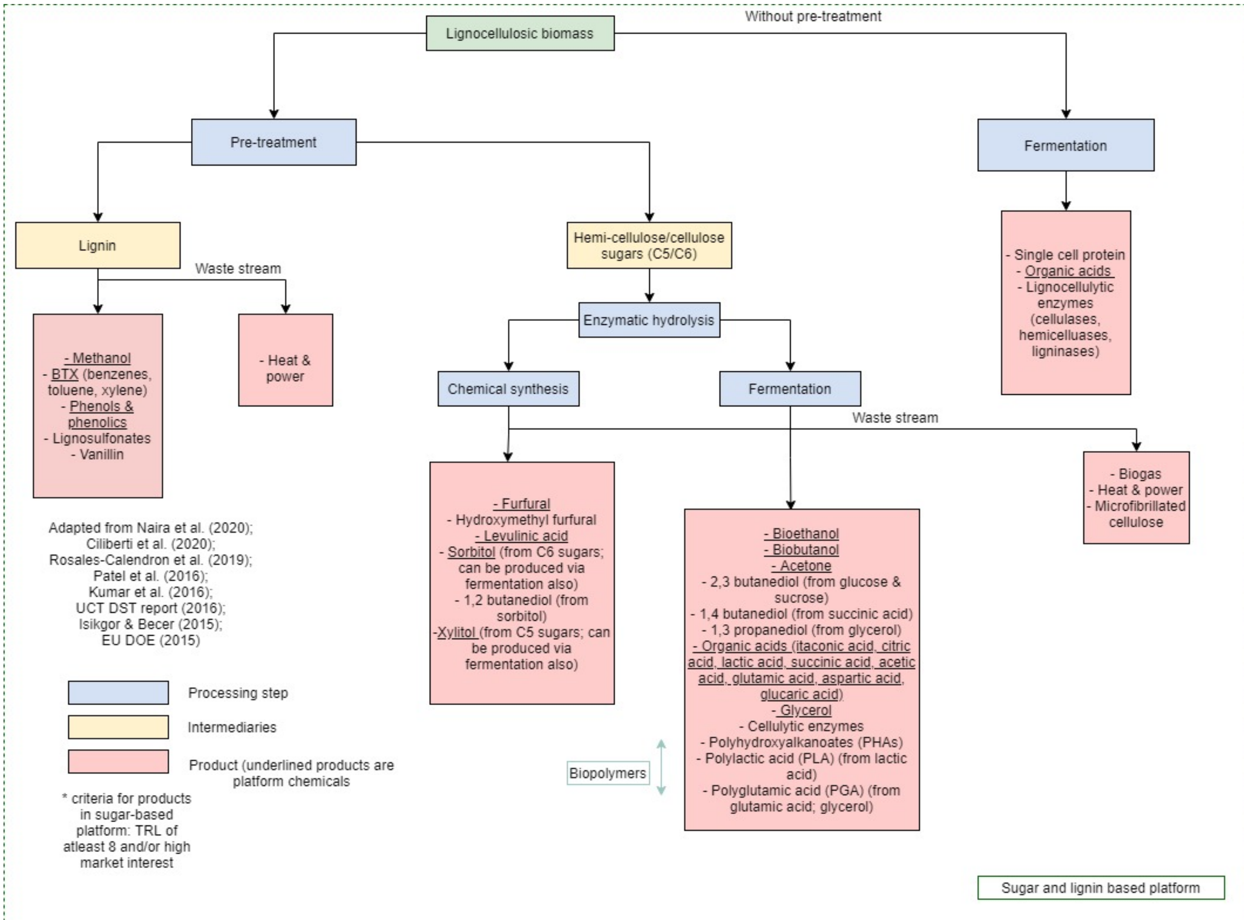
4.1.2 General overview of the sugar and lignin production platforms

Figure 12 showcases the multi-product potential of the sugar and lignin platforms when processing lignocellulosic biomass directly or decomposing and processing its three main components – cellulose, hemi-cellulose and lignin. These two platforms generally consist of biochemical routes, which uses enzymes and microorganisms, as opposed to the high temperatures and catalysts used in thermochemical processes (National Research Council (US) Chemical Sciences, 2012).

It is important to recall that the products listed in Figure 12 are only a small subset of the plethora of possible products which can be synthesised in these two platforms as the criteria of high market interest and TRL of 8 were used to screen products whose production technology have at least reached commercial scale. Of particular interest is also the high number of platform chemicals in Figure 12, which can feed into various value chains.

The major challenge resides in the recalcitrant nature of lignocellulosic biomass to be decomposed efficiently into its components. Decomposition is necessary since the lignin portion of the lignocellulosic biomass has to be separated from sugars contained within hemicellulose and cellulose, in order to allow for their individual successful conversion to value-added products. The hemicellulose and cellulose components have two further steps to go through on their paths to platform chemicals and/or final products: i) a hydrolysis step to release the sugars, xylose (C5) and glucose (C6), and ii) a chemical or biological (fermentation) step to convert the sugars to products (Zhu & Pan, 2022). All of these steps result in several bottlenecks and challenges, which need to be overcome in order for successful processing of lignocellulosic biomass via the sugar and lignin platforms (Chandel et al., 2018).

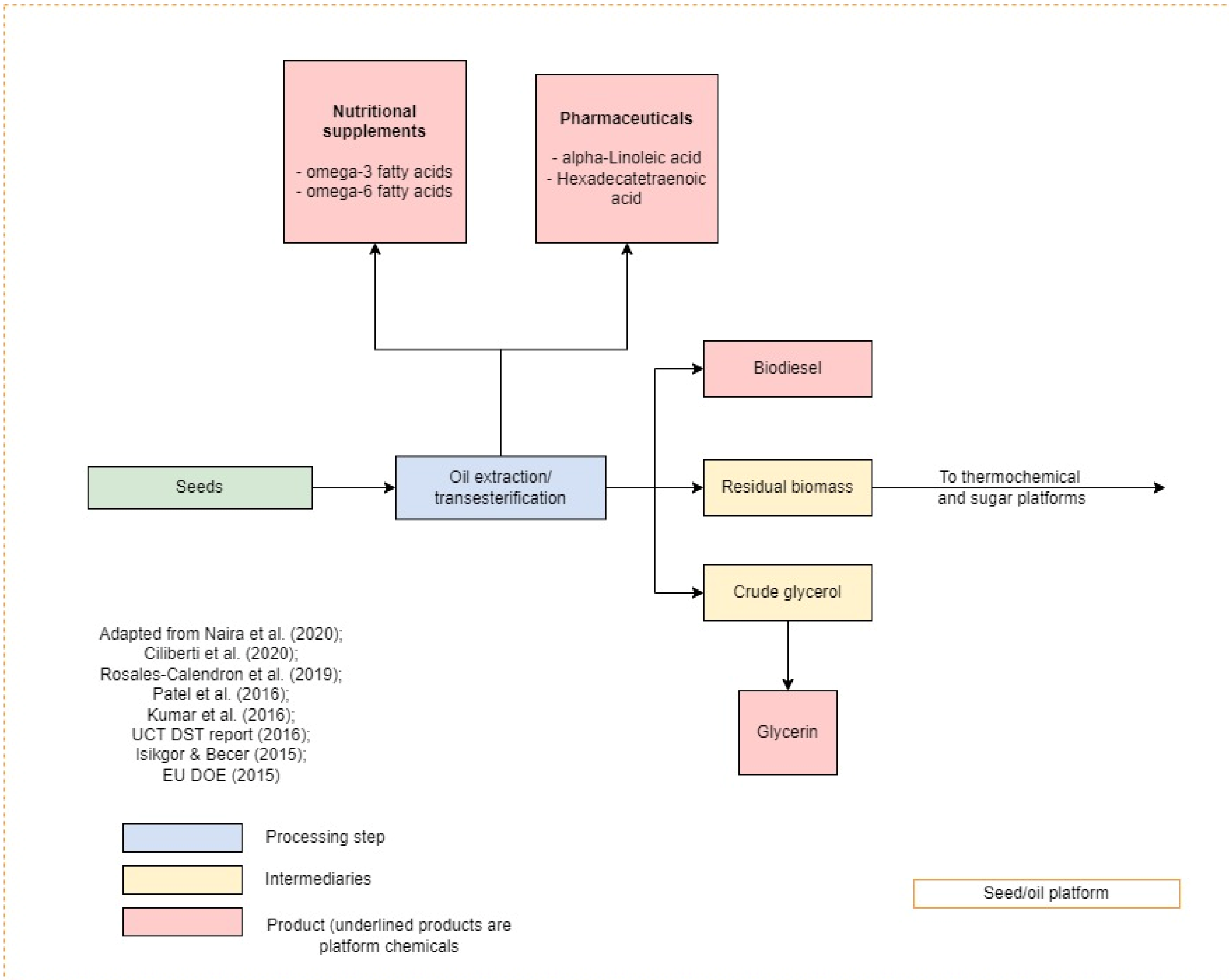
Figure 12: Short-listed products of interest for the sugar and lignin platforms using lignocellulosic biomass as feedstock



