

# **Determining the feasibility of selected alternative products co-produced from sugarcane**

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## DECLARATION

I declare that the report submitted herewith to the North-West University in partial fulfilment of the requirements for the Master of Business Administration (MBA) degree is my original work. It has been text-edited by professional communication standards and has not been previously submitted to any other institution for evaluation purposes.

A handwritten signature in black ink, appearing to read 'RH' with a stylized flourish above it.

Raymond Homan

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To my beautiful wife Colani, this degree would have remained a dream without you Love. Your unwavering support has enabled me to complete this race.

To God, the Father of my Lord Jesus Christ, I hope this work has brought glory and honour to Your name.

Colossians 3:23-24: <sup>23</sup>Whatever you do, work heartily, as for the Lord and not for men, <sup>24</sup>knowing that from the Lord you will receive the inheritance as your reward. You are serving the Lord Christ. - English Standard Version

## ABSTRACT

Co-production of alternative products with sugar from sugarcane is an absolute necessity to ensure the survival and secure the future of a struggling South African sugar industry. This study investigates the feasibility of various possible products for co-production. It utilises techno-economic analyses conducted by others and subjects production scenarios to cost-benefit analyses. In doing this, all production scenarios are compared in the current post-COVID-19 economic climate.

Each production scenario's internal rate of returns and net present values are calculated and compared during the cost-benefit analyses. These empirical calculations suggest that production scenarios for specific plant configurations are viable. It also found that some initially feasible scenarios are no longer feasible given the current economic environment and increased cost of capital required to fund the construction. Lower product selling prices also led to the elimination of once-feasible production scenarios.

Specific production scenarios for co-products levulinic acid, succinic acid and furfural were found to be viable. This is based on the superior IRR and NPV values these products returned in the cost-benefit analyses.

For the production scenario, producing levulinic acid only, decreasing its selling price by 40%, still maintained a feasible production scenario with an IRR of 18% and an NPV of US\$ 109.50 million. For the production scenario, producing succinic acid only, decreasing its selling by 25%, still maintained a feasible production scenario with an IRR of 21% and an NPV of US\$ 224.52 million. For the production scenario, co-producing levulinic acid and furfural, a reduction in both products' selling price by 50% still provided an IRR of 21% and an NPV of US\$ 391.91 million.

These findings are encouraging and require investors, sugar milling companies and entrepreneurs to plan and execute projects to construct add-on facilities to existing sugar mills wherein these products can be co-produced with sugar. Co-production of these products will ensure that the sugar industry survives and solidifies its future.

**Key terms:** Sugarcane co-products, furfural, levulinic acid, succinic acid, cost-benefit analysis

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# CHAPTER 1 NATURE AND SCOPE OF STUDY.

## 1.1 Introduction

The sugar industry started in South Africa by processing sugarcane to produce sugar and molasses in the mid-19th century (Lewis, 1990:77). Sugarcane is grown in Kwa-Zulu Natal and Mpumalanga by farmers, alternatively called growers. Sugar mills in these provinces produce sugar by milling the sugarcane. The sugar industry employs roughly 65,000 people directly and indirectly, providing an estimated 270,000 jobs (SASA, 2020:4).

There are currently twelve operational sugar mills that are owned and operated by milling companies: RCL Foods with mills in Malelane, Pongola, and Komatipoort; Tongaat Hullet Limited with mills in Maidstone, Felixton, and Amatikulu; Illovo Sugar Limited with mills in Noodsberg, Eston, and Sezela; Umfolozi Sugar Mill in Mtubatuba; Gledhow Sugar Company in KwaDukuza; and UCL Company Ltd in Dalton.

White refined sugar, brown sugar (fit for consumption) and molasses are produced for the domestic market. Raw sugar (brown sugar not fit for consumption, which requires further processing) is produced for export. Exported raw sugar is processed at other facilities. Other products made from sugarcane include ethanol alcohol, animal feed, furfural, and electricity for export by cogeneration (SASA, 2020:4).

Sugar production in South Africa has declined by roughly 25% (2.75 Mt to 2.1 Mt per annum) in the last 20 years (SASA, 2020:5). This is due to lower international prices than South African production costs, which has resulted in losses of up to R 2 billion/year.

The Health Promotions Levy (sugar tax) introduced in 2018 has forced beverage producers to find alternatives to sugar, reducing demand and, in some instances, sugar replacement. The imposition of the sugar tax led to a R1.2 billion loss in industry revenue in the year of inception (SASA, 2020:5). As stated by SASA (2020:5), the South African sugar industry is in crisis.

This study investigates, sifts, and selects alternative products co-produced from sugarcane and determines their feasibility in the South African sugar industry. A well-conducted feasibility study of economically viable alternative products may entice the business fraternity to invest more resources into the ailing sector, ultimately producing various co-products from sugarcane.

Thus, growers will plant more sugarcane and millers will mill and process the cane, leading to new growth in an already declining industry. It may also lead to more significant job creation and new business ventures starting from within the sugar industry.

## **1.2 Background to the study**

In response to the sugar industry decline highlighted in the introduction, the South African Sugar Association, together with industry role players such as millers, refiners, cane growers, government and other related industrialists, have proposed a master plan titled “South African Sugarcane Value Master Plan to 2030” (SASA, 2020:2).

This master plan proposes three scenarios for the sugar industry: Scenario one - Unmanaged Decline; Scenario two - Managed Shrink; and Scenario three - Re-structure and Diversify for Growth (SASA, 2020:7).

Scenario one considers the exit of small-scale growers and independent millers in the short to medium term should there be no intervention in the current sugar industry environment. Such withdrawals will disrupt the industry and may lead to supply shortages and increased price pressures (SASA, 2020:7).

Scenario two considers managing a capacity reduction process to bring production capacities for sugar and molasses in line with current market demands. During the preparation of the Master Plan, it was agreed that scenario two must be avoided entirely (SASA, 2020:8).

Scenario three considers the diversification of products in the sugar industry, as successfully demonstrated by India and Brazil, which have diversified and produced biofuels, alcohol, animal feeds, and electricity from sugarcane. Brazilian and Indian producers also invest in chemical production for bio-based plastics, packaging, and pharmaceuticals (SASA, 2020:9).

Opportunities for bioethanol (fuel blending, pharmaceutical-grade, industrial, and potable), bio-jet fuel, electricity from biomass, no- and low-calorie sweeteners, and biochemicals were identified in the Master Plan under scenario three. During the preparation of the Master Plan, a consensus was reached among stakeholders to target scenario three (SASA, 2020:9).

Techno-economic analyses have been conducted for the co-production of various alternative products with sugar by Morakile (2021:1), Morakile *et al.* (2022:1), Pachón *et al.* (2019:1), Gnansounou, Vaskan and Pachón (2015:364), (Ratshoshi *et al.*, 2021:1871) and others. These researchers have found that xylitol, glutamic acid, electricity for export, levulinic acid

and other chemicals can be produced from sugarcane and are, to some extent, economically viable.

However, much of this research on co-products from sugarcane was conducted before the COVID-19 pandemic, the July 2021 riots, the April 2022 floods in KwaZulu Natal and the resulting economic slowdown (Arndt *et al.*, 2020; News24, 2021; Vhumbunu, 2021). Therefore, alternative co-products are identified, evaluated, and selected to determine their feasibility to ultimately propose viable co-products for production with sugar.

### **1.3 Definition of terms**

The following terms are used in this study and are defined here:

- CBA – cost-benefit analysis
- Cogeneration – simultaneous generation of electricity and heat used in a sugar factory
- IRR – internal rate of return
- Lignocellulose – agricultural plant residues
- Master Plan - South African Sugarcane Value Master Plan to 2030
- NPV – net present value
- PI – profitability index
- Sugarcane products – any product derived from processing sugarcane
- TEA – techno-economic analysis

### **1.4 Products specifically investigated in this study**

- Acetone
- Animal feed
- Biocide
- Bioelectricity

- Biogas
- Carbon dioxide
- Citric acid
- Corrugated boards
- Dextran
- Diethyl oxalate
- Ephedrine
- Ether
- Explosives such as nitromiel
- Fatty acid esters
- Fibre and particle boards
- Filter cake
- Furfural and furfuryl alcohol
- Gamma valerolactone
- Glutamic acid
- Glycerol
- Green top leaves and dry trash
- Industrial ethyl alcohol (ethanol)
- Lactic acid
- Levulinic acid
- Monosodium glutamate

- Oxalic acid
- Polybutylene succinate
- Polydextrose
- Polylactic acid
- Potable alcohols (ethanol)
- Pulp and paper
- Succinic acid
- Sustainable aviation fuel (SAF) from bioethanol
- Xylitol
- Yeast

## **1.5 Problem statement**

To address a declining sugar industry and resuscitate businesses' appetite, new research is required to present a viable business case for the co-production of selected alternative products from sugarcane. This aligns with the Master Plan presented by SASA (2020:9) for their proposed scenario three as indicated in the Master Plan.

Given the strenuous current economic climate and the poor state of the sugar industry, it is necessary to evaluate and select possible co-products and execute a feasibility study of those preferred products.

This leads to the following main research question: What alternative products are feasible for co-production with sugar from sugarcane, given the current state of the sugar industry?

To answer the primary research question, an investigation is required to select products based on economic viability when considering the current economic climate and value proposition. To ultimately provide a business case for viable sugarcane co-products, this study will:

- Identify various possible products for co-production from sugarcane from available academic literature.

- Select alternative products for co-production with sugar based on manufacturability, product selling price, predicted market growth, and available techno-economic assessments for production from sugarcane.
- Conduct a cost-benefit analysis of selected products to determine their feasibility for co-production.

This study will contribute to the body of knowledge of economically viable sugarcane co-products, especially considering current economic conditions. It will assist the management of industry role players to identify alternative sugarcane co-products and provide a baseline document for their consideration when building their company-specific business plans.

## **1.6 Research objectives**

The primary objective of this study is to determine the feasibility of co-production of selected products from sugarcane in the South African sugar industry. To achieve the primary aim of this study, the secondary objectives listed below were undertaken:

- SO1 – Conduct a literature review of the sugar industry, including a PESTEL analysis of the sugar industry and a Five Forces Framework analysis.
- SO2 – Conduct a literature review of alternative products for co-production with sugar from sugarcane.
- SO3 – Select co-products for further evaluation by process of elimination based on specific criteria.
- SO4 – Execute a cost-benefit analysis on selected potential co-products to facilitate product selection of viable co-products for production with sugar.

## **1.7 Scope of the study**

This study does not include engineering calculations or process engineering modelling. It relies on research conducted by engineers and other researchers who have conducted TEAs and considered technical, financial, and chemical process requirements for product co-production from sugarcane. It expands on their research from a purely business and financial viability perspective in the current economic climate. It dives into business feasibility considerations rather than technical engineering considerations.

## **1.8 Field of study**

The field of this study overlaps both entrepreneurship and operations management.

## **1.9 Industry under investigation**

This study focuses on the sugar industry.

## **1.10 Geographical demarcation**

This study is geographically demarcated to South Africa.

## **1.11 Research design and methods**

This study is structured as a secondary study with no human participants. It was carried out in two phases: Firstly, a literature review was done on the sugar industry and possible, feasible alternative products for co-production with sugar from sugarcane.

Once the literature review was complete, a cost-benefit analysis of potential co-products was conducted to assist with co-product selection based on the internal rate of return and net present values of the specific products.

## **1.12 Literature review**

This literature review considered potential co-products that could be produced from sugarcane in the South African sugar industry. It also considered the production of co-products produced internationally and from other sectors to establish baseline costs of production and sale of these products.

This secondary information was obtained from local and international scientific journals, post-graduate students' theses and dissertations, local regulatory documentation and publications from industry and government. These resources were sourced using Google Scholar, NWU Online Library affiliated journals, and government and industry stakeholders' websites.

## **1.13 Empirical study**

The required data for this study is empirical data produced by other researchers and organisations obtained from the public domain. Empirical data produced from this research is presented in this study.

### **1.13.1 Research paradigm**

According to Saunders *et al.* (2019:140), a paradigm is a perspective or lens (based on internal assumptions) that the world is viewed through, and which individuals use to interpret and

understand the interworking of a group. Positivism focuses on strict empiricist methods to obtain scientific data free of human influence (Saunders *et al.*, 2019:144).

Scientific methods and measurable numbers constitute acceptable knowledge in positivism (Saunders *et al.*, 2019:144). Melnikovas (2018:35) states that only empirical data is trustworthy for positivism, whilst Saunders *et al.* (2019:146) state that research in the positivism paradigm relies on the deductive approach.

This study relies on the accuracy of calculations (empiricist methods) presented by other researchers and those conducted in this study. The researcher considered the financial viability of co-products for production with sugar and other calculated values to deduce whether selecting specific products is acceptable for selection. This research has adopted a positivist philosophical perspective based on deductive analysis and the reliance on empiricist methods.

### **1.13.2 Research approach**

Deductive reasoning is the logical derivation of conclusions from a set of theoretical propositions on which a specific argument is based for which those prepositions have been met (Saunders *et al.*, 2019:152).

In this study, the researcher deduced from the empirical data captured and processed in financial calculations whether feasible financial cases exist in the research topic.

This research tested a theoretical preposition when calculating possible net present values, internal rate of returns and cash flows that could be generated for the co-production of alternative products. It also tested and confirmed whether a business case exists for co-production of other products from sugarcane.