4.1.3 General overview of the seed oil production platform

While the platforms in Section 4.1.1 and Section 4.1.2 are applicable to both bast fibre and bamboo lignocellulosic biomass, the seed oil platform (Figure 13) relates to only the bast fibre seed biomass (in this study: hemp and kenaf). The oil contained within hemp and kenaf seeds is a valuable feedstock to produce supplements, pharmaceuticals, biodiesel, and its derivatives. Transesterification is the process through which seed oil is transformed into biodiesel – a chemical reaction between fat and alcohol in the presence of a catalyst. Hemp seeds are considered as promising feedstock for biodiesel production due to the plant's high yield and ability to grow on soils demonstrating low fertility; hemp biodiesel can also be blended with other fuels. The residual fibres from the rest of the plant also offer an additional lignocellulosic feedstock, which can be processed using the thermochemical (Figure 11) and sugar and lignin production platforms (Figure 12). However, hemp remains a niche crop and there are various legislative roadblocks, which prevents its large-scale cultivation and processing, resulting in high biodiesel production costs (Alcheikh, 2015).

Figure 13: Short-listed products of interest for the seed oil platform using lignocellulosic biomass (hemp and kenaf seeds) as feedstock



4.1.4 Classification of biorefinery products

Following the discussions in Sections 4.1.1 - 4.1.3, a total of 60 biorefinery products were identified in the trade data. These 60 biorefinery products were classified into four broader categories of product: namely, energy products (12 products); low-value biomass products (23 products); high-value bio-plastics (1 product); and high-value platform chemicals (24 products). The full list of biorefinery products as well as their broader product grouping and product complexity level are summarised in Table 4, in order of rising complexity.

Table 4: Identified biorefinery products, by product category, classified as energy products (12 products); low-value biomass products (23 products); high-value bio-plastics (1 product); and high-value platform chemicals (24 products).

H06 code	Product description	Biorefinery product category	PCI*
121190	Plants of a kind use for perfumery, pharmacy, insecticidal use (fresh or dried), nes	Low-value biomass products	-2.805
270500	Coal gas, water gas, producer gas and similar gases, other than petroleum gases and other gaseous hydrocarbons.	Energy product	-2.794
120720	Cotton seeds	Low-value biomass products	-2.615
270900	Petroleum oils and oils obtained from bituminous minerals	Energy product	-2.562
440200	Wood charcoal	Energy product	-1.880
440799	Wood, nes sawn or chipped lengthwise, sliced or peeled, whether or not planed	Low-value biomass products	-1.811
120799	Oil seeds and oleaginous fruits, nes	Low-value biomass products	-1.734
330129	Essential oils (incl. concretes and absolutes),	Low-value biomass products	-1.214
292242	Glutamic acid and its salts	High-value Platform Chemicals	-1.205
440920	Non-coniferous wood, continuously shaped along any edges	Low-value biomass products	-1.002
330190	Concentrates of essential oil; terpenic by-products of deterpenation of essential oil; extracted oleoresins; aqueous solutions of essential oil, others	Low-value biomass products	-0.883
290511	Methanol (methyl alcohol)	High-value Platform Chemicals	-0.857
281410	Anhydrous ammonia	Low-value biomass products	-0.806
320190	Tanning extracts of vegetable origin, other tannins and their salts, ethers, esters and other derivatives	Low-value biomass products	-0.665
151529	Maize oil, fractions, refined not chemically modified	Low-value biomass products	-0.591
281420	Ammonia in aqueous solution	Low-value biomass products	-0.326
151590	Other fixed vegetable fats and fractions, nes	Low-value biomass products	-0.317
310100	Animal or vegetable fertilizers	Low-value biomass products	-0.262
294200	Other organic compounds, nes	High-value Platform Chemicals	-0.197
360610	Liquid or liquefied gas fuels in containers of a kind used for filling or refilling cigarette or similar lighters and of a capacity not exceeding 300 cm3	Energy product	-0.098
271600	Electrical energy	Energy product	-0.070
270300	Peat (incl. peat litter)	Energy product	0.136
262090	Ash and residues; (not from the manufacture or iron or steel), containing mainly metals or metal compounds nes	Low-value biomass products	0.236

H06 code	Product description	Biorefinery product category	PCI*
120400	Linseed	Low-value biomass products	0.362
470692	Pulp of fibrous cellulosic material (other than wood or cotton linters pulp), chemical: Other, of bamboo	Low-value biomass products	0.388
293212	2-Furaldehyde (furfuraldehyde)	High-value Platform Chemicals	0.460
380210	Activated carbon	Low-value biomass products	0.784
230620	Oil-cake and other solid residues of linseed	Low-value biomass products	1.026
152090	Glycerol (excl. crude), including synthetic	High-value Platform Chemicals	1.066
380700	Wood tar; wood tar oils; wood creosote; wood naphtha; vegetable pitch; brewers' pitch and similar preparations based on rosin, resin acids or on vegetable pitch	Energy product	1.098
290242	m-Xylene	High-value Platform Chemicals	1.114
152010	Glycerol, crude; glycerol waters and glycerol lyes	Low-value biomass products	1.141
230310	Residues of starch manufacture and similar residues	Low-value biomass products	1.182
293213	Furfuryl alcohol and tetrahydrofurfuryl alcohol	High-value Platform Chemicals	1.213
440130	Wood; sawdust, waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms	Energy product	1.389
280410	Hydrogen	Energy product	1.542
290122	Propene (propylene)	High-value Platform Chemicals	1.601
470693	Pulps of fibres derived from recovered (waste and scrap) paper or paperboard or of other fibrous cellulosic material: Obtained by a combination of mechanical and chemical processes	Low-value biomass products	1.647
290243	p-Xylene	High-value Platform Chemicals	1.726
291811	Lactic acid, its salts and esters	High-value Platform Chemicals	1.879
290244	Mixed xylene isomers	High-value Platform Chemicals	1.919
290544	D-glucitol (sorbitol)	High-value Platform Chemicals	1.981
290220	Benzene	High-value Platform Chemicals	2.139
290121	Ethylene	High-value Platform Chemicals	2.151
290230	Toluene	High-value Platform Chemicals	2.157
291241	Vanillin (4-hydroxy-3-methoxybenzaldehyde)	High-value Platform Chemicals	2.301
290930	Aromatic ethers and their halogenated, sulphonated, nitrated or nitrosated derivatives	High-value Platform Chemicals	2.385

H06 code	Product description	Biorefinery product category	PCI*
291521	Acetic acid	High-value Platform Chemicals	2.526
382390	Chemical products, nes (bio-diesel)	Energy product	2.565
290514	Acyclic alcohols and their halogenated, sulphonated, nitrated or nitrosated derivatives: Butanols (excl. butan-1-ol "n-butyl alcohol")	Energy product	2.610
290513	Butan-1-ol (n-butyl alcohol)	Energy product	2.664
290241	o-Xylene	High-value Platform Chemicals	2.708
291411	Acetone	High-value Platform Chemicals	2.834
390799	Polyesters, in primary forms, nes	High-value Platform Chemicals	2.948
391390	Other: Natural polymers (for example, alginic acid) and modified natural polymers (for example, hardened proteins, chemical derivatives of natural rubber), not elsewhere specified or included, in primary forms	High-value Bio-plastics	3.098
290711	Phenol (hydroxybenzene) and its salts	High-value Platform Chemicals	3.130
380400	Residual lyes from the manufacture of wood pulp, whether or not concentrated, desugared or chemically treated, including lignin sulphonates	Low-value biomass products	3.315
350790	Other: Enzymes; prepared enzymes not elsewhere specified or included (for lignocellulosic enzymes)	Low-value biomass products	3.607
291830	Carboxylic acids with aldehyde or ketone function but without other oxygen function, their anhydrides, halides, peroxides, peroxyacids and their derivatives	High-value Platform Chemicals	3.775
290539	Other: Diols except ethylene and propylene glycol	High-value Platform Chemicals	5.386

Source: Authors' calculations using BACI International Trade Database (Gaulier & Zignago, 2010).

Note: (1) Products colour-coded according to product grouping category. (2) Products listed in order of increasing complexity.

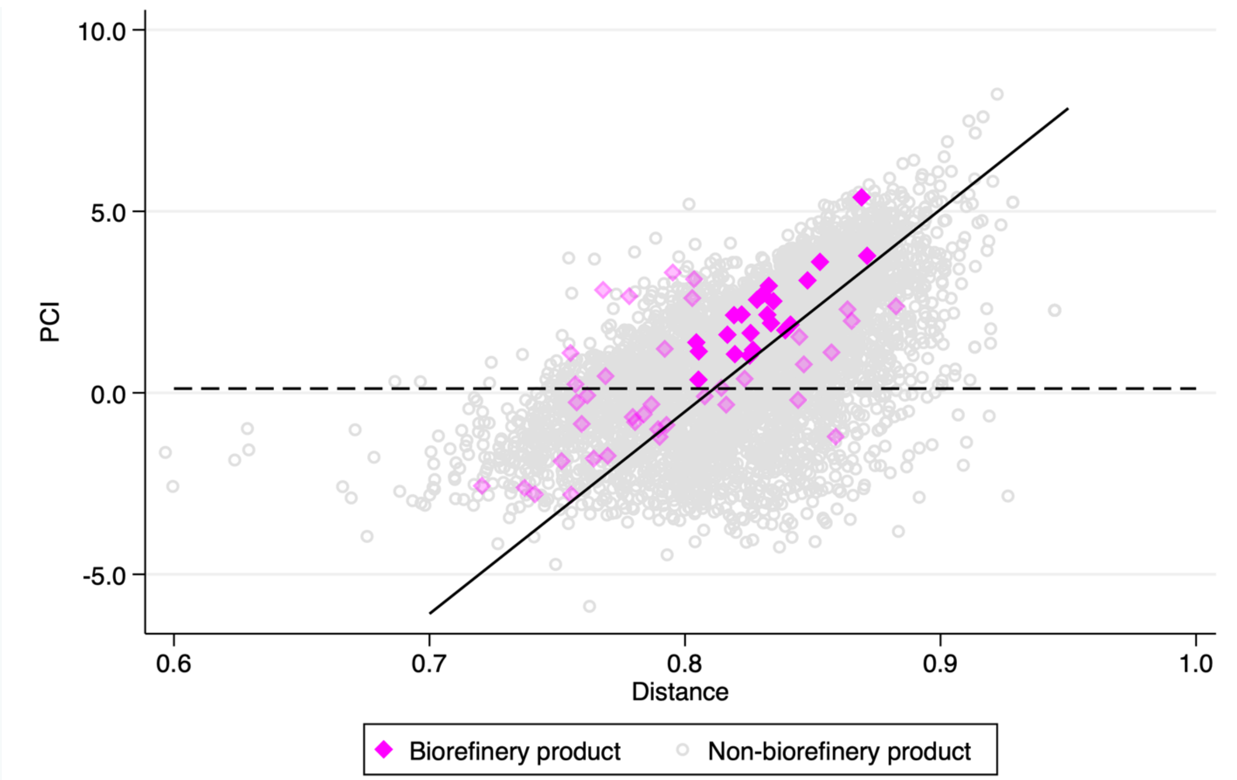
* PCI = product complexity index

4.2 Frontier Biorefinery Products

At this point, we understand the universe of products that could be produced from a biorefinery production process – specifically, the list of 60 biorefinery products listed in the previous section stipulate exactly what these products are and their respective product categories and complexity levels. However, as discussed in Section 3.4.3, the method of identifying frontier products can focus industrial policy on those products that will specifically drive economic development in South Africa. Combining the frontier product approach with the list of biorefinery products identified above allows us to identify so-called *frontier biorefinery products*. These products are defined as being those products which are identified as both frontier products under the method described in Section 3.4.3, as well as being flagged as biorefinery products. This section aims to describe these products in more detail.

To begin, Figure 14 applies the method described in Figure 9, and depicts the distance and product complexity index (PCI) for all products at the 6-digit HS level for South Africa. However, instead of highlighting all frontier products, Figure 14 highlights only biorefinery products. All biorefinery products are identified as magenta diamonds in the diagram. Amongst these 60 biorefinery products, only 22 coincide with frontier products. These frontier biorefinery products are highlighted as the solid-filled magenta diamonds in the diagram, while the faded diamonds represent non-frontier biorefinery products.

Figure 14: Distance and PCI of biorefinery vs non-biorefinery products



Source: Authors' calculations using BACI International Trade Database (Gaulier & Zignago, 2010).

Note: Bold diamonds indicate frontier biorefinery products, while faded diamonds indicate non-frontier biorefinery products.

PCI = product complexity index

As mentioned above, only 22 of the 60 biorefinery products are identified as frontier biorefinery products according to the frontier product approach. The list of frontier biorefinery products is presented in Table 5 along with the relevant product category, 6-digit level harmonised system product code (H06), and PCI. The range of frontier biorefinery products clearly encompasses a variety of different product categories, including low-value and high-value products as well as energy products.