### **1.13.3 Methodological choice**

Bryman *et al.* (2014:63) state that quantitative research emphasises the quantification of collected data, adopts a deductive approach to test hypotheses, takes on a positivist epistemology and considers reality as external and objective.

Bryman *et al.* (2014:63) state that qualitative research emphasises words rather than quantification of collected data, takes an inductive approach to generate rather than test theories, rejects the natural scientific model and views social reality as everchanging and ever-growing as interpreted by the individual.

Given these definitions, this research follows a mono-quantitative research approach. It uses numerical data from the literature, which was used in financial calculations to make scientific deductions on product viability. The findings from these deductions are considered the concluding outcome of this research. This research did not use qualitative data obtained from inductive reasoning. It also did not use a mixed method approach combining quantitative and qualitative data.

#### **1.13.4 Research strategy**

This study is a secondary study with no human participants. All numerical data was collected from existing literature for inclusion in the financial cost calculations. Where numerical data is historic, escalation was applied to these values, and the costs were adapted as required. This study did not use experiments; instead, it used mathematical models to determine the financial viability of co-products. Thus, this study did not use non-experimental research as it relied on the outcomes of the calculations during the cost-benefit analysis.

#### **1.13.5 Time horizon**

According to Melnikovas (2018:34), the time horizon in the research onion is the layer that defines the time frame of the research. The time frame can either involve data collected over a long period repeatedly to compare such data or over a short term where data is collected at a single point in time of study, also known as a cross-sectional study (Melnikovas, 2018:34).

This study was conducted in a cross-sectional timeframe (short period) as data was collected at a single point in time and not repeatedly over various points.

#### **1.13.6 Study population and sampling**

Scientific articles from journals and publications were sourced from industry bodies explicitly focussing on the extraction of sugar and co-products from sugarcane, which forms the target population. Scientific articles on lignocellulose feedstocks used to produce other chemicals were collected as an accessible population.

These resources were used to obtain cost information of co-products derived from sugarcane and similar products derived from other biomaterials. These articles and resources were based on the South African sugar industry, the international sugar industry and other related industries that produce products from lignocellulose.

As this research followed a quantitative research approach, more than thirty academic articles were collected that present sugar co-products and costing information for such co-products. In addition, product market research information was extracted from online resources provided by market analysts.

#### **1.13.7 Collection of data**

Secondary data from other researchers and industry bodies were readily available and collected in this study. This data was obtained easily from online resources, so it assisted in rapid data collection and allowed more time to be spent on data analysis. Data analysis incurred more time than initially anticipated as the researcher required more time to familiarise with the data. As there was no control over the data quality, the researcher used reputable academic journals for data collection purposes to ensure good quality data was procured.

#### **1.13.8 Data analysis**

This study is a secondary data study. This study aimed to conduct a financial feasibility study of the co-production of sugar and selected co-products through a cost-benefit analysis. Literature reviews found that others have considered capital and operational costs of facilities to produce different co-product variations.

These biorefineries were simulated and modelled in these studies to determine the capital and production-related operational costs for the current economic climate. However, these studies did not consider markets, logistics, location and other business considerations for their various coproducts and the financial implications of these items.

Data analysis was done using a defined model, preparation of cash flows and cost-benefit analysis calculations to compare various products based on cost data obtained for sugarcane co-products from research resources. The methods included considering the highest, lowest, averages and most recent costing data available. This costing data was inserted into the Excel model and presented in tables to differentiate and compare selected co-products based on the output results obtained.

#### **1.13.9 Reliability and validity (trustworthiness)**

Reliability relays the consistency of the measurement, and validity considers the accuracy of measurement (Heale & Twycross, 2015:66). To ensure that the data was reliable and valid,

the researcher confirmed whether the definitions used for constructs in this research matched the data procured from other researchers.

It was confirmed that original cost data measurements measured what is said to have been measured in the datasets obtained from the literature review. Lastly, the researcher confirmed the validity of this research by comparing data from different researchers when conducting the cost-benefit analyses.

#### **1.14 Ethical considerations**

Potential ethical issues that could arise during this study were considered, but none were found. The selected topic of this study is worthy and is not a topic of contention. This topic will neither offend nor insult any party.

Information required to complete this study was readily available from articles, journals, quarterly reports, theses, industry regulatory assessments, dissertations, and online resources. Sources that required permission to use were not used in this study. All sources were referenced following ethical practices to reduce the risk of plagiarism.

Data analysis was conducted on an ethical basis by use of tools provided in Microsoft Excel and other software platforms. All data procured for the completion of this study was stored on a cloud-based platform that uses password authentication. This data was also backed up on a hard disk drive and stored in a safe.

Ethical risks were mitigated during the various phases of the study by using the check sheet presented here before moving on to a new chapter.

- Are all sources referenced?
- Are all permission documents signed and stored in the cloud?
- Have all documents, such as dissertation draft versions and supporting documents, been backed up on the cloud?
- Has the password for the cloud been memorized and secured?
- Is any written statement offensive or distasteful?
- Is autosave activated for the dissertation draft?

Considering the ethical risks of implementing the PoPI Act, no personal information of any party was used which was not obtained from public resources.

## **1.15 Contribution of the study**

### **1.15.1 Theoretical contribution**

This research contributes to the body of knowledge of viable sugarcane by-products for production and sale in the South African context. It contributes further to entrepreneurial and operational spheres of knowledge, considering requirements for expanding existing product offerings or starting anew.

### **1.15.2 Practical contribution**

It is envisaged that this research contributes to businesses wanting to expand product offerings manufactured from sugarcane. It provides a strong baseline for businesses to conduct product diversification analyses and build business-specific business plans for new sugar cane by-products.

### **1.15.3 Industry contribution**

This research contributes to the industry by providing a business case for alternative products co-produced from sugarcane. This business case may spur industry players to expand their product offerings and produce new alternative products. It may encourage growers to plant more sugarcane, leading millers to increase milling capacity. It may lead to new growth in a declining industry as it also provides an answer to the Sugar Master Plan strategy of product diversification.

## **1.16 Expected limitations of the study**

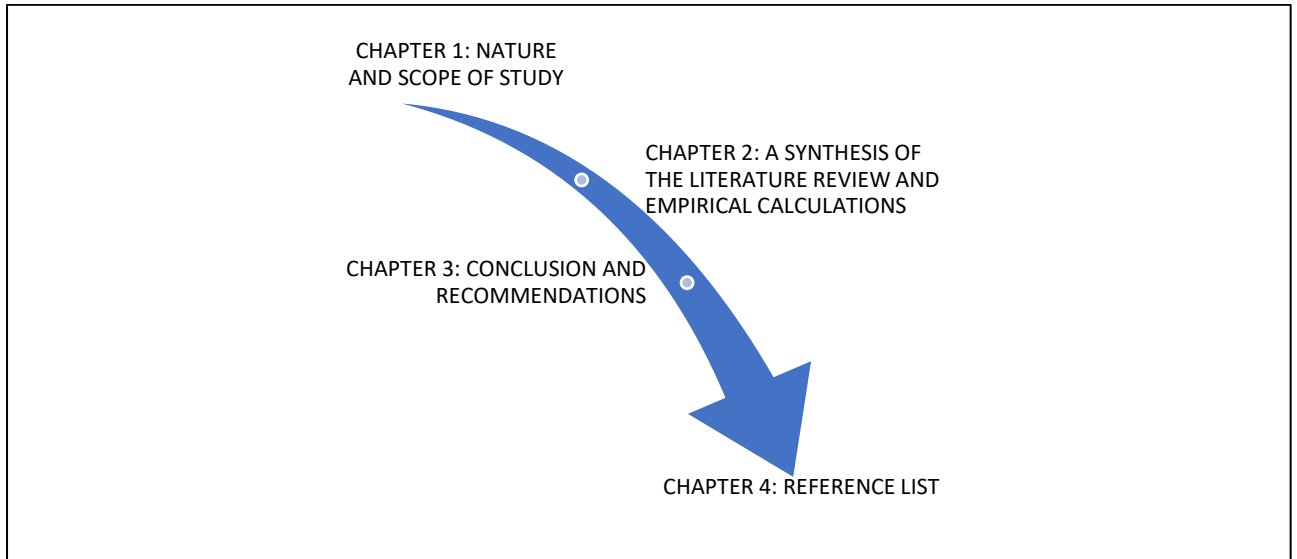
This study is limited geographically to South Africa. Although the information provided is of value in other sugarcane-producing countries, the focus of this study is limited to a South African context. This aligns with the Sugar Master Plan, which endeavours to find viable by-products from sugarcane.

Another limitation of this study is the available commercial information about the various sugar milling companies, which these companies keep confidential for competitive reasons.

### 1.17 Layout of the study

The layout of the study is depicted in Figure 1. Chapter one provides the nature and scope of the study. Chapter two offers a synthesis of the literature review and empirical calculations, followed by chapter three, which provides conclusions and recommendations. Lastly, chapter four presents the bibliography.

**Figure 1: Layout of the study**



## **CHAPTER 2     A SYNTHESIS OF THE LITERATURE REVIEW AND EMPIRICAL CALCULATIONS**

This chapter is presented as a synthesis of the literature review and empirical calculations on the feasibility of alternative co-products from sugarcane. Initially, this chapter presents a literature review of the global and local sugar industry in South Africa. A PESTEL analysis was conducted as part of this literature review to provide a macroeconomic assessment of the local sugar industry. Porter's Five Forces Framework is presented after that to inform the reader of the local competitive environment.

Biorefineries are briefly discussed, followed by the presentation of potential alternative by-products that may be coproduced from sugarcane. For each by-product listed, its use in the industry, current global market share and future market share are listed. Current market prices were also listed for products of interest that were investigated further and subjected to an empirical study.

As part of co-product shortlisting, an elimination process was conducted to identify potential co-products by searching for co-products for which others conducted techno-economic analyses (TEAs). Products for which TEAs were unavailable were eliminated. Products for which TEAs were available were then reviewed, and those applicable to a South African context were then subjected to an empirical study.

The empirical study consisted of a cost-benefit analysis wherein the net present value (NPV), internal rate of return (IRR) and profitability index (PI) for each product under investigation was calculated. Cost data obtained from the respective TEAs and their corresponding products were input into a baseline model in Excel. Products with superior IRR and NPV values were selected and presented as viable products that can be co-produced from sugarcane.

### **2.1    Global sugar industry**

Globally, sugar is produced by processing sugarcane and sugarbeet. Sugarcane is grown in Australia, Brazil, India, Mexico, Pakistan, and Thailand. Sugarbeet is grown in the European Union and Russia, whilst both crops are grown in Africa, China, and the United States of America (OECD, 2022:183). Although sugar is manufactured from sugarcane and sugarbeet, this study will only consider the South African sugar industry in sugarcane production.

According to OECD (2022:181), sugarbeet production is estimated to reach 284Mt by 2031. Global sugarcane production is forecasted to deliver 1924 Mt of sugarcane by 2031, an estimated 168 Mt more than current production. It is envisaged that Brazil and India will contribute 52% and 19% of this growth (OECD, 2022:181). By 2031, the estimated total annual sugar production will be 190 Mt from sugarcane and sugarbeet (OECD, 2022:182).

According to OECD (2022:47,176), South Africa produced 2.024Mt sugar on average from 2019 to 2021. This positions South Africa as the second largest sugar producer in Africa, with Egypt in the first position, which averaged 2.627Mt for 2019-2021. When considering South Africa, OECD (2022:183) estimate an approximate growth in sugarcane production of 0.2 Mt by 2031, ascribed to government support measures.

Brazil and India currently dominate the international sugar industry. They are forecasted to supply 21% and 18% of the world's sugar by 2030, respectively (OECD, 2021:151).

Forecasts show that 80% of sugar crops (78% of sugarcane and 96% of sugarbeet) will be used to produce sugar. The remaining 20% will be used to produce ethanol from 2022 to 2031 (OECD, 2022:182).

Estimates show that by 2031, Brazil will produce 37% of the world's sugarcane. Brazil's sugarcane will produce 24% of the global sugar supply and 83% of the global sugarcane-derived ethanol (OECD, 2022:182).

It is noteworthy to mention that Brazil produces ethanol from more than half its sugarcane, and in all likelihood, Brazil will maintain the title as the largest sugarcane producer globally (OECD, 2022:182).

As was found with the COVID-19 pandemic, this growth is not inevitable, and OECD (2022:187) state that new opportunities could be found in bioethanol, bioplastics, and biogas, among others.

## **2.2 South african sugar industry**

This section discusses the South African Sugar industry, its role players, and its production capacity. A PESTEL analysis was also conducted to give insight into the industry and its regulatory environment. Porter's Five Forces Framework was included to highlight the industry's competitive environment.

### **2.2.1 Introduction**

In South Africa, sugar is manufactured from sugarcane, which is grown and harvested by farmers who are represented by the South African Cane Growers Association (SACGA) and the South African Farmers Development Association (SAFDA) (SASA, 2022). Sugarcane farms are situated in Kwa-Zulu Natal and Mpumalanga.

The harvested cane, in turn, is processed by sugar mills owned by sugar milling companies RCL Foods, Tongaat Hulett Limited, Illovo Sugar Limited, Umfolozi Sugar Mill, Gledhow Sugar Company, and UCL Company Ltd (SASA, 2020:4).

These mills extract value from the cane by making sugar, molasses, and bagasse, which are burnt in boilers for energy production or used in animal feed production. Illovo Sugar Limited also produces ethanol from molasses, furfural from bagasse and other chemicals and flavourings from sugarcane (ISA, 2023a, 2023b). RCL Foods and Tongaat Hulett Limited also provide molasses and bagasse for animal feed manufacturing by their respective feed companies, Molatek and Voermol (Molatek, 2023; THL, 2023).

The South African Sugar Association (SASA) and the grower and miller members operate and control the industry. SASA is a self-governing organization whose affairs are administered by the Council of SASA. This council comprises members of the sugar milling entities as well as SAFDA and SACGA (SASA, 2019:5).

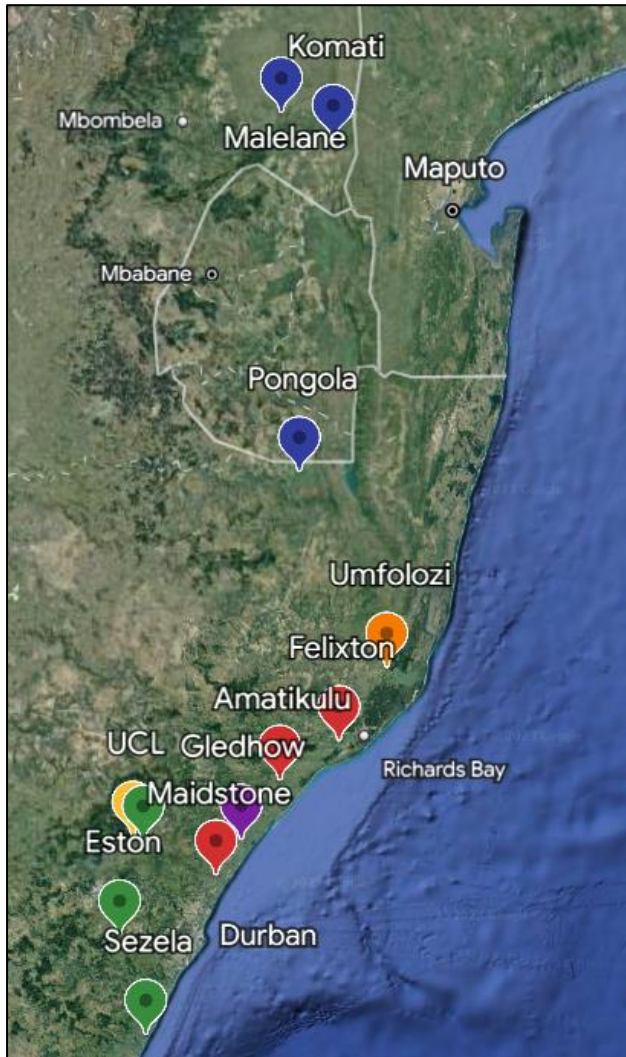
The industry operates under the statutory requirements of the Sugar Act (Act 9 of 1978), the Sugar Industry Agreement (2000), amended in 2018, and the Constitution of the South African Sugar Association (SASA, 2020:4). It is thus regulated by the government.

The sugar price is set at a notional price by SASA, millers and growers. Cane growers are recompensed per tonne of sugarcane delivered to the sugar mills based on the recoverable value (RV) of sucrose from the sugarcane as tested and determined by SASA's cane testing services at the mills.

Income from sugar and molasses sales is divided between millers (36% income), who are individually recompensed for the portion of sugar produced by each miller and growers (64% income) (SASA, 2020:5). Note that millers diversified downstream products are not included in the Sugar Act and Sugar Industry Agreement and as such are not included in the division of proceeds (SASA, 2020:9).

Figure 2 presents a map indicating the positions of the twelve operating sugar mills. The blue pins indicate the RCL Foods mills, whilst the green and the red pins indicate Illovo Sugar Limited and Tongaat Hulett Limited mills, respectively. The yellow pin indicates the UCL mill, and the orange pin indicates the Umfolozi mill. The purple pin indicates the Gledhow mill.

**Figure 2: Image of a map indicating sugar mill locations**



Sugarcane crushing and sugar production market share is presented in Table 1 for the various sugar manufacturing businesses. This information is based on estimates of 2019 production data for the various sugar mills adapted from SASA (2023).

More recent data is unavailable as crushing and manufacturing data have been kept confidential since 2019 to ensure the industry is not at risk from competing countries with sugar manufacturing businesses. In Table 1, it was assumed that sugar produced from

sugarcane is, on average, 11% in line with industry standards. Table 1 shows that RCL Foods, Tongaat Hulett Limited and Illovo Sugar Limited are the largest producers. The bulk sugarcane crushed is rounded to 18 Mt.

**Table 1: Indication of companies, sugar mills and market share of sugarcane crushed and sugar produced as estimated in 2019 (SASA, 2023)**

Company	Market share cane crushed	Sugar Mill	Tonnes cane crushed	Sugar Produced (tonnes)	Market share of sugar produced
<b>RCL Foods</b>	29%	Komati	2,362,678	259,895	13%
		Malelane	1,597,041	175,675	9%
		Pongola	1,257,740	138,351	7%
<b>Tongaat Hulett Limited</b>	24%	Amatikulu	1,256,000	138,160	7%
		Darnall*	103,717	11,409	1%
		Felixton	1,793,981	197,338	10%
		Maidstone	1,152,095	126,730	6%
<b>Illovo Sugar Limited</b>	29%	Eston	1,229,689	135,266	7%
		Noodsberg	1,485,659	163,422	8%
		Sezela	1,909,484	210,043	11%
		Umzimkulu*	594,019	65,342	3%
<b>Umfoloji Sugar Mill</b>	7%	Umfoloji Sugar Mill	1,234,114	135,753	7%
<b>UCL Company</b>	4%	UCL Sugar Mill	811,667	89,283	4%
<b>Gledhow Sugar Company</b>	7%	Gledhow Sugar Mill	1,310,350	144,139	7%
		<b>Total</b>	<b>18,098,234</b>	<b>1,990,806</b>	<b>100%</b>

\*This sugar mill was closed prior to 2020 and is no longer operational

Note that Gledhow Sugar Company initiated business rescue proceedings in March 2023 due to losses incurred in the July 2021 unrest, flood damage to infrastructure in April 2022, and increased supply costs due to the Russia-Ukraine war (GSC, 2023).

Tongaat Hulett Limited also entered into business rescue in October 2022 as it could not recover from large debts incurred from an accounting scandal in 2019 (Kew, 2022; THL, 2022). At the time of writing this dissertation, both these businesses were still in business rescue. However, Tongaat Hulett had secured a buyer for its business in the Tanzanian sugar giant Kagera Sugar Limited (Thukwana, 2023).

## **2.2.2 Pestel analysis**

A PESTEL analysis was conducted to thoroughly understand the business environment and external factors that influence the sugar industry. A PESTEL analysis is a tool that helps businesses evaluate the external environment effects regarding the political, economic, sociocultural, technological, environmental, legal and regulatory aspects and how it influences a company (Peteraf *et al.*, 2021:54).

### **2.2.2.1 Political factors**

The government provides tariff protection against importing low-priced sugar, ensuring the sugar industry can sell sugar in the local market. Without this tariff protection, local buyers will import sugar from the flooded global sugar market at prices lower than the local sugar market's cost prices.

In recent years, the government failed to impose tariffs on the import of sugar, leading to bulk imports by customers and thus reduced demand for locally grown sugar, leading to subsequent losses. The government may fail to provide tariff protection in the future (Mamaila, 2020).

The government also imposed a sugar tax (health promotion levy) in 2018 to combat obesity in South Africa (SASA, 2020:5).. This sugar tax forced customers such as beverage producers with high sugar content to reduce the sugar content in their drinks, resulting in less demand and increased losses. Many of these businesses have since started investing in alternative sweeteners, reducing their sugar demand. Subsequently, two competitor sugar mills (Darnall and Umzimkulu) have closed (Mamaila, 2020).

The sugar tax has also caused and will continue to drive reductions in sugar demand and sugarcane farming. Reductions could also lead to business losses, resulting in further sugar mill closures.

The government, through poor management of ESKOM, cannot provide electricity to sugarcane farmers. Lack of electricity specifically affects cane growers growing for RCL Foods, as these farms are all under irrigation. Load-shedding hinders farmers from irrigating their sugarcane and sometimes causes equipment failure. Equipment failure leads to higher maintenance costs, resulting in lower profits, making it less attractive to grow sugarcane.

Poor irrigation decreases cane quality and sucrose levels, lowering sugar production efficiencies. Thus, the same amount of work produces less sugar than when higher-quality cane is processed, reducing profits and forcing the sale of sugar at higher prices to cover production costs. It also reduces the sugarcane feedstock levels and results in bagasse feedstock shortages as the sugar mills require bagasse to fire their boilers and power the plant. In response to lower bagasse, more coal is required to operate a sugar mill as some mills supply bagasse to their animal feed mills.

Between stages four and six, the industry is estimated to incur a loss of R723 million due to poor crop irrigation and higher irrigation costs during peak hours. Load-shedding between stages six and eight could incur a loss of R1.8 billion, whilst load-shedding beyond stage eight could incur losses of R2.4 billion or more (Govender, 2023).

Land expropriation without compensation threatens farmers and reduces investor confidence (Niekerk, 2021:23). This does not promote further land purchasing or crop production. In response, some farmers have emigrated to pursue opportunities in other countries (Maromo, 2018).

### **2.2.2.2 Legal/regulatory factors**

Each milling company must pay levies to operate in the sugar industry as set out by SASA. SASA then redistributes these levies to all role players in the industry. Tongaat Hulett Limited, currently in business rescue due to its fraudulent business practices, under the control of its business rescue practitioners, did not pay its levies. As such, other sugar mills had to cover the shortfall.

### **2.2.2.3 Environmental factors**

Recent floods and irregular rainfall patterns have caused harm to the industry as well. Waterlogged lands from excessive rain inhibit farmers from accessing lands and harvesting cane. This leads to production slowing down. Gledhow Sugar Mill has not recovered from the April 2022 flood damage and has gone into business rescue (GSC, 2023). Their business rescue initiation has further put the sugar industry at risk. A collapse could leave growers without a mill to process cane and thus open to significant losses.

ABB (2023a) states that sugar mills are accustomed to high emission levels, which may be problematic as emission regulations are tightened in the future. Emissions in sugar mills should be managed to ensure compliance with regulations.

### **2.2.2.4 Economic conditions**

Lack of jobs and poor economic conditions combined with political interference led to the looting and unrest of 2021, wherein some sugarcane farms were burnt, and mills could not operate (News24, 2021; Vhumbunu, 2021). Should the economic and social instability in South Africa not be addressed, it could spell out more trouble for the sugar mills. Some farmers have lost confidence in the economy and sugar industry and have been forced to diversify crops and reduce their sugarcane planting efforts, resulting in lower cane feedstock (Botha, 2022). A weaker rand causes losses in fertilizer imports but higher profits in the sugar export market.

### **2.2.2.5 Social**

Social aspects are addressed in the section on economic conditions.

### **2.2.2.6 Technology**

In line with the fourth industrial revolution and the internet of things, sugar mills can digitalize manufacturing processes to save costs, better manage their assets, and improve supply chain efficiency (ABB, 2023b). Digitalized manufacturing processes also assist in the optimization of energy consumption, reduction of emissions, and reduction of inventory and material costs. However, these plant modifications come at a cost, which, given the current economic climate and the fact that all sugar mills in South Africa are older than twenty-five years old, are not always feasible.

### **2.2.2.7 Summary**

The introduction of the sugar tax, lack of tariff protection and load-shedding have been identified as the three most significant factors that cast the sugar industry into turmoil and reduced local sugar demand and supply.

The industry's future is uncertain as Tongaat Hullet Limited and Gledhow Sugar Company battle through business rescue. The collapse of these businesses could potentially cause the entire industry to collapse, leaving growers without cane processing facilities and the country with a sugar deficit, forcing the government to lift tariffs and allow imports. Such a collapse would lead to a loss of sugar demand and sales locally. In response to these uncertain times, it is proposed that the industry, through the voice of SASA, drive the government to lift the sugar tax.

Businesses should also mitigate these uncertain times and consider the production of alternative products that can be co-produced from sugarcane to stabilize an ailing sugar industry. The focus should shift from producing sugar to producing chemicals with sugar as a by-product. Suppose there is a reduction in local sugar demand. In that case, one can always sell the sugar internationally and maintain the production of high-value chemical products, ensuring the business's survival. Diversification of products may entice growers to plant more sugarcane, increasing sugarcane feedstock.

### **2.2.3 Five forces framework**

To better understand the competitive environment, a Five Forces Framework was conducted to analyse the competitors in the sugar industry. According to Porter (2008:24,27), five forces shape industry competition and affect businesses' profit. These forces are listed as:

- Rivalry amongst existing competitors.
- Bargaining power of suppliers.
- Bargaining power of buyers.
- The threat of new entrants.
- The threat of substitute products or services from businesses in other industries (Porter, 2008:24,27).

The findings of the competitive analysis are presented in Table 2.