Table 5: Frontier biorefinery products, classified as energy products (2 products); low-value biomass products (6 products); high-value bio-plastics (1 product); and high-value platform chemicals (13 products).

H06 code	Product description	Biorefinery product category	PCI*
120400	Linseed	Low-value biomass products	0.362
230620	Oil-cake and other solid residues of linseed	Low-value biomass products	1.026
152090	Glycerol (excl. crude), including synthetic	High-value Platform Chemicals	1.066
152010	Glycerol, crude; glycerol waters and glycerol lyes	Low-value biomass products	1.141
230310	Residues of starch manufacture and similar residues	Low-value biomass products	1.182
440130	Wood; sawdust, waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms	Energy product	1.389
290122	Propene (propylene)	High-value Platform Chemicals	1.601
470693	Pulps of fibres derived from recovered (waste and scrap) paper or paperboard or of other fibrous cellulosic material: Obtained by a combination of mechanical and chemical processes	Low-value biomass products	1.647
290243	p-Xylene	High-value Platform Chemicals	1.726
291811	Lactic acid, its salts and esters	High-value Platform Chemicals	1.879
290244	Mixed xylene isomers	High-value Platform Chemicals	1.919
290220	Benzene	High-value Platform Chemicals	2.139
290121	Ethylene	High-value Platform Chemicals	2.151
290230	Toluene	High-value Platform Chemicals	2.157
291521	Acetic acid	High-value Platform Chemicals	2.526
382390	Chemical products, nes (bio-diesel)	Energy product	2.565
290241	o-Xylene	High-value Platform Chemicals	2.708
390799	Polyesters, in primary forms, nes	High-value Platform Chemicals	2.948
391390	Other: Natural polymers (for example, alginic acid) and modified natural polymers (for example, hardened proteins, chemical derivatives of natural rubber), not elsewhere specified or included, in primary forms	High-value Bio-plastics	3.098
350790	Other: Enzymes; prepared enzymes not elsewhere specified or included (for lignocellulosic enzymes)	Low-value biomass products	3.607
291830	Carboxylic acids with aldehyde or ketone function but without other oxygen function, their anhydrides, halides, peroxides, peroxyacids and their derivatives	High-value Platform Chemicals	3.775
290539	Other: Diols except ethylene and propylene glycol	High-value Platform Chemicals	5.386

Source: Authors' calculations using BACI International Trade Database (Gaulier & Zignago, 2010).

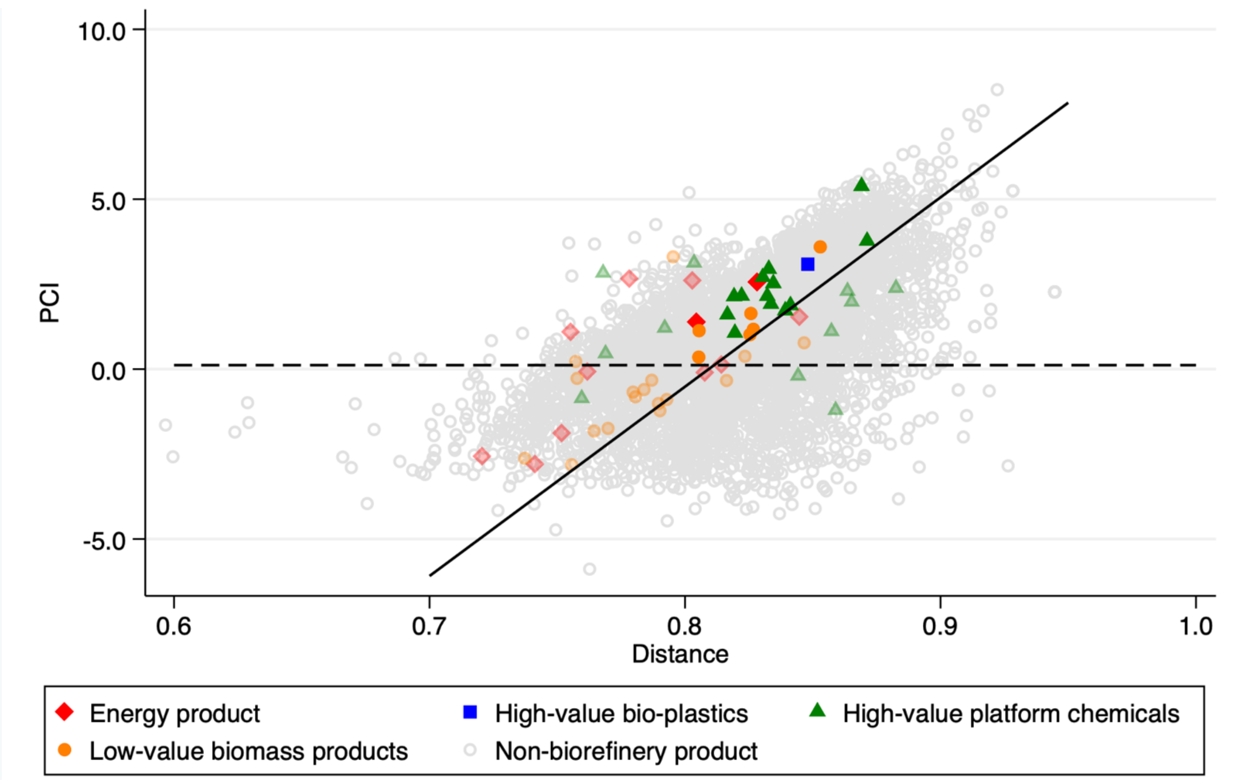
Note: (1) Products colour-coded according to product grouping category. (2) Products listed in order of increasing complexity.

* PCI = product complexity index

When considering the product categories of these frontier biorefinery products, it is clear that high-value platform chemicals are the most common product category amongst frontier biorefinery products. A total of 13 products (or 59 percent) of frontier biorefinery products are captured in the "High-value Platform Chemicals" category, while only 6 products (27 percent) fall under the "Low-value Biomass Product" category. Furthermore, high-value platform chemicals are unsurprisingly clustered towards higher PCI values, while low-value biomass products are clustered towards lower PCI values. This result is potentially more easily seen graphically, as depicted in Figure 15.

In Figure 15, we reproduce the graph depicting the relationship between products' distance and PCI, however, we now disaggregate products according to their product category. As with Figure 14, faded symbols indicate non-frontier biorefinery products, while solidly-filled symbols indicate frontier biorefinery products. Here, it is slightly clearer to see that frontier high-value platform chemical products (represented by the green triangles) are generally positioned higher up than frontier low-value biomass products (represented by orange circles).

Figure 15: Distance and product complexity index (PCI) of biorefinery and non-biorefinery products, by category



Source: Authors' calculations using BACI International Trade Database (Gaulier & Zignago, 2010).

Note: Bold symbols indicate frontier biorefinery products in each category, while faded symbols indicate non-frontier biorefinery products.

However, economic complexity is not the only metric of interest in choosing the products one may diversify into. As discussed in Section 3.4.4, a number of secondary criteria exist which can be used to provide additional policy insights into the products we choose to diversify into. These secondary criteria include measures of inequality, revealed labour intensity (RLI) (calculated as the multiplicative inverse of the revealed capital intensity), and global demand. Table 6 presents a summary of these metrics for a variety of product clusters, including the current portfolio of products produced by South Africa with revealed comparative advantage, the full set of frontier products, as well as the various subdivisions of the identified biorefinery products.