**Table 2: Five Forces Framework for the local sugar industry**

Force	Parties involved	Notes	Pressure*		
			S	M	W
Suppliers	Cane growers	Growers have less confidence in the sugar industry and are diversifying to alternative crops. Thus, growers have bargaining power when negotiating tariffs with industry. However, growers are positioned near specific mills. They cannot change to other mills quickly, thus creating a reliance on those mills and reducing the negotiating power when cane supply contracts are drafted. The cane supply is diminishing for irrigated crops due to poor irrigation caused by load-shedding. Lower cane yields put pressure on mills as these may not reach budget targets.		x	
	Consultants	There are various external consultants to select from both locally and abroad.			x
	Equipment suppliers	There are limited reliable local boiler suppliers and limited local specialist equipment suppliers. Sometimes, businesses are forced to look to international suppliers for equipment or maintenance. When the rand is weak, the exchange rate induces further pressure.	x		
Buyers	Retailers, Spar, Shoprite, PnP, Checkers, and more.	Various buyers sell sugar packaged as house brands. They also sell the manufacturers' brands. A specific buyer may negotiate low prices, but the pressure is reduced by selling to other buyers at better prices. However, the buyers can switch suppliers quickly depending on contractual agreements. Also, buyers could import their sugar easily if tariffs are lifted, which has happened before.	x		
New potential entrants	South African Government	There has been mention of the government considering building a sugar mill. CAPEX to build a mill is more than R1 billion and would be opposed by political parties.			x
	Other new potential entrants	The industry is unattractive at this stage due to the high CAPEX requirements to build a mill, the negative impacts of load-shedding on irrigated crops, and the sugar price volatility. Competition from larger milling companies may deter smaller new entrants from entering the market.			x

Force	Parties involved	Notes	Pressure*		
			S	M	W
<b>Firms in other industries</b>	Coca-Cola, Nestle and others	Other than sugar companies, no identifiable national companies provide alternatives to sugar. Only international firms provide alternatives to sugar for their use, such as Coca-Cola and Nestle. No large suppliers and thus not yet a threat			x
<b>Rivalry among competing sellers</b>	Illovo Sugar, Tongaat Hullet Limited, Gledhow Sugar, UCL Sugar, Umfolozi Sugar	Buyers can switch brands at a low cost. Products are weakly differentiated. Firms have high fixed costs. Major competitors are equal in size, with three mills each. The RCL Foods and Tongaat Hullet Limited also sell animal feed, whilst Illovo Sugar Limited sells furfural and other chemical by-products.	x		

\*S = Strong, M = Moderate, W = Weak

Forces from suppliers are moderate except for equipment suppliers, which are sometimes limited locally and thus are categorised as a strong force. Thus, businesses are required to obtain equipment and materials abroad. Forces from buyers remain high.

Forces from potential new entrants remain weak, as do those from firms in other industries. Rivalry among competitors remains strong, as is expected for the sugar industry. As mentioned, two mills have closed, with two other milling groups currently in business rescue.

### 2.3 Biorefineries

There has been much research for sugar mills to produce alternative co-products such as chemicals and other by-products from sugarcane. For sugar mills to co-produce these chemicals whilst manufacturing sugar, they should take a biorefinery approach.

A biorefinery is a facility that processes biological material to produce chemicals, energy and fuels (Merriam-Webster-Inc, 2023; SMRI, 2023). Klein *et al.* (2018:291) point out that establishing an integrated biorefinery rests on process integration and the benefits therein. Integrating processes and using the utilities and energy already provided by a mill will allow for savings in operational costs of the add-on process facility Klein *et al.* (2018:294).

As such, sugar mills should not be considered sugar mills only but biorefineries that extract maximum value from their sugarcane feedstock by producing a range of products. Adopting

this mindset means that sugar is not the only product but one of many manufactured products. It requires capital investment to alter and extend current sugar mill production capabilities to allow for co-production of alternative products from sugarcane feedstock.

Biorefineries can be classified into three categories, namely first-generation (1G), second-generation (2G) and third-generation (3G) biorefineries (Chowdhury *et al.*, 2018:355,356). The classification is linked to the feedstock and its use to produce biofuels, biochemicals, food, energy and feed. 1G biorefineries use sugars, animal fats, vegetable oils and starches, which are food or feed value for consumption, whilst 2G biorefineries use lignocellulosic feedstocks such as bagasse, woodchips, and other agro-wastes which are considered fuel sources and non-food or feed value feedstocks. 3G biorefineries use fresh water and marine algae as feedstocks (Chowdhury *et al.*, 2018:355,356).

There are, however, instances where 1G and 2G feedstocks are combined to produce a product. These instances are called 1G2G biorefineries (Ratshoshi *et al.*, 2021:1871). In this study, 1G feedstocks include molasses, whilst 2G feedstocks include bagasse and harvesting residues (Ratshoshi *et al.*, 2021:1871).

## **2.4 Alternative sugarcane products**

Various alternative products are derived from sugarcane. Some of these are co-produced with sugar, whilst others are produced as alternatives to sugar. Travella and Oliveira (2017:41) have categorised alternative co-products into subgroups sucro-chemicals, molasses-derived products, fibrous co-products, green top leaves and dry trash and filter cake. Products for each category are listed here (Travella & Oliveira, 2017:41):

- Sucro-chemicals – Oxalic acid, glycerol, lactic acid, fatty acid esters, ethers, polydextrose and diethyl oxalate.
- Molasses-derived products – Potable alcohols, ethyl alcohol, yeast, monosodium glutamate, lactic acid, oxalic acid, ephedrine and glycerine.
- Fibrous co-products – Pulp and paper, particleboards and fibreboards, corrugated boards and furfural.
- Green top leaves and dry trash – Green top leaves as feed or for field applications and cane trash as boiler fuel.
- Filter cake – Manure, compost and biogas (Travella & Oliveira, 2017:41).

Solomon (2011:411-416) confirms that in India, alternative products from sugarcane include paper, insulating board, particle board, biogas, furfural, bioelectricity, animal feed, ethanol, potable alcohol, baker's yeast, carbon dioxide, citric acid, dextran, monosodium glutamate, acetone, ephedrine, biocide, and explosives such as nitromiel.

Santos *et al.* (2020:34,35) confirm that sugarcane processing produces carbon dioxide as a byproduct of the ethanol manufacturing process in Brazil. In addition, Santos *et al.* (2020:34,35) also state that biodegradable plastics can be manufactured from sugarcane, which can biodegrade in less than a year, compared to plastics manufactured from petroleum refining processes, which can take between 100 and 200 years. A biodegradable plastic manufactured from sugarcane is polylactic acid (PLA) (Pachón *et al.*, 2018:2).

SASA (2020:9) also confirms that several platform, speciality, and biobased polymers can be produced from sugarcane. These include biochemicals such as glutamic acid, levulinic acid, furfural, lactic acid and xylitol (Morakile *et al.*, 2022:1; Pachón *et al.*, 2018:1).

In the following sections, potential co-products that were identified are discussed. Their current and forecasted market sizes are presented with information about their use and the relevant industry. Current market prices were also listed for products of interest that were subjected to the cost-benefit analyses.

#### **2.4.1 Oxalic acid**

Oxalic acid is a colourless toxic organic acid in crystal form used as a reducing agent in the extraction of iron as well as a cleaning and bleaching agent across multiple industries (FMI, 2023; Sahoo *et al.*, 2001:157). It has shown promising results for manganese extraction from low-grade Joda ore containing manganese and iron (Sahoo *et al.*, 2001:157).

It is also used to disinfect health care equipment and manufacture medicines such as borneol. It is also used for varroa mite control, which negatively impacts honeybee growth and for the production of many industrial chemicals, salts and oxalates (FMI, 2023).

The global market indication of oxalic acid was US\$ 960 million in 2023, with an estimated compound annual growth rate (CAGR) of 4.9% over the next ten years to US\$ 1550 million by 2033 (FMI, 2023).

### **2.4.2 Glycerol**

Glycerol, or glycerine, is an odourless chemical fluid that falls into the alcohol spectrum of molecules. It is used as a sweetener, solvent, and plasticizer in the food industry as it is biodegradable, hygroscopic, and miscible with water. It is used to manufacture pharmaceutical products such as cough syrups, vaccinations and other medicines (AMR, 2022). Glycerol also improves hydration and performance in athletes and skin conditions (GVR, 2021a).

In 2020, the personal care and cosmetics industry maintained a 40.8% market share for the use of glycerol in various products, including skin care products, shaving creams, hair care products and soaps, to name a few (GVR, 2021a).

Glycerol is produced as a byproduct of biodiesel production from animal fats, vegetable oils, and petrochemical feedstock (AMR, 2022; GVR, 2021a). Growth in biodiesel production globally has led to a growth in glycerol production.

In 2020, the glycerol market was valued at US\$ 2.4 billion, with an expected CAGR of 6.4% in revenue from 2021 to 2027. According to GVR (2021a), the estimated market size for 2027 is US\$ 3.7 billion, making glycerol an attractive product.

### **2.4.3 Lactic acid**

GVR (2023c) states that lactic acid is primarily used to produce polylactic acid (PLA), a biodegradable polymer compostable thermoplastic made from renewable sources. Sugarcane was the primary feedstock for lactic acid, accounting for 38.9% of raw materials in 2022.

Lactic acid enhances flavour and increases food shelf life by controlling pathogenic microorganisms' development. Lactic acid is also used in the pharmaceutical industry for skin moisturisers to improve dry skin, remove acne scars and prevent damage to skin tissue (GVR, 2023c).

The lactic acid market size was valued at US\$ 3.37 billion in 2023, with an estimated CAGR of 8% up to 2030, projected to result in a US\$ 5.8 billion industry (GVR, 2023c). Lactic acid prices for the end of the third quarter of 2023 were found to be US\$ 1240/tonne for North America, US\$ 1140/tonne for Asia Pacific and US\$ 1200/tonne for Europe (CA, 2023b). For this study, the price is assumed to be the average of the three at US\$ 1193.33/tonne.

#### **2.4.4 Fatty acid esters**

Fatty acid esters (FAEs) are used in the personal care, food processing and pharmaceutical markets. It is also used to treat gastrointestinal illness and other diseases. COVID-19, however, impacted the industry, forcing the closure of some factories globally (GVR, 2020a). Subsequently, there has been a decline in demand for personal care and cosmetic products, reducing the demand for FAEs. The market value of FAEs was captured at US\$ 2.2 million in 2019 and is estimated to grow to US\$ 3.13 million in 2027 at a CAGR of 4.5% (GVR, 2020a).

#### **2.4.5 Ether**

Ether or diethyl ether was historically used as an anaesthetic but was replaced due to its high volatility and the negative effects it has on patients. Adverse effects included liver damage and increased intracranial pressure, which may lead to convulsions (Aronson & L., 2016; Still, 2023). Ether is a solvent for manufacturing plastics and dyes and is a starting fluid (Still, 2023). The ether market was valued at US\$ 8.75 billion in 2020 and is estimated to grow to US\$ 12.5 billion by 2025 at a CAGR of 7.4% (IARC, 2022).

#### **2.4.6 Polydextrose**

Polydextrose is manufactured from glucose and is a synthetic polymer. It is used in deserts, beverages, breakfast cereals and other confectionaries and has a low glycemic index (GVR, 2017). It is thus often used as a sugar replacement in diabetic and sugar-free products.

In 2015, the market share for polydextrose was US\$ 225 million (GVR, 2017). At an estimated CAGR of 5.6%, the estimated market value is 387.99 US\$ million. GVR (2017) states that an increase in health-conscious consumer behaviour will drive the market for polydextrose as an alternative sweetener.

#### **2.4.7 Diethyl oxalate**

Diethyl oxalate is the dimethyl ester of oxalic acid and is a colourless organic compound used as a pharmaceutical ingredient in polymers and for manufacturing dyes. Additionally, it is used as a solvent to make esters, fragrances, and resins (PMR, 2022).

Diethyl oxalate market size was valued at US\$ 98.862 million in 2021 and estimated at US\$ 165.686 million in 2032, based on a CAGR of 4.9% (PMR, 2022).

#### **2.4.8 Potable alcohols (ethanol)**

Potable alcohol (ethanol) is manufactured from ethylene and sugars, which are also used to manufacture industrial ethanol. Raw materials include molasses, bagasse, sugarcane, maize stover, wheat, rice, and maize (GVR, 2022b).

Potable ethanol is used in spirits, beers, and cosmetic products, such as creams, toothpaste, hair shampoos and conditioners, and other food and beverage applications (GVR, 2022b). The global potable alcohol market size was US\$ 2.5 billion in 2022. It is estimated to reach a market value of US\$ 3.2 billion in 2030 at a CAGR of 4.3%. Brazil, India, China and Thailand manufacture alcohol from sugarcane and molasses (GVR, 2022b).

#### **2.4.9 Industrial ethyl alcohol (ethanol)**

Ethyl alcohol is an industrial alcohol that is a volatile, flammable, colourless liquid. It is also manufactured from maize and sugarcane fermentation. It can be blended with fuel for motor vehicle applications and is currently being implemented in the US as part of the Clean Air Act. Blended fuels release fewer toxic materials than fossil fuels (GVR, 2020c).

Ethyl alcohol is also used in the pharmaceutical industry to process vaccines, vitamins and other medicines, highlighting the opportunity for sale to pharmaceutical companies. During the COVID-19 pandemic, hand sanitisers were also manufactured from ethanol (GVR, 2020c).

The market value for industrial alcohols, including ethanol and other alcohols such as methanol, isopropyl and others, was US\$ 131.8 billion in 2019. The estimated CAGR is 8.3%, and the market value is US\$ 248.8 billion in 2027 (GVR, 2020c).