Table 6: Complexity and socio-economic index measures of biorefinery products, by category

	Number of products	Average PCI*	XGini	Revealed Labour Intensity Index	Complexity Outlook Gain	Average market growth (2010 to 2019)
Current RCA** products	835	0.117	41.581	0.050	-	0.007
Biorefinery products	60	0.858	39.209	0.037	0.430	-0.008
Energy products	*12*	*0.383*	*39.947*	*0.032*	*0.236*	*-0.007*
High-value bio-plastics	*1*	*3.098*	*31.643*	*0.006*	*1.207*	*0.019*
High-value platform chemicals	*24*	*1.881*	*38.106*	*0.025*	*0.694*	*0.010*
Low-value biomass products	*23*	*-0.058*	*40.304*	*0.052*	*0.222*	*-0.029*
Frontier products	1 703	2.548	35.296	0.017	0.957	-0.009
Biorefinery frontier products	22	2.182	36.049	0.020	0.914	-0.011

Source: Authors' calculations using BACI International Trade Database (Gaulier & Zignago, 2010), Penn World Table version 10.01 (Feenstra, Inklaar & Timmer, 2015) and World Income Inequality Database (UNU-WIDER, 2021).

Note: (1) Revealed Labour Intensity Index is normalised to lie between 0 and 1 for ease of presentation. (2) Complexity Outlook Gain represents the relative gain in the Complexity Outlook Index relative to the baseline value of 0.592.

* PCI = product complexity index; **RCA= revealed comparative advantage

The results show that, on average, compared to South Africa's current RCA products, biorefinery products are more complex, associated with lower inequality levels, and better positioned to link to future diversification paths. These results are positive, as they indicate that even before considering the frontier approach to narrow down the products of interest for industrial policy, the presence of a biorefinery may lead to positive developmental impacts for South Africa.

On the other hand, biorefinery products are associated with a lower revealed labour intensity and declining global market demand between 2010 and 2019. Context is key when interpreting these results, however. Just because biorefinery products as a whole show lower revealed labour intensity does not mean that they will lead to jobless growth. In fact, the opposite is true: expanding into the production of biorefinery products is likely to create jobs, however, the lower RLI measure indicates that the rate at which jobs will be created is likely to be lower than if we simply expanded production along the intensive margin. Further, when we consider the broader industrial context within which the biorefinery emerges – shown in Figure 1 – we see that the residual biomass emerges toward the end of a multi-product value chain that starts with the cultivation of fibrous plants on degraded mining land, the harvesting of these plants, the processing of the biomass to extract fibres, and the manufacture of lead products. All of these activities create jobs and some are relatively more labour-intensive – particularly, the agri-processing stages of the value chain. Similarly, the indicator of shrinking global demand is small at approximately 0.8 percent negative growth per annum, which could be the result of a fledgling market that could be bolstered by greater availability of products in the market.

Consistent with the previous results, high-value biorefinery products (whether platform chemicals or bio-plastics) seem to be driving the results as regards complexity, however, they also seem to provide the best results as regards decreasing inequality and complexity outlook gains. Interestingly, these product categories are also the only ones in the table that are experiencing growing global demand, which suggests that perhaps the previously observed shrinking global demand for biorefinery products is being driven by low-value products instead. Unfortunately, these high-value products are also the most capital-intensive, meaning that the RLI index for these two categories of products is particularly low.

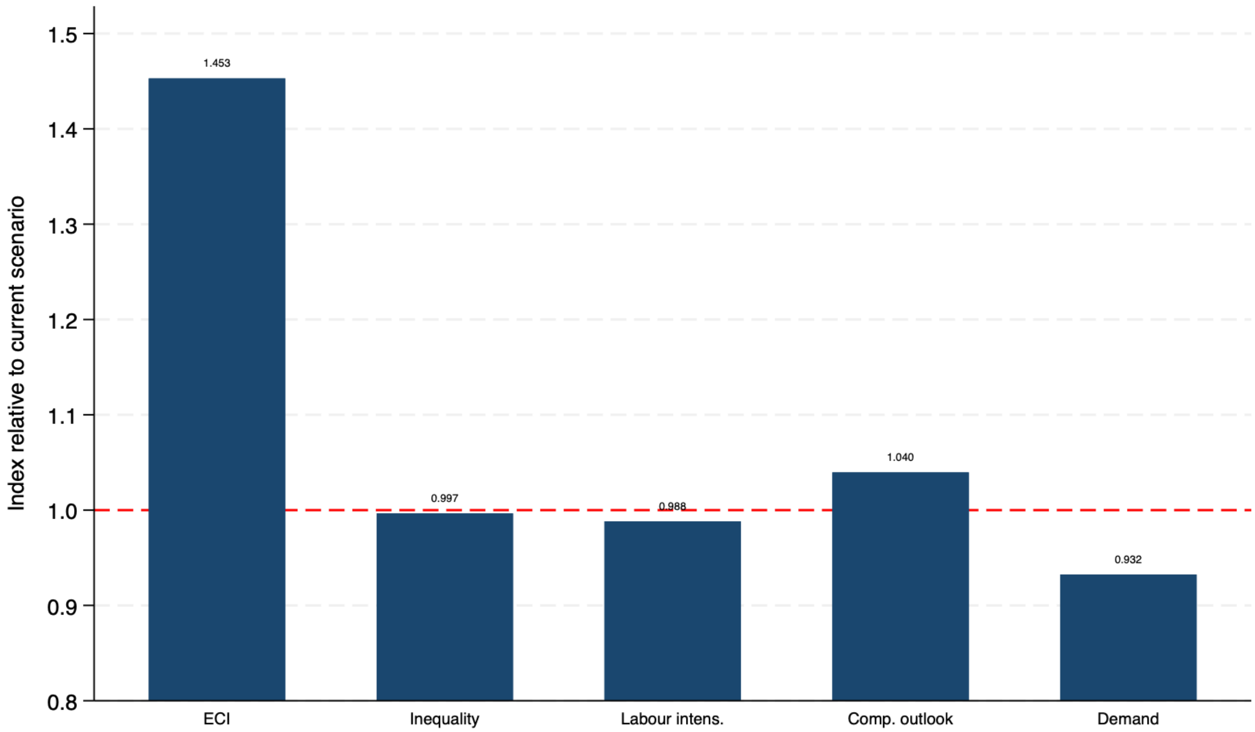
Regarding frontier products, however, we see an interesting result: Frontier biorefinery products seem to perform worse than the general set of frontier products across almost all indices. The only exception is that frontier biorefinery products are, in fact, more labour intensive than the set of all frontier products, indicating that perhaps a biorefinery-led industrial pathway would be advantageous to providing a more labour-inclusive growth path for South Africa.

Frontier biorefinery products do still show general improvement over the current RCA export basket, even if the extent of the improvement is slightly muted compared to the general set of frontier products. In Figure 16, we plot out the relative index value compared to the current scenario for each of economic complexity, inequality, labour intensity, complexity outlook index, and global demand. In this graph, the current value of each index in South Africa is normalised to 1, and we then compare the relative change in each index to the current level in a normalised way.

As was the case with the full set of biorefinery products, we see that frontier biorefinery products have positive impacts on economic complexity, complexity outlook and inequality, while there are negative impacts on RLI and global demand. A particularly large impact is seen on economic complexity, whereby expansion into the set of frontier biorefinery products will increase economic complexity by 45.3 percent.