Ethanol was estimated in 2019 to have a total market share of US\$ 89.1 billion, and with an estimated CAGR of 4.8%, it is believed to reach a market value of US\$ 129.36 billion in 2027 (GVR, 2020b).

Ethanol is produced in South Africa on a large scale by SASOL from fossil fuels, Illovo Sugar Limited (55 million litres) from sugarcane molasses, Mabele fuels (150 million litres) from grain sorghum, and NCP Alcohols (54 million litres) from maize (USGC, 2022). The ethanol price was captured as US\$ 766.73/tonne or US\$ 0.60495/litre on 27 October 2023, the price used in this study (TE, 2023).

#### **2.4.10 Yeast**

Yeast is derived from molasses and is used in the foods and beverages industry for baking and brewing beer. GVR (2021e) states that globally, baker's yeast comprised 67% of the US\$ 11.42 billion global bioethanol yeast market in 2020, resulting in a US\$ 7.65 billion share. Brewer's yeast comprised 33% of the global market, resulting in US\$ 3.77 billion (GVR, 2021e).

The bioethanol yeast market share is estimated to grow to US\$ 32.67 billion in 2028 at a CAGR of 14.04%. Assuming that baker's and brewer's yeast maintain the current split, the global market share in 2028 will result in US\$ 21.89 billion for baker's yeast and US\$ 10.78 for brewer's yeast (GVR, 2021e).

#### **2.4.11 Monosodium glutamate**

Monosodium glutamate (MSG) is a flavour enhancer derived from L-glutamic acid. MSG is made by fermenting sugar beet, molasses and sugarcane (Lang, 2023). MSG market size was projected at US\$ 4.95 billion in 2022 and US\$ 8.62 billion in 2032 at a CAGR of 5.7% (FMI, 2022).

#### **2.4.12 Ephedrine**

Ephedrine, a decongestant and bronchodilator, is used in cough syrups to treat bronchospasms induced by asthma (CMI, 2023; Solomon, 2011). It is also used during spinal anaesthesia to avoid intra-operative hypotension.

Market information for ephedrine is not readily available. However, GDM (2021) highlighted that significant exporters of ephedrine and its salts in 2021 included India (US\$ 4.01 million), Germany (US\$ 1.67 million) and Italy (US\$ 640 thousand). Significant importers in 2021 included the United States of America (US\$ 2.3 million), Nigeria (US\$ 799 thousand) and Russia (US\$ 595 thousand) (GDM, 2021).

#### **2.4.13 Pulp and paper**

Solomon (2011:410) indicates that Tamil Nadu Newsprints Limited (TNPL) produces 400 thousand tonnes of paper per annum from bagasse, and about 25 tonnes of craft paper is produced by smaller companies daily. Mysore Paper Mills Ltd produces 60 thousand tonnes of paper annually from bagasse (Solomon, 2011:410).

Pulp and paper had a market size of US\$ 348.32 billion in 2022 and an estimated market value of US\$ 387.54 billion in 2032 at a CAGR of 1.07% (KR, 2023). The wood segment for raw materials had the most significant market share, but due to digitization, there may be a slump in the pulp and paper industry. This slump, however, will be offset by the requirement for packaging as more consumers are exposed to online shopping platforms that require packaging for their products (KR, 2023).

According to KR (2023), the sanitary segment of the pulp and paper market will experience growth with increased disposable income and personal hygiene awareness in emerging nations.

#### **2.4.14 Fibre and particle boards**

Solomon (2011:410) states that medium-density and high-density fibre boards are manufactured from bagasse in India. Fibre boards are made by binding bagasse fibre with resin. Insulating board is also made from bagasse by treating it with steam or hot water under pressure and serves as an insulation material. The fibre board market size was estimated at US\$ 25.1 billion in 2022 and will grow to US\$ 54.7 billion by 2032 at a CAGR of 8.1% (FMR, 2022).

#### **2.4.15 Corrugated boards**

Corrugated board is used for packaging, and increases in its use are driven by the e-commerce market's need for affordable packaging materials (GVR, 2022d). Solomon (2011:410) explains that bagasse is used to make pulp, which is used to manufacture paper and corrugated board. The corrugated board market share is estimated to grow from US\$ 152.2 billion in 2023 to US\$ 227.8 billion in 2030 at a CAGR of 6.8% (GVR, 2022d).

#### **2.4.16 Furfural and furfuryl alcohol**

Furfural is a liquid chemical of yellow colour which is only produced by processing lignocellulosic biomass. It is also used to produce various non-petroleum-based chemicals (Mamman *et al.*, 2008:449; SHITC, 2023b). It is predominantly used in resin production and accounts for 70% of the market (Mamman *et al.*, 2008:449). Furfural is also used to produce levulinic acid, and the minimum selling price for furfural is \$1000 per tonne, according to the research by Velaga and Peela (2022:3326).

Furfural can also be made with other biomaterial feedstocks, such as timber and maize cobs, to name a few. Furfuryl alcohol, a clear colourless liquid, is produced by further refining furfural. Furfural and furfuryl alcohol are used as base chemicals to manufacture various chemical products. Furfural and furfuryl alcohol are used in multiple industries, such as the agrochemical, pharmaceutical, food and beverage and applications such as the manufacturing of casting resins used in steel casting operations to bind sand moulds (GVR, 2023g; Lowitt, 2020:6). There is also potential to manufacture spandex from tetrahydrofuran a derivative of furfural (Lowitt, 2020:7).

There is a drive to more sustainable businesses focusing on climate change, which plays a significant role in the chemical manufacturing industry. Furfural can be produced from biowaste bagasse at sugar mills, making it more environmentally friendly. Sugar mills are electricity-positive as they produce electricity, making this a very environmentally friendly process.

The furfural market size was valued at US\$ 556.74 million in 2022. It is assumed that the market size will increase to US\$ 954.36 million by 2030 at a CAGR of 7% (GVR, 2023g). The furfuryl alcohol market size was valued at US\$ 472.7 million in 2020. The market is assumed to increase to US\$ 821.6 million by 2028 at a CAGR of 7.2% (GVR, 2021d). The furfural market price fluctuates as it is heavily impacted by Chinese producers (De Jong & Marcotullio, 2010:20).

A search for prices from suppliers of furfural found that the furfural price ranges between US\$ 2500/tonne and US\$ 4000/tonne from Chinese supplier Shandong Hanteng International Trade Co., Ltd for which China has some of the significant suppliers (Hongye Holding Group Corporation and Shandong Crownchem Industries) of furfural globally (Lowitt, 2020:8; SHITC, 2023a). For this study, Furfural's price is taken as the average and calculated as US\$ 3250/tonne.

Currently, in South Africa, Illovo Sugar Limited is the sole furfural producer in the sugar industry. Research was conducted to expand a sugar mill in the Nkomazi area to produce furfural, but this project was cancelled. The project was costed at R 675 million (Lowitt, 2020:3).

#### **2.4.17 Green top leaves and dry trash**

The practice in South Africa is to burn the green top leaves. Burning green top leaves reduces trash whilst processing the sugarcane, affecting the farmer's fee calculation and payments by reducing the cane juice ratio to fibre. Burning also drives away snakes that could harm cane cutters when they manually harvest the cane. As such, this product was not investigated.

#### **2.4.18 Biogas**

Solomon (2011:411) states that biogas can be produced by fermentation of bagasse through inoculation or by adding farm manure and can be used to drive petrol or diesel engines. The biogas generally comprises 60-65% methane, 30-35% carbon dioxide and small quantities of hydrogen. The calorific value of the biogas is in the range of 5500 kcal/m<sup>3</sup> (Solomon, 2011:411). Keerthana Devi *et al.* (2022:2) found that 94% of biogas produced from agricultural waste was produced from sugarcane, making sugarcane the most significant feedstock.

According to GVR (2023e), the global market value of biogas was US\$ 61.72 billion in 2022 and is estimated to grow to US\$ 87.85 billion at a CAGR of 4.3% by 2030. GVR (2023e) found that electricity applications accounted for 30% of the market share as renewable energy made traction. In 2019, roughly 220 million kWh of electricity was produced from livestock operations, whilst 1 billion kWh of electricity was produced from municipal sewage treatment (GVR, 2023e). There is an opportunity for biogas from sugarcane to contribute to the global production.

Furtado *et al.* (2023:1) found that vinasse, a biowaste product from ethanol production, can be used to make biogas for burning in boilers with bagasse, which reduces coal usage and allows the electrical plant to run longer into the off-season. The used case model increased power generation capacity from 200 days to 330 days by extending the lifetime use of bagasse. Note that biogas production would require an ethanol production plant to extract sugarcane vinasse from the ethanol process (Braude & Montmasson-Clair, 2019:20).

Purwanta *et al.* (2022:874) found that commercial sale of biogas was less profitable than using it as fuel in the boilers. It is instead advised that biogas should be used to offset coal use in the boilers. Alfonso-Cardero *et al.* (2021:33) also proved that biogas to electricity was more economically viable than producing biomethane for fuel and energy production.

#### **2.4.19 Levulinic acid**

Levulinic acid is a white crystalline solid soluble in water and ethanol and a platform chemical for developing other chemicals. It has pharmaceutical, pesticide, cosmetic, and food additives applications (GVR, 2023d).

Levulinic acid may have challenges with market penetration in developing countries as the demand in those countries may be low. It will also face opposition to synthetic chemicals already established in those developing countries (GVR, 2023d). However, developed countries face environmental pressure, which may increase the chemical's opportunity and allow market penetration amongst synthetic chemicals (GVR, 2023d).

According to Ghorpade and Hanna (1997:49), levulinic acid has potential uses in plastics, textiles, animal feed, resin and antifreeze, as it is a highly versatile chemical. Aden *et al.* (2004:46) confirmed that levulinic acid is a building block for many chemical processes and products, including fuel, biodiesel additives, polymers, and herbicides.

The minimum selling price for levulinic acid produced from lignocellulosic biomass is \$1011 per tonne, according to the research by Velaga and Peela (2022:3326). However, the current market price ranges between US\$ 3700/tonne and US\$ 50000/tonne (FTC, 2023c). In this study, a price of US\$ 3700/tonne is assumed to be the market price. GVR (2023d) states that the global levulinic acid market was US\$ 80.7 million in 2022 and will rise to US\$ 151.5 million in 2030 at a CAGR of 8.2%.

#### **2.4.20 Glutamic acid**

Glutamic acid is produced from coryneform bacteria, glucose, and molasses through various steps such as fermentation, centrifugation, carbon adsorption, and others (GVR, 2021c).

Glutamic acid has applications in both the food and cosmetics industries and is used to make skin products, makeup and anti-ageing creams (GVR, 2021c; Richard & Margaritis, 2001:3). Johnson *et al.* (2022:9) showed the vital use of  $\alpha$ -glutamic acid in drug delivery systems and antiviral applications.

Wang *et al.* (2019:37502) produced a dual-network hydrogel sunscreen using poly- $\gamma$ -glutamic acid that provided protection against broad UVA and UVB ranges and easily integrated with skin whilst providing good water-resistant capabilities.

The selling price for glutamic acid was US\$3625 per tonne when producing it from lignocellulose in a sugar mill (Özüdoğru *et al.*, 2019:263). However, recent pricing data puts the price in the range of US\$ 2220 per tonne (CA, 2023c). The global glutamic acid market size in 2020 was valued at US\$ 9.54 billion and is estimated to grow to US\$ 17.16 billion by 2028 at a CAGR of 7.6% (GVR, 2021c).

#### **2.4.21 Xylitol**

Xylitol is an artificial sweetener produced from chemical biomass treatment processes (Aden *et al.*, 2004:61). Xylitol has 40% less calories than sugar. It can be supplied in powder or fluid form and is used in the foods and beverages industry as a sweetener for drinks and confectionary products (GVR, 2021b).

The minimum selling price for xylitol is \$3000 per tonne (FTC, 2023b; Özüdoğru *et al.*, 2019:259). The global market for xylitol was valued at US\$ 447.88 million in 2020 and is estimated to grow to US\$ 738.1 million by 2028 at a CAGR of 6.4% (GVR, 2021b).

#### **2.4.22 Animal feed**

Animal feed for sheep, goats and cattle is manufactured by mixing bagasse, molasses and minerals in specific concentrates to produce a balanced feed product (Molatek, 2023; THL, 2023). Molatek (RCL Foods' business) and Voermol (Tongaat Hulett Limited's business) are two major animal feed producers using bagasse and molasses as feedstock. As these businesses are already using bagasse and molasses to create alternative products from sugarcane, this co-product will not be investigated further.

#### **2.4.23 Bioelectricity**

Solomon (2011:411) states that in India, sugar mills provide at least 1900 MW of electricity by burning bagasse in boilers and using the steam to propel turbines to generate electricity. These sugar mills can generate 7000 MW of electricity, potentially supplying 3000 MW to the grid. In South Africa, some sugar mills also provide excess electricity to the grid. As this is already practised in South Africa, this product will not be investigated further.

#### **2.4.24 Succinic acid**

Succinic acid can be either petroleum-based (derived from butane) or biobased (derived from sugars (GVR, 2022c). Biobased succinic acid produces less carbon dioxide than petroleum-based succinic acid. Succinic acid is a raw material in producing polyurethane,

tetrahydrofuran, and other chemically derived products. GVR (2022c) confirmed that the global succinic acid market was valued at US\$ 222.9 million in 2021 and is estimated to grow to US\$ 512.8 million by 2030 at a CAGR of 9.7%. The price for succinic acid was found to be US\$ 1962/tonne in North America, US\$ 1842/tonne for China, US\$ 1872/tonne for South Korea, US\$ 1987/tonne for Italy and US\$ 2007/tonne for the United Kingdom (CA, 2023a).