Although this impact is large it is somewhat expected, given that by construction frontier products are required to have a PCI value greater than the average economic complexity of all products currently exported with comparative advantage in the country (ECI).

Figure 16: Changes in outcome indices from producing all frontier biorefinery products



Source: Authors' calculations using BACI International Trade Database (Gaulier & Zignago, 2010), Penn World Table version 10.01 (Feenstra, Inklaar & Timmer, 2015) and World Income Inequality Database (UNU-WIDER, 2021).

Note: (1) All indices are normalised as a ratio relative to their current value. (2) Red horizontal line at 1 shows the relative comparison point for index of interest. (3) Opportunity gain index calculated as Complexity Outlook Index (COI) plus the Complexity Outlook Gain (COG) obtained from diversifying into the specified frontier products. (4) ECI = economic complexity index

More interestingly, we can see that the complexity outlook gain index increases by 4 percent, which suggests that expansion into frontier biorefinery products will allow South Africa to be in a slightly better position for accessing further diversification opportunities in the future. Frontier biorefinery products are also associated with decreased inequality, although this decrease is a marginal 0.3 percent. The RLI associated with diversifying into the set of frontier biorefinery products shows a decrease of 1.2 percent relative to current levels, but as discussed above, this simply indicates that job growth in these industries may be slower, not that expansion into these products predicts jobless growth. Further, the broader fibrous plant value chain from which the biorefinery emerges is set to generate jobs at varying levels of intensity.

Finally, demand – as proxied for by average market growth between 2010 and 2019 – is set to decrease by approximately 6.8 percent relative to current levels. This is potentially of more concern as it indicates that diversification into frontier biorefinery products pushes South Africa into markets that are shrinking with time. However, this proxy for global demand is crude and is likely quite noisy. In real terms, these markets are shrinking at a rate of 1.1 percent per annum, which is possibly the result of post-crisis instability, as well as the fact that markets for biorefinery products have not yet been fully established in the global economy.

4.3 Analysis of product clusters

4.3.1 Techno-feasibility

Using hemp as a case study, three product clusters (Table 7) are proposed in this study. It is important to note that in the case of the post-mine biorefinery initiative, two thirds of the hemp stems are available for processing since one third is being directed towards bast fibre processing for lead fibre products. As such, product clusters 1, 2 & 3 are additional products which can be produced from the remaining hemp stems.

Table 7: Product clusters investigated for the study

Product cluster 1	Product cluster 2	Product cluster 3
Bioethanol as biofuel	Bioethanol as biofuel and platform chemical	Bioethanol as biofuel
Succinic acid as platform chemical	(Bio) Ethylene as platform chemical	Biodiesel as biofuel
Residual biomass (lignin) for heat and power	Residual biomass (lignin) for heat and power	Glycerol as platform chemical
		Residual biomass (lignin) for heat and power

Bioethanol and biodiesel (TRL 9) are chosen as biofuels of choice in this analysis due to their high substitution potential for traditional transport fuels (Okolie et al., 2020). South Africa also has the capability to produce bioethanol biologically, more specifically from molasses, a lignocellulosic waste by-product in the sugarcane industry. Similarly, biodiesel is being produced in the country on small scale from recycled vegetable oil (Kohler, 2016). With the backdrop of developing countries like Brazil and India rapidly expanding their biofuels industry, a Biofuel Industrial Strategy was further approved by the South African government in 2007, which prescribed a target 4.5% market penetration of liquid road transport fuel by 2013, with proposed E10 blends for petrol (of which bioethanol usually forms 10%) and B5 blends for diesel (of which biodiesel usually forms 5%) (Sukati, 2014; Kohler, 2016). However, over the years, there has been a major lack of regulatory framework and guidelines from the South African government related to the production of biofuels, leading to decreased interest from the private sector to invest in biofuels, which in turn is significantly delaying the commercial production of biofuels in the country (van Zyl & Prior, 2009; Braude, 2014). As a result, South Africa currently has the know-how and capability to produce both bioethanol and biodiesel from organic feedstocks, but there are significant legislative and financial roadblocks to ensuring their large-scale production.

For platform chemicals, we chose to focus our analysis on succinic acid, bioethylene and glycerol. This choice was informed by the studies and reviews in Table 3, which suggest high market interest and versatility of these products to fit into various downstream South African industries, coupled with the technical feasibility of producing these products alongside bioethanol and biodiesel. Succinic acid is a common organic acid, which can be used in many food, chemical and pharmaceutical industries with applications ranging from high-value niche products such as personal care products and food additives, to large volume applications such as bio-based polymers like polybutylene succinate (PBS). Bioethylene is mainly used to make polyethylene, which is one of the most popular thermoplastics materials. Other products from bioethylene include poly (vinyl chloride), polystyrene, antifreeze (ethylene glycol), adhesives, solvents and detergents. However, the production of succinic acid and bioethylene is yet to be established locally when compared to bioethanol and biodiesel production in South Africa. Glycerol is a valuable by-product of the biodiesel production process and after refining, it can be considered as a platform chemical and feed in various industries (Takkellapati et al*.,* 2018).

After the processing of the lignocellulosic biomass to yield biofuels and bioproducts, there will be still be some residual biomass left-over (mostly in the form of lignin), which can be used as a heat or energy source through simple energy generation technologies (e.g., direct combustion/co-combustion), in order to close the material loop and maximise resource efficiency in the biorefinery, in line with Figure 10.

Using the data in Table 8 (assuming an average of 12 metric ton/ha of dry hemp matter extracted and an average of 25% of extracted matter converted to bast fibre), the product yields from the remaining lignocellulosic biomass (9 metric ton/ha) for the three different product clusters were calculated to illustrate their production potential based on 1 hectare of land (Table 9).

Table 8: Data used for pre-liminary techno assessment of product clusters

		Reference
Amount of dry hemp matter extracted metric ton/ha)	4 – 20	(Duque Schumacher et al., 2020)
Amount of extracted matter converted to bast fibre (%)	20 – 30	
Bioethanol yield from (kg/ton dry hemp)	149	(Kuglarz et al., 2016)
Succinic acid yield (kg/ton dry hemp)	115	
Dry lignin yield (kg/ton dry hemp)	142	
Bioethylene from bioethanol (per ton)	0.574	(Mohsenzadeh et al., 2017)
Biodiesel from hemp seeds (kg/ha)	667	(Alcheikh, 2015)
Glycerol from biodiesel (wt %)	10	

For comparison, since biofuels are being produced commercially worldwide, the 2020 projected yields of bioethanol and biodiesel produced biochemically from different lignocellulosic feedstock are presented in Table 10. While the yield of bioethanol from hemp in this study falls on the lower end of typical bioethanol yields in Table 9, the yield of biodiesel from hemp is higher than typical biodiesel feedstock – a techno-economics assessment by Viswanathan et al. (2021) revealed that a hectare of industrial hemp can produce 67 gallons (approximately 254 litres) more diesel than soybean.

Table 9: Estimated production yields for the different clusters

Product cluster 1	
Bioethanol (kg/ha)	1341
Succinic acid (kg/ha)	1035
Lignin for fuel (kg/ha)	1278
Product cluster 2	
Bioethanol (kg/ha)[1]	671
Bioethylene (kg/ha)	385
Lignin for fuel (kg/ha)	1278
Product cluster 3	
Bioethanol (kg/ha)	1341
Biodiesel (kg/ha)	667
Glycerol (kg/ha)	67
Lignin for fuel (kg/ha)	1278

[1]Assuming total bioethanol produced is split evenly (50 %) between bioethanol production and bioethylene production.