#### **2.4.25 Carbon dioxide**

Solomon (2011:413) states that carbon dioxide is manufactured during fermentation to produce alcohol. The carbon dioxide yield is 16% of the weight of the molasses, and roughly 70% to 75% is recovered from this process. Carbon dioxide is used in carbonated drinks.

GVR (2023f) states that the global carbon dioxide market was valued at US\$ 10.27 billion in 2022 and is estimated to grow to US\$ 15.46 billion by 2030 at a CAGR of 5.2%.

#### **2.4.26 Sustainable aviation fuel (SAF) from bioethanol**

Bioethanol is ethanol produced from bio-based feedstocks, which are low-carbon alternatives to petroleum-based fuels (RSB, 2020a:9). According to RSB (2020b:2), 20 Mt of sugarcane is produced annually and converted to sugar. 10Mt of sugarcane is processed and satisfies the local demand, and 10Mt is processed and diverted to export.

RSB (2020b:2) proposes that the sugarcane processed for the export market be converted into ethanol, as 1 tonne of sugarcane can be converted to 70l of ethanol, resulting in 700Ml of ethanol production. The current estimated demand for ethanol is 1.8 billion litres in the aviation sector and 600Ml in the road transport sector, which far outweighs what can be produced (RSB, 2020b:2).

MaMR (2022) states that the SAF market will grow from US\$ 219 million in 2021 to US\$ 15.716 million by 2030 at a CAGR of 60.8%. The high CAGR results from the drive to reduce carbon dioxide emissions as SAF produces 80% less than CO<sub>2</sub> than fossil jet fuel.

However, the production cost range for SAF from sugarcane for 2018 was R18.30 per litre – R61.00/litre, compared to the selling price of R7.22/litre. SAF also provides greenhouse (GHG) gas savings, for which carbon tax savings could be offset against the cost of production (RSB, 2020b:7).

Research by Diederichs *et al.* (2016:331) found that producing jet fuel from lignocellulosic biomass, including sugarcane juice and ethanol produced from sugarcane, resulted in the

production of jet fuel of a minimum selling price between two and four times higher than market jet fuel price. In a separate study, Kumar *et al.* (2018:92) confirmed the same pricing range. Considering that the minimum market prices could not be achieved, this product was not investigated further.

#### **2.4.27 Filter cake**

Filter cake use in composting is already implemented on some farms in South Africa. Filter cake is often provided to farmers free of charge as it becomes a waste removal issue for the sugar mills. As such, filter cake is not investigated.

#### **2.4.28 Polylactic acid**

PLA is a biodegradable plastic used in agricultural, textile, pharmaceutical, transport and packaging industries (Alves de Oliveira *et al.*, 2018:220). The drive to reduce greenhouse gasses has also increased the opportunities for using PLA instead of petroleum-based plastics (GVR, 2023h).

A niche application of PLA is the manufacture of 3D-printed medical implants that biodegrade over time as they are not toxic in solid form (Rogers, 2015). The global market for PLA was valued at US\$ 624.97 million in 2022 and is estimated to grow to US\$ 2,772.93 million by 2030 at a CAGR of 21.4% (GVR, 2023h).

PLA was priced at the end of the second quarter at US\$ 3800/tonne in North America, US\$ 2855/tonne in Asia Pacific and US\$ 3985/tonne in Europe (CA, 2023d). For this study, the price is taken as the average of the three at US\$ 3546.67/tonne.

#### **2.4.29 Citric acid**

Citric acid is a flavour enhancer that extends food shelf-life due to its prevention of microbial growth. When it is added to foods, it adds sourness to the flavour. Citric acid is available in powder or liquid form. Citric acid powder accounted for 63.3% of the total market share of US\$ 2.5 billion in 2016 compared to liquid citric acid, with the remainder accounting for 36.7% of the market (GVR, 2018).

Citric acid is often used as an alternative to lemon juice and vinegar in the food and beverage industry. It is also used in industrial applications to reduce and prevent limescale buildup in boilers. Lastly, it is used in water treatment to enhance laundry detergent effectiveness (GVR,

2018). It is envisaged that the market will grow from US\$ 3.52 billion in 2022 to US\$ 5.12 in 2032 at a CAGR of 3.82% (PR, 2023).

Citric Acid was priced at the end of the third quarter of 2023 at US\$ 896/tonne in North America, US\$ 780/tonne in Asia Pacific and US\$ 1240/tonne in Europe (CA, 2023b). This study takes the price as the average of the three at US\$ 972/tonne.

#### **2.4.30 Dextran**

Dextran is used to decrease blood viscosity and to treat hypovolemia. Its use in the pharmaceutical and food and beverages industries is rising. In the food and beverages industry, it is used as a preservative and blending agent; in the pharmaceutical industry, it is used in medicines to treat blood clots (BRI, 2023). In 2021, the global market for dextran was US\$ 203.9 million. The market is estimated to grow to US\$ 328.4 million by 2031 at a CAGR of 4.9% (BRI, 2023).

#### **2.4.31 Acetone**

Acetone is used in personal care products such as nail polish remover and some skin care products. It is also used in paints and coatings, the pharmaceutical industry to produce hand sanitisers and excipient drugs, and it is used to produce Methyl Methacrylate (MMA) and Bisphenol-A (BPA), of which both products are used in the manufacture of resins (GVR, 2023b). The acetone market was valued at US\$ 5.69 billion in 2022 and is estimated to grow to US\$ 10.23 billion in 2030 at a CAGR of 7.6% (GVR, 2023b).

#### **2.4.32 Biocide**

Biocides are used in cosmetics and wipes, cleaning products, disinfectants and detergents, insecticides, antiseptics, fungicides and herbicides (GVR, 2023a). Biocides have, however, in the past lead to public health scares and are thus controlled by using a chemical ranking score to indicate toxicity and characteristics of exposure.

The biocides market size was valued at US\$ 8.5 billion in 2022 and is estimated to grow to US\$ 11.88 billion by 2030 at a CAGR of 4.2%. Biocides are valuable as they are increasingly used to treat bacteria and other microorganisms to enhance food shelf life (GVR, 2023g).

### 2.4.33 Gamma valerolactone

Gamma valerolactone (GVL) is a colourless organic compound used as a fuel and fuel additive (Kapanji *et al.*, 2021). The global GVL market was valued at US\$ 702.17 million in 2022. It is estimated to grow to US\$ 801.99 million by 2028 at a CAGR of 2.24% (RRW, 2023). Reliable pricing information for GVL could not be found. Thus, the price of US\$ 1000/tonne was adopted for this study (Kapanji *et al.*, 2021).

### 2.4.34 Polybutylene succinate

Polybutylene succinate (PBS) is a biodegradable synthetic aliphatic polyester used in food packaging and the pharmaceutical and agricultural industries (GVR, 2022a). PBS is also used to manufacture polyvinyl chloride (PVC), paints, wire and shoes (GVR, 2022a). Ratshoshi *et al.* (2021) have found that PBS can be manufactured from sugarcane using 1G and 2G feedstocks.

PBS' global market share was valued at US\$ 308.24 million in 2022. It is expected to grow to US\$ 1.39 billion in 2030 at a CAGR of 19.7% (GVR, 2022a). The current selling price for PBS is US\$ 4650/tonne (FTC, 2023a). Considering the drive for bioplastics, sustainable packaging and green materials that are less hazardous to the environment, this product is expected to show tremendous growth in the years to come (GVR, 2022a).

### 2.4.35 Explosives such as nitromiel

Although Nitromiel is presented by Solomon (2011:414) as an explosive manufactured from sugarcane, no further literature was found on this topic. For this reason, Nitromiel was not investigated.

### 2.4.36 Summary

Table 3 lists potential co-products from sugarcane identified during the literature survey.

**Table 3: Potential co-products from sugarcane, their historic and estimated future market growth**

Section	Product	Base year	Value (US\$ Million)	Forecast year	Value (US\$ Million)	CAGR
2.4.1	Oxalic acid	2023	960.00	2033	1,550.00	4.9%

Section	Product	Base year	Value (US\$ Million)	Forecast year	Value (US\$ Million)	CAGR
2.4.2	Glycerol	2020	2,400.00	2027	3,700.00	6.4%
2.4.3	Lactic acid	2023	3,370.00	2030	5,800.00	8.0%
2.4.4	Fatty acid esters	2019	2.20	2027	3.13	4.5%
2.4.5	Ether	2020	8,750.00	2025	12,500.00	7.4%
2.4.6	Polydextrose	2015	225.00	2025	387.99	5.6%
2.4.7	Diethyl oxalate	2022	98.86	2032	165.69	4.9%
2.4.8	Potable alcohols (ethanol)	2022	2,500.00	2030	3,200.00	4.3%
2.4.9	Industrial Ethyl alcohol (ethanol)	2019	89,100.00	2019	129,360.00	4.8%
2.4.10	Yeast	2020	11,420.00	2028	32,670.00	14.0%
2.4.11	Monosodium glutamate	2022	4,950.00	2032	8,620.00	5.7%
2.4.12	Ephedrine	Eliminated from investigation				
2.4.13	Pulp and paper	2022	348,320.00	2032	387,540.00	1.1%
2.4.14	Fibre and particle boards	2022	25,100.00	2032	54,700.00	8.1%
2.4.15	Corrugated boards	2023	152,200.00	2030	227,800.00	6.8%
Furfural and furfuryl alcohol2.4.16	Furfural and furfuryl alcohol	2022	556.74	2030	954.36	7.0%
2.4.17	Green top leaves and dry ash	Eliminated from investigation				
2.4.18	Biogas	2022	61,720.00	2030	87,850.00	4.3%
2.4.19	Levulinic acid	2022	80.70	2030	151.50	8.2%
2.4.20	Glutamic acid	2020	9,540.00	2028	17,160.00	7.6%
2.4.21	Xylitol	2020	447.88	2028	738.10	6.4%
2.4.22	Animal feed	Eliminated from investigation				
2.4.23	Bioelectricity	Eliminated from investigation				

Section	Product	Base year	Value (US\$ Million)	Forecast year	Value (US\$ Million)	CAGR
2.4.24	Succinic acid	2021	222.90	2030	512.80	9.7%
2.4.25	Carbon dioxide	2022	10,270.00	2030	15,460.00	5.2%
2.4.26	Sustainable aviation fuel	2021	219.00	2030	15,716.00	60.8%
2.4.27	Filter cake	Eliminated from investigation				
2.4.28	Polylactic acid	2022	624.97	2030	2,772.93	21.4%
2.4.29	Citric acid	2022	3,520.00	2032	5,120.00	3.82%
2.4.30	Dextran	2021	203.90	2031	328.40	4.9%
2.4.31	Acetone	2022	5,690.00	2032	10,230.00	7.60%
2.4.32	Biocide	2022	8,500.00	2030	11,880.00	4.2%
2.4.33	Gamma valerolactone	2022	702.17	2028	801.99	2.24%
2.4.34	PBS	2022	308.42	2030	1,390.00	19.7%
2.4.35	Nitromiel	Eliminated from investigation				

## 2.5 Co-product shortlist

The researcher took the following steps to facilitate product selection from the products listed in section 2.6. Products were ranked based on their estimated future market size from largest to smallest market. After that, a search was conducted for TEAs prepared by others on the various co-products listed in Table 3, considering their feasibility from a technical and economic point of view.

It was found that many techno-economic analyses were carried out by researchers attempting to find viable co-products from sugarcane. Morakile *et al.* (2022:14) conducted a techno-economic assessment on levulinic acid, glutamic acid, and xylitol production from sugarcane. They found that co-production of these chemicals would increase the profitability of sugar mills in South Africa.

Pachón *et al.* (2018:1) conducted a techno-economic assessment of two scenarios compared to a standard sugar mill (baseline scenario): co-production of sugar and lactic acid and co-

production of sugar, lactic acid, and furfural. It was determined that the co-production scenario of sugar, lactic acid and furfural produced the best economic performance compared to the baseline scenario and the lactic acid and sugar co-production scenario (Pachón *et al.*, 2018:1).

In the study, Pachón *et al.* (2018:12) found that the production cost was reduced for all products, and the production costs were \$1926 per tonne for lactic acid and \$1192 per tonne for furfural. Sugar production cost was reduced from \$416 per tonne (baseline scenario) to \$374 (Pachón *et al.*, 2018:12).

Mandegari, Farzad and Görgens (2017:707,709) have also listed various techno-economic analyses conducted by others for biofuels, biochemicals and bio-based monomers and polymers from sugarcane.

There have been many combinations of products, which in turn require different factory configurations, all of which need different investment and operation capital. Some combinations considered are xylitol, citric acid and glutamic acid, as was investigated by Özüdoğru (2018) and Özüdoğru *et al.* (2019). Some other co-product combinations that were found were:

- Furfural and ethanol (Ntimbani *et al.*, 2021)
- Lactic acid and ethanol (Mandegari, Farzad, van Rensburg, *et al.*, 2017)
- Succinic acid (Klein *et al.*, 2017)
- Biogas - (Keerthana Devi *et al.*, 2022:2)

In these TEAs, the researchers investigated different co-production scenarios and implementation processes at the mills. Those co-products without TEAs were eliminated, along with products that were eliminated during the initial investigation into possible co-products. Table 4 presents the co-products that were successfully sifted, including their respective TEA references.