It is crucial to highlight that hemp is not a food crop and thus bioethanol and biodiesel production will not compete directly with production of food, as is the case when food crops are cultivated to produce biofuels instead of food, such as in Brazil (sugar cane) and USA (maize). Utilising food crops in the production of biodiesel leads to ethical issues surrounding the fight against eradicating hunger in under-developed countries. This is the reason why there is a big move towards optimising and implementing large scale production of biofuels from non-food biomass (termed 2nd generation biofuels). However, there is an understanding that processing non-food crops to biofuels is more complex, with less favourable techno-economics owing to its recalcitrant nature, which necessitates costly pre-treatment methods (Lee & Lavoie, 2013; Okolie et al., 2020).

Table 10: Projected yields of bioethanol and biodiesel per hectare of crop feedstock using a biochemical conversion route adapted from Ecofys et al.,(2015) and Achinas et al., (2019)

Type of biofuel	Feedstock	Energy productivity 2020 (kg/ha)
Bioethanol[1]	Wheat	1578
	Maize	2391
	Barley	1397
	Sugar beet	5397
	Sugar cane	4395
	Cereal straw	560
Biodiesel[1]	Sunflower oil	21,4
	Palm oil	76,9
	Rapeseed	45,4
	Soybean	14,9

[1]Assuming a density of 789 kg/m^3 for bioethanol and 874 kg/m^3 for biodiesel.

It is harder to evaluate the yield of succinic acid (TRL 8) from hemp in the context of South Africa since pilot and large-scale biochemical production of succinic acid is usually done from refined sugars (sucrose, glucose and fructose), sorghum, starch, corn, beet or cane molasses – with operations typically restricted in the global north – and the main challenge residing in the high cost of product purification (Jansen & van Gulik, 2014; Okolie et al., 2020). Succinic acid production from inexpensive and readily available feedstocks such as lignocellulosic biomass is still being investigated at a laboratory and prototype scale (Zhou et al., 2023).

Bioethylene production from bioethanol is an established commercial technology (TRL 8 - 9), with the leading producers being Brazil, India and China; with Brazil having an estimated production capacity of 200kt per annum of bioethylene (E4tech, RE-CORD & WUR, 2015). However, the production process still suffers from the high cost of bioethanol production and efficient biomass pre-treatment methods, especially for lignocellulosic biomass (Okolie et al., 2020).

Crude glycerol is a by-product of the biodiesel process, and its effective utilisation can favourably increase the techno-economics of the overall biodiesel production process. However, the cost of refining crude glycerol is high and biodiesel producers sometimes prefer to discard glycerol rather than refine it. Refined glycerol can be used as feedstock in the production of other value-added chemicals and for animal feeds, although the markets are not yet established, leading to an ineffective use of the glycerol (Yang et al., 2012; Chilakamarry et al., 2021).

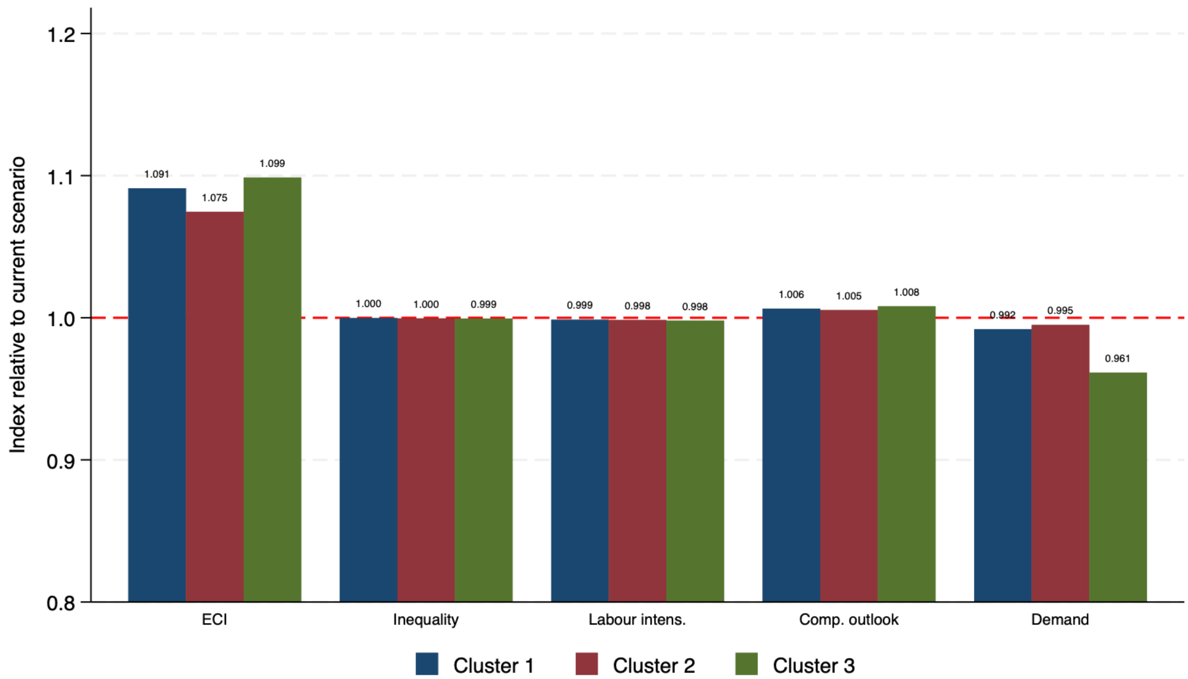
4.3.2 Complexity analysis

In Section 4.2, we analysed the impact on a number of socio-economic and complexity-related indices to determine how diversification into frontier biorefinery products would potentially impact South Africa's development path. However, as we have discussed above, it is clear that a strategy that includes diversification into all 22 frontier biorefinery products is not feasible, in part due to the availability of necessary feedstocks, but also because the establishment of 22 new fledgling industries in the South African context will likely overextend available infrastructure and resources – a strategy that is unlikely to be successful in the short-term. As a result, we consider three diversification pathways that incorporate the three clusters of biorefinery products defined above.

To this end, we reproduce the relative index value analysis presented in Section 4.2, but now isolating the impacts of each individual cluster of biorefinery products on each index. The results are presented in Figure 17. Just as before, all indices are normalised so that their current value is equal to 1, and then the relative size of the index after diversification is represented by the height of the bar in the graph.

The first result that is clear from this graph is that the effects on each index are substantially more muted than they were in Figure 16. This is hardly surprising given the fact that each individual cluster consists of at most 5 products, whereas the full set of frontier biorefinery products analysed before included 22 products. Since the indices are all predicated on averaging values across products, it is not surprising that 5 products added to the basket of RCA products have a smaller impact on index values than the addition of 22.

Figure 17: Changes in outcome indices from producing biorefinery frontier products, by cluster



Source: Authors' calculations using BACI International Trade Database (Gaulier & Zignago, 2010), Penn World Table version 10.01 (Feenstra, Inklaar & Timmer, 2015) and World Income Inequality Database (UNU-WIDER, 2021).

Note: (1) All indices are normalised as a ratio relative to their current value. (2) Red horizontal line at 1 shows the relative comparison point for index of interest. (3) Opportunity gain index calculated as Complexity Outlook Index (COI) plus the Complexity Outlook Gain (COG) obtained from diversifying into the specified frontier products. (4) ECI = economic complexity index.

Regardless of this, it is clear that all clusters increase economic complexity and complexity outlook measures, however, there is very little impact on inequality now. In fact, Cluster 1 and Cluster 2 have no discernible impact on inequality measures, while Cluster 3 is predicted to lower inequality by 0.1 percent. On the other hand, the impact on RLI is substantially more favourable than for the full set of frontier biorefinery products, since all clusters seem to lead to RLI values that are approximately on par with their previous values. The greatest discrepancy comes in when considering demand, however: Cluster 3 is positioned in markets that are particularly slow-growing between 2010 and 2019 compared to Clusters 1 and 2.

From a policy perspective, the three clusters of biorefinery products offer different opportunities: Cluster 2 offers the most modest gain in economic complexity, but potentially keeps South Africa better positioned in growing global markets. On the other hand, Cluster 3 provides the largest gains in economic complexity and complexity outlook gain – i.e., opportunities for future diversification into more complex products –

but comes at the cost of being positioned in global markets that have historically seen worse growth than any of the other available clusters. None of the clusters have any particular impact on inequality or labour absorption, and thus these factors become irrelevant for consideration across the clusters defined in this case.

The advantage of such an analysis that considers economic development and industrial policy from a multi-faceted lens is that it allows the policymaker to make an informed and comprehensive decision as to which avenues to pursue. The policymaker can consider the trade-offs between various economic indicators to decide which avenue they most want to pursue, or which avenue is most appropriate for the country's overall development goals. In this case, considering a biorefinery approach, one can at least rest assured that any choice available will reduce inequality, which is a key consideration in the South African context of high inequality and high unemployment. Furthermore, any cluster chosen will lead to job creation at approximately the same rate as it would if we expanded the current export basket. It is thus not clear that any one cluster is strongly more advantageous than another, and the informed policymaker would have to assess the economic trade-offs in tandem with South Africa's technological readiness for various production processes before choosing which cluster of biorefinery products would best suit their needs and best cater to the end goals of the chosen micro-industrial policy.

5 Conclusion

In this paper we undertake an explorative study into the biorefinery concept, with specific focus on its potential to foster resource efficiency, economic resilience, and flexibility in the fibrous plant industry, by leveraging off existing industrial capabilities in such a manner to drive industrial diversification and build economic complexity in line with circular economy principles. We determine what technically feasible non-fibre-based materials – "biorefinery products" – can be produced using residual fibrous plant biomass by means of a biorefinery approach. We find that lignocellulosic biomass can serve as feedstock to a wide array of products using different conventional and biorefinery technologies via different production platforms: namely, thermochemical, sugar and lignin, and seed oil. We identify 60 biorefinery products, which can be categorised into high-value platform chemical, low-value biomass products, energy products, and high-value bioplastics.

We then use economic complexity and industrial relatedness theory and metrics – in the form of the frontier product approach – to identify biorefinery products that are feasible given current industrial capabilities and desirable in terms of potential economic complexity gains; which we call frontier biorefinery products. The frontier products approach, emerging from the smart specialisation literature, provides a robust data-centric approach that offers an empirical basis to inform industrial policy targeting. Using this approach we identify 22 frontier biorefinery products. The majority of these frontier products are high-value platform chemicals (13), with the remaining products being low-value biomass products (6), energy products (1), and a high-value bioplastic product (1).

The biorefinery concept aims for resource efficiency. This is enabled by the production of a cluster of biorefinery products at the biorefinery. In the techno-economic analysis we determine three product clusters that satisfy the following criteria: the presence of existing industrial knowhow in emerging industries (as is the case with bioethanol and bio-diesel); high market interest and versatility to fit into various downstream South African industries (as is the case with succinic acid, bio-ethylene and glycerol); and to close the material loop, heat and energy production from lignin. However, while technical feasibility illustrates the possibility of concomitantly producing between 3 and 4 products in each cluster using a biorefinery approach, each product has its own set of processing challenges when it comes to using lignocellulosic biomass as a feedstock in large-scale operations. We further assess these three product clusters by examining their impact on a number of socio-economic and complexity-related indices to determine how diversification into these frontier biorefinery product clusters would potentially impact South Africa's development path. Therefore, the choice over which cluster to pursue is informed by, firstly, technical considerations related to processing, and secondly, the potential economic outcomes, captured by the various product-level metrics detailed in this paper. This offers a degree of flexibility and thus serves as a useful tool for the industrial policymaker's toolbox.

The solutions to intractable challenges, such as the abandoned mine challenge, do not reside in a single intellectual discipline but rather reside within the interconnected network of inter-disciplinary interaction and research. As such, a key contribution to emerge from this paper is the application of an iterative inter-disciplinary research methodology – the inter-disciplinary micro industrial policy approach (IMIP). This research brings together engineering expertise, in the form of material scientists and bio-process engineers, and economic expertise, in the form of development economists. Researchers from these disciplines followed an iterative inter-disciplinary research process, where discipline-specific research tasks fed into joint research tasks, which in turn fed back into discipline-specific tasks, and so forth. The application of economic complexity theory and metrics in the IMIP is given scope to shift into very specific and unique industrial policy contexts, such as the abandoned mine challenge, due to the technical expertise and unique problem-solving skills of the engineering research team. As such, the IMIP has the potential to be a powerful industrial policy tool.

This extension of previous research by Harrison, et al. (2019), Broadhurst, Chimbganda and Hangone (2019) and Allen et al. (2019) demonstrates how regenerative agriculture on abandoned mining land has further industrial potential with socio-economic and environmental benefits. The original research by Harrison, et al. (2019), Broadhurst, Chimbganda and Hangone (2019) and Allen et al. (2019) explored the potential to regenerate degraded mining land through the cultivation of fibrous plants on this land, and explored the potential to develop downstream agri-processing and manufacturing activity through the harvesting of fibrous plants from this land, the processing of fibres from the harvest, and the manufacture of lead products – such as non-woven textiles – from these fibres. This paper explored the potential to further use the residual biomass and extract additional value from a biorefinery. As such, this broader industrial intervention in the post-mine context offers a diverse portfolio of economic activity, ranging from low-value employment-intensive agricultural and agri-processing activities, to increasingly capital-intensive high value-add activities in the manufacture of fibre-based lead products and platform chemicals in the biorefinery. As such, this regenerative agriculture has the potential to be the basis for the creation of a much broader and more diverse economic value chain, that can benefit a broad array of economic actors.

Biorefining residual lignocellulosic biomass towards value-added products offers a unique opportunity to develop a dynamic and diversified fibrous economy. However, the recalcitrant nature of lignocellulosic biomass presents several challenges towards large-scale implementation of biorefinery operations, including large capital outlays, high operating expenses, and adequate research and development. However, European and emerging market economies, such as Brazil, India and China, are keeping biorefinery and sustainability at the top of their climate change and economic diversification agendas. Pairing post-mine development with biorefinery operations can thus offer South Africa an opportunity to jointly tackle various environmental, economic and societal issues, while stimulating new industries to advance developing countries in the move towards low carbon technologies and clean products. This will, however, require a long-term vision coupled with significant investment and the adequate legal, legislative and political frameworks.

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