**Table 4: Products and corresponding TEAs found during the literature review**

Section	Product	Base year	Value (US\$ million)	Forecast year	Value (US\$ million)	CAGR	TEA references
2.4.8 and 2.4.9	Ethyl alcohol, including potable alcohols	2019	89,100.00	2019	129,360.00	4.8%	(Gnansounou, Vaskan & Pachon, 2015; Mandegari, Farzad, van Rensburg, <i>et al.</i> , 2017; Moncada <i>et al.</i> ,

Section	Product	Base year	Value (US\$ million)	Forecast year	Value (US\$ million)	CAGR	TEA references
							2013; Ntimbani <i>et al.</i> , 2021; Ramirez <i>et al.</i> , 2018)
2.4.18	Biogas	2022	61,720.00	2030	87,850.00	4.3%	(Alfonso-Cardero <i>et al.</i> , 2021; Furtado <i>et al.</i> , 2023; Keerthana Devi <i>et al.</i> , 2022; Purwanta <i>et al.</i> , 2022)
2.4.20	Glutamic acid	2020	9,540.00	2028	17,160.00	7.6%	(Morakile, 2021; Morakile <i>et al.</i> , 2022; Özüdoğru <i>et al.</i> , 2019)
2.4.3	Lactic acid	2023	3,370.00	2030	5,800.00	8.0%	(Mandegari, Farzad, van Rensburg, <i>et al.</i> , 2017; Morakile <i>et al.</i> , 2022; Pachón <i>et al.</i> , 2018)
2.4.29	Citric acid	2022	3,520.00	2032	5,120.00	3.82%	(Özüdoğru, 2018; Özüdoğru <i>et al.</i> , 2019)
2.4.28	Polylactic acid	2022	624.97	2030	2,772.93	21.4%	(Bressanin <i>et al.</i> , 2022; Ratshoshi <i>et al.</i> , 2021)
2.4.34	Polybutylene Succinate	2022	308.24	2030	1,390.00	19.7%	(Ratshoshi <i>et al.</i> , 2021)
2.4.16	Furfural and furfuryl alcohol	2022	556.74	2030	954.36	7.0%	(Kapanji <i>et al.</i> , 2021; Ntimbani <i>et al.</i> , 2021; Pachón <i>et al.</i> , 2018)
2.4.33	GVL	2022	702.17	2028	801.99	2.24	(Kapanji <i>et al.</i> , 2021)
2.4.21	Xylitol	2020	447.88	2028	738.10	6.4%	(Morakile <i>et al.</i> , 2022; Özüdoğru, 2018; Özüdoğru <i>et al.</i> , 2019)
2.4.24	Succinic acid	2021	222.90	2030	512.80	9.7%	(Klein <i>et al.</i> , 2017; Morakile, 2021)
2.4.19	Levulinic acid	2022	80.70	2030	151.50	8.2%	(Kapanji <i>et al.</i> , 2021; Lopes <i>et al.</i> , 2021; Velaga & Peela, 2022)

It was found that some of the TEAs were for sugar mills in other countries, such as Brazil and Columbia. The TEAs were then sifted again to find those that apply to the South African sugar industry. Although findings from the TEAs of other countries are insightful and provide considerations for future implementation, it was deemed fit to use those for the South African sugar industry only. The reason is that most of these TEAs considered a similar baseline model of a typical South African sugar mill that processes 300 tonnes of sugarcane per hour.

From this elimination process, the selected TEAs presented in Table 5 were considered for product selection and inclusion into the cost-benefit analyses to inform the researcher of the financial implications of expanding a sugar mill to co-produce alternative products.

**Table 5: Selected products and corresponding TEAs for review**

Section	Product	Selected TEA References
2.4.8 and 2.4.9	Ethyl alcohol, including potable alcohols	Mandegari, Farzad, van Rensburg, <i>et al.</i> (2017) Ntimbani <i>et al.</i> (2021)
2.4.18	Biogas	No TEA was selected, and the co-product was eliminated due to a lack of research on a South African sugar mill model.
2.4.20	Glutamic acid	Morakile <i>et al.</i> (2022) Özüdoğru <i>et al.</i> (2019)
2.4.3	Lactic acid	Morakile <i>et al.</i> (2022) Mandegari, Farzad, van Rensburg, <i>et al.</i> (2017) Pachón <i>et al.</i> (2018)
2.4.29	Citric acid	Özüdoğru <i>et al.</i> (2019)
2.4.28	Polylactic acid	Ratshoshi <i>et al.</i> (2021)
2.4.34	Polybutylene Succinate	(Ratshoshi <i>et al.</i> , 2021)
0	Furfural and furfuryl alcohol	Ntimbani <i>et al.</i> (2021) Pachón <i>et al.</i> (2018) (Kapanji <i>et al.</i> , 2021)
2.4.33	GVL	(Kapanji <i>et al.</i> , 2021)
2.4.21	Xylitol	Morakile <i>et al.</i> (2022)

Section	Product	Selected TEA References
		Özüdoğru <i>et al.</i> (2019)
2.4.24	Succinic acid	Morakile (2021)
2.4.19	Levulinic acid	(Kapanji <i>et al.</i> , 2021)

It was found that the sugar mills could provide single or multiple co-products by altering the production processes depending on the desired co-product. However, it was found that each TEA had preferred co-products based on financial analyses conducted by the respective researchers. Each of the investigated TEAs also had different plant configurations. Note that once a configuration was selected, it would not be easily changed after construction. From these TEAs, the proposed co-products were selected for cost-benefit analyses. The internal rate of return, minimum selling price, and net present values were used as selection criteria in these TEAs.

## 2.6 Empirical study: cost-benefit analysis

Additional plant and equipment are required to produce co-products with sugar at an existing sugar mill successfully. As such, any of the existing twelve sugar mills in South Africa would ideally require a significant expansion project to construct and commission a co-product process line. Such an expansion project comes at a high price, as pointed out by Lowitt (2020:3), who in 2020 found that for a furfural plant, a budget estimate of R 675 million was required if it were to be built onto an existing sugar mill.

The question is how to consider the feasibility of such a project given the current economic climate in South Africa and the low appetite for investment in an ailing industry. Orsmond and Cohn (2015:170) highlight that the main aim of a feasibility study is to answer the question “Can it work?”. Nevertheless, what does this look like in the context of this research? Considering that this study has a purely business angle and does not provide technology designs but instead uses TEAs by others as a platform from which to springboard.

The answer rests in cost-benefit analyses, which make use of different tools such as the hurdle rate (HR), return on investment (ROI), internal rate of return (IRR), net present value (NPV), profitability index (PI), payback period (PP), sensitivity analysis and the discounted payback

period (DPP) (Linn, 2010:32,35; 2011:68-70). As part of this study, the feasibility study will be implemented as a cost-benefit analysis using the NPV, IRR, PI, and sensitivity analysis.

### 2.6.1 NPV

The NPV is a measure of profitability and the size of profits used in evaluating projects (Brigham *et al.*, 2019:288). It measures the increase in wealth an investor will gain if an investment is made. This is done by subtracting the investment amount from the sum of all the estimated future cash flows that have been discounted at a discount rate, including an estimation of inflation built into the discount rate (Brigham *et al.*, 2019:290).

Note that the NPV assumes the investment is made immediately, once off and considers a single project as standalone and not because of the successful completion of another project. It does not consider market reactions or those of competitors or abandoning a project. All risk is assumed to be included in the discount rate (Brigham *et al.*, 2019:290). The discount rate represents the minimum required rate of return by shareholders for the specific project (Smart *et al.*, 2010:239).

The formula for NPV is given as (Linn, 2011:69):

$$NPV = \sum_{t=1}^n \frac{CF_t}{(1+r)^t} - CF_0$$

Where  $NPV$  is the net present value,  $r$  is the discount rate,  $CF_0$  is the initial investment made at project inception,  $CF_t$  is the cash flow for the period  $t$ , and  $n$  is the number of periods.

It can be deduced from the formula that a positive NPV indicates growth in the investment. In contrast, a negative NPV indicates that returns are less than the investment required at the discount rate to make it profitable.

### 2.6.2 IRR

The IRR is the discount rate that ultimately provides an NPV of 0, indicating the highest discount rate that can be charged before the project becomes unprofitable (Brigham *et al.*, 2019:290).

Considering the formula for NPV and setting the NPV to 0 (Linn, 2010:33),

$$\sum_{t=1}^n \frac{CF_t}{(1 + IRR)^t} - CF_0 = 0$$

Where IRR is the internal rate of return,  $CF_0$  is the initial investment made at project inception,  $CF_t$  is the cash flow for the period  $t$ , and  $n$  is the number of periods.

### 2.6.3 PI

The profitability index indicates the profit per one unit of currency of the initial cost of a project (Brigham *et al.*, 2019:292). The formula is given as (Brigham *et al.*, 2019:292),

$$PI = \frac{CF_0 + NPV}{CF_0}$$

Where  $PI$  is the profitability index,  $NPV$  is the net present value, and  $CF_0$  is the initial investment made at project inception.

### 2.6.4 Sensitivity analysis

Sensitivity analysis is essential to determine the risk involved with a change in any of the variables affecting a project (Linn, 2010:35). As an example, the price of a co-product may increase or decrease, ultimately affecting the NPV, PI, and IRR which may alter a decision to initiate or cancel the kick-off of a specific project.

### 2.6.5 Other economics factors

Other economic factors that must be considered are the present value of money and the effect of inflation. To determine the present value of estimated values in the past, one must calculate the future value discounted against the inflation rate.

#### 2.6.5.1 Future value

The formula for future value is (Brigham *et al.*, 2019:114)

$$FV_n = CF_0(1 + i)^n$$

Where  $FV_n$  is the future value at point  $n$  in time,  $i$  is the interest rate, and  $CF_0$  is the initial investment made at project inception.

### 2.6.5.2 Inflation rate

The South African inflation rate is given in Table 6 for the years 2010 through 2022.

**Table 6: Annual South African inflation rates, 2010 through 2022 (MT, 2023)**

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Inflation	4.09%	5.00%	5.72%	5.78%	6.13%	4.54%	6.57%	5.18%	4.52%	4.12%	3.21%	4.61%	7.04%

Monthly inflation is given for 2023 for January 2023 through September 2023 in Table 7. Future inflation is considered the average of 6.04%.

**Table 7: Monthly inflation rates for January 2023 through September 2023 (StatsSA, 2023a)**

Month	January	February	March	April	May	June	July	August	September	Average
Interest	6.90%	7.00%	7.10%	6.80%	6.30%	5.40%	4.70%	4.80%	5.40%	6.04%

### 2.6.5.3 Construction inflation rate

The construction inflation indicating the increase in construction costs is presented for September 2018 to September 2023 in Table 8. Earlier years were not available. Construction inflation before 2018 is taken as the average of 7.1%, as presented in Table 8.

**Table 8: Construction inflation rates (StatsSA, 2023b)**

Year	2018	2019	2020	2021	2022	2023	Average
Inflation	5.8%	4.8%	-0.2%	14.9%	11.2%	6.10%	7.1%

### 2.6.5.4 Investment deposit rates

The best fixed-term investment rate currently available is 11.25% over a five-year fixed term (Walter, 2023).

#### **2.6.5.5 Risk-free rate**

The risk-free rate is the rate of return for an investment with zero risk over a specific period for which investors will obtain a return (Burger, 2012:95). The risk-free rate for a ten-year South African Government Bond is 8.25% with a 10.66% yield as at 29 October 2023 (WGB, 2023).

#### **2.6.5.6 Producer price index**

The producer price index (PPI) indicates the increase in selling price for producers of various products. This PPI is calculated considering many different products and pricing information provided by producers. One of these categories of products is chemical products. For chemical products, the year-on-year index increase from September 2020 to September 2021 was 8.2%; for September 2021 to September 2022, it was 20.5%; for September 2022 to September 2023, it was 4.9% (StatsSA, 2023c).

Given that the economy is still recovering from the damage caused by the COVID-19 pandemic and that these changes in indexes do not indicate a trend, a fair estimate of annual chemical price increase is considered 5%.

#### **2.6.6 Cost-benefit analysis process**

A CBA was conducted using Microsoft Excel with input variables from TEAs conducted by others applied to a baseline model. Cash flows were calculated for use in NPV, IRR and PI calculations. A sensitivity analysis was also conducted. The steps that were taken during the CBA are listed here:

Step 1: Determine the present value of the product scenario's total required capital investment (TCI) under investigation. This was done by calculating the future value of the TCI from the base financial costing year wherein the original financial study by others was conducted. The final TCI used in this study for each scenario was based on the future value applied at a construction inflation rate discussed in section 2.6.5.3. The TCI in this study was then taken in the year 2023. The construction inflation rate was used as it gave a good indication of the increase in construction costs in recent years.

Step 2: Calculate the fixed operating costs (FOC) and variable operating costs (VOC) for these production facilities over the project life span commencing in 2026. Note that 2026 is estimated to be the first production year. This was done by calculating the future value of the FOC at the inflation rate, assuming salaries would be maintained at least at the inflation rate. The VOC

was calculated similarly using inflation and adding a 2% arbitrary risk premium to allow for increases in materials and chemicals required in these processes. A similar approach was taken for studies that combined FOC and VOC as the total cost of production (TCOP). To calculate TCOP, the inflation rate was used, adding a 2% arbitrary risk premium.

Step 3: Calculate the product sales values for 2026 and onwards by multiplying the annual production hours with the production rate and the selling price per unit mass of the product. The selling price increases yearly at a producer price inflation rate discussed in section 2.6.5.6.

Note that no sales were made in the project's first three years (2023-2025), but that sales are only realized from the fourth year (2026) at 50%, 75% in the fifth year and 100% from the sixth year onwards.

Step 4: Calculate the electricity sales if included in the original model. This was done by using the original electricity price of US\$ 0.08/kWh assumed by Mandegari, Farzad, van Rensburg, *et al.* (2017) and calculating the future value of each year at the inflation rate. After that, each yearly price is multiplied by the annual power produced for that year.

Step 5: Add all the sales items to obtain final sales.

Step 6: Subtract the construction costs for the first three years at 10% of the project value for the first year, 60% in the second year, and 30% in the third year. From the fourth year, subtract the operational FOC and VOC costs.

Step 7: Once all the costs and sales are determined, calculate the net cash flow by subtracting costs from sales over the project life.

Step 8: Deduct 28% tax from the net cash flow and obtain the total net cash flow after tax.

Step 9: Calculate the NPV with a 12% discount rate. As the discount rate represents the opportunity cost for shareholders, consideration was made to use the risk-free return rate, the government bond yield, and the fixed deposit return as possible guide rates. It was decided to use 12% as this rate is higher than a ten-year government bond yield of 10.66% and the return rate of a fixed deposit over five years of 11.25% (Walter, 2023; WGB, 2023). The IRR and PI were then calculated.

Step 10: Once the preceding nine steps were completed, selecting the three best-performing scenarios with their respective co-products with the greatest IRR and NPV values were made.

After that, these three scenarios and products were subjected to a sensitivity analysis. The sensitivity analysis considers changes in product pricing.

Note that the specific scenarios are not discussed in detail pertaining to the technical set up and plant required. This study only considers the financial application and requirements. Reviewing the respective TEAs discussed in this study for technical details on the different plant configurations and installation is recommended.

### **2.6.7 Baseline model**

For the CBAs conducted in this research, assumptions were made to enable a like-for-like measurement of the economic measures of the co-products under investigation. Some assumptions and variables were copied from other investigations and are referenced accordingly.

Annual production hours are considered from 16 March until 30 November. 5% of the lost time available was included in this calculation for unplanned breakdowns, and allowance was made for eight hours of planned maintenance biweekly on maintenance stop days.

Production hours =  $(260 \text{ days} \times 24 \text{ hours}) \times 95\% - (8 \text{ hours} \times 37 \text{ weeks})/2 = 5780 \text{ hours}$

The proposed financing of the project is employing 100% equity. The design and construction duration was assumed as three years. No sales are made during construction, but the construction cash outflows are 10% in the first year, followed by 60% in the second year and the final 30% in the third year. A startup duration of two years was assumed with a production capacity of 50% in the fourth year of the project, 75% in the fifth year and 100% from the sixth year and onwards. The income tax rate was 28%, and historic inflation rates were used, as presented in section 2.6.5.2. The future inflation rate was 6.04%, as calculated in section 2.6.5.2. An acceptable IRR is 9.7% (Mandegari, Farzad, van Rensburg, *et al.*, 2017).

Selling prices for investigated products are presented in sections 2.4 and 2.6.8. Initially, the electricity selling price was US\$ 0.08/kWh, but for this study, it increased yearly with inflation, as calculated in section 2.6.5.2 (Mandegari, Farzad, van Rensburg, *et al.*, 2017).

The project is assumed to be a 25-year project. The project is assumed to kick off in September 2023 and will be complete by September 2048. Due to construction, the first production year is estimated to be 2026.

### 2.6.8 Model application and CBA

In this section, the baseline model and the variables obtained from the selected TEAs are subjected to the steps set out in section 2.6.6. Each of the selected TEAs, products under review and scenarios are discussed with its input variables and specific outputs obtained from the CBA. The input variables are presented in tables, followed by the output values in tables. The tables indicating outputs show the TCI in 2023, costs and sales for 2026 and 2048, which are the project's first and last production years. Note that all cash flows were calculated for the duration of the project. It is, however, deemed impractical to present all these cash flows for the various tested scenarios. The output tables also include the investigated scenarios' NPV, IRR and PI.

The TEA by Mandegari, Farzad, van Rensburg, *et al.* (2017) considered the production of ethanol, electricity and lactic acid in four scenarios, namely: scenario 1 – ethanol from slurry; scenario 2 – lactic acid from slurry; scenario 3 - ethanol from cellulose, lactic acid from hemicellulose; and scenario 4 - lactic acid from cellulose, ethanol from hemicellulose.

Mandegari, Farzad, van Rensburg, *et al.* (2017) found that scenario 2 had the best IRR of 31.1% as compared to IRRs of scenario 1 (10%), scenario 3 (14.2%) and scenario 4 (25.4%).

Mandegari, Farzad, van Rensburg, *et al.* (2017) also considered electricity sales in their assessment. The lactic acid price was taken as US\$ 1450/tonne, and the ethanol price was US\$ 765/tonne, whilst electricity was sold for US\$ 0.08/kWh (Mandegari, Farzad, van Rensburg, *et al.*, 2017:1,7). The costing year was 2015 and required FV calculations to calculate the present values of the products and operating costs for the project's duration.

Table 9 lists the input variables used in this study, namely, total capital investment (TCI), variable operating cost (VOC), fixed operating cost (FOC) and the product production rates as obtained in the study of Mandegari, Farzad, van Rensburg, *et al.* (2017:11).

**Table 9: Input variables obtained from the study by Mandegari, Farzad, van Rensburg, *et al.* (2017:11)**

Descriptor	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cost year: 2015	Ethanol from slurry	Lactic acid from slurry	Ethanol from cellulose, lactic acid from hemicellulose	Lactic acid from cellulose, ethanol from hemicellulose
TCI (US\$ million)	280.8	377.9	330.9	369.9
VOC (US\$ million/year)	11	21.2	13.3	18.3
FOC (US\$ million/year)	6.6	8.9	8.1	8.9
Ethanol production (t/hour)	11	0	7.48	2.02
Lactic acid production (t/hour)	0	19.22	4.65	14.42
Electricity production (MWh/hour)	7.1	7.41	4.63	6.48

Table 10 presents the TCI as calculated for 2023. It also provides the VOC, FOC and sales for 2026 and 2048, respectively. Lastly, it provides the NPV, IRR and PI calculated during the CBA. Scenario 2 produced the greatest NPV of US\$ 220.04 million and the best IRR at 15% compared to the other scenarios. It also has a favourable PI of 4.38. As such, lactic acid production is selected above the other product scenarios.

However, considering product price volatility, a multiple-product process may be attractive, highlighting scenario 4 with an NPV of US\$ 52.55 million, an IRR of 13% and a PI of 1.83 as an option.

These findings align with those of Mandegari, Farzad, van Rensburg, *et al.* (2017), who found that scenario 2 and scenario 4 were the best performers. Note that scenario 1 and scenario 3 are not considered feasible due to the negative NPV. This is mainly attributed to the ethanol price being almost the same as this study used US\$ 766.73/tonne. Mandegari, Farzad, van Rensburg, *et al.* (2017) used US\$ 765/tonne. However, the production costs and the TCI required are much higher than presented in the study by Mandegari, Farzad, van Rensburg, *et al.* (2017). This was due to the high construction inflation rate.

**Table 10: Results obtained from the CBA using the base model for ethanol, lactic acid and electricity production**

Descriptor	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	<b>Ethanol from slurry</b>	<b>Lactic acid from slurry</b>	<b>Ethanol from cellulose, lactic acid from hemicellulose</b>	<b>Lactic acid from cellulose, ethanol from hemicellulose</b>
<b>TCI (US\$ million) in 2023</b>	483.16	551.13	482.58	539.46
<b>Costs in 2026</b>				
<b>VOC (US\$ million/year)</b>	24.12	46.48	29.16	40.12
<b>FOC (US\$ million/year)</b>	11.77	15.87	14.44	15.87
<b>Sales 2026</b>				
<b>Ethanol sales (US\$ million/year)</b>	30.46	0	20.7	5.59
<b>Lactic acid sales (US\$ million/year)</b>	0	82.82	20.02	62.12
<b>Electricity sales (US\$ million/year)</b>	3.91	4.08	2.55	3.57
<b>Costs 2048</b>				
<b>VOC (US\$ million/year)</b>	132.30	254.97	159.96	220.09
<b>FOC (US\$ million/year)</b>	42.79	57.71	52.52	57.71
<b>Sales 2048</b>				
<b>Ethanol sales (US\$ million/year)</b>	311.48	0	211.71	57.19
<b>Lactic acid sales (US\$ million/year)</b>	0	847.04	204.76	635.35
<b>Electricity sales (US\$ million/year)</b>	14.24	14.86	9.28	13
<b>NPV (US\$ million)</b>	-214.21	220.04	-203.73	52.55
<b>IRR</b>	n/a	15%	n/a	13%
<b>PI</b>	n/a	4.38	n/a	1.83

Ntimbani *et al.* (2021:1) investigated seven scenarios to produce furfural and ethanol from bagasse and harvest residues, which were all energy self-sufficient, producing electricity as well. Scenario 1 was to produce furfural only, and scenario 2 was to produce ethanol only. Scenarios 3 through 7 were to produce both ethanol and furfural at varying operating conditions. Ntimbani *et al.* (2021:5) used a selling price of US\$ 0.08/kWh for electricity, US\$ 2200/tonne for furfural and US\$ 0.596/litre for ethanol.

The IRRs that were obtained in their study are 12.92% for scenario 1, 10.18% for scenario 2, 3.64% for scenario 3, 7.19% for scenario 4, 12.78% for scenario 5, 8.64% for scenario 6, 10.54% for scenario 7 (Ntimbani *et al.*, 2021:7). The cost year was 2018. Note that each

scenario also produced electricity for sale to the grid. Table 11 lists the various scenarios and input values for each product and scenario under investigation.

**Table 11: Input variables obtained from the study by Ntimbani *et al.* (2021)**

Descriptor	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Cost year: 2018	Furfural only	Ethanol Only	Ethanol and Furfural	Ethanol and Furfural	Ethanol and Furfural	Ethanol and Furfural	Ethanol and Furfural
TCI (US\$ million)	272	294	327	306	305	305	322
TCOP (US\$ million/year)	13.7	18.12	18.37	18.17	18.57	18.17	18.89
Ethanol production (t/hour)	0	11.18	4.2	4.11	2.45	5.17	1.65
Furfural production (t/hour)	3.8	0	0.69	1.53	3.75	1.56	3.45
Electricity production (MWh/hour)	23.37	14.57	22.07	20.87	21.63	20.23	23.66

Table 12 presents the TCI as calculated for 2023. It also provides the TCOP and sales for 2026 and 2048, respectively. Lastly, it provides the NPV, IRR and PI calculated during the CBA.

Scenario 1, which is for furfural production only, had the greatest NPV of US\$ 227.09 million and an IRR of 18%. Scenario 5 had the second-best NPV of US\$ 202.78 million and an IRR of 17%, followed by scenario 7, with an NPV of 98.18 and an IRR of 14%. Note that the PI of scenario 5 is 5.69 compared to the PI of scenario one, which is 2.8.

Considering the close IRR and NPV values and that scenario five is for multi-product production, which could respond better to fluctuating product prices, it may be a better solution. However, scenario one is selected as the best option for furfural production for this study based on its superior NPV and IRR values. The scenarios tested in this study matched the ranking of those in the study by Ntimbani *et al.* (2021).

Scenarios 2, 3, 4 and 6 produced negative NPVs and were thus eliminated. The negative NPS values are attributed to the weak ethanol price corresponding to this study, the increased operating costs and the TCI required if this project started in 2023.

**Table 12: Results obtained from the CBA using the base model for ethanol, furfural and electricity production**

Descriptor	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
	Furfural only	Ethanol Only	Ethanol and Furfural	Ethanol and Furfural	Ethanol and Furfural	Ethanol and Furfural	Ethanol and Furfural
<b>TCI (US\$ million) in 2023</b>	385.66	416.85	463.64	433.86	432.45	432.45	456.55
<b>Costs in 2026</b>							
<b>TCOP (US\$ million/year)</b>	24.23	32.05	32.49	32.14	32.84	32.14	33.41
<b>Sales 2026</b>							
<b>Ethanol sales (US\$ million/year)</b>	0	30.96	11.63	11.37	6.79	14.3	4.57
<b>Furfural sales (US\$ million/year)</b>	44.63	0	8.10	17.92	44.05	18.3	40.53
<b>Electricity sales (US\$ million/year)</b>	12.89	8.03	12.17	11.51	11.93	11.16	13.05
<b>Costs 2048</b>							
<b>TCOP (US\$ million/year)</b>	132.93	175.82	178.24	176.30	180.18	176.30	183.29
<b>Sales 2048</b>							
<b>Ethanol sales (US\$ million/year)</b>	0	316.64	118.99	116.3	69.42	146.29	46.71
<b>Furfural sales (US\$ million/year)</b>	456.5	0	82.8	183.25	450.5	187.21	414.5
<b>Electricity sales (US\$ million/year)</b>	46.87	29.22	44.26	41.85	43.38	40.57	47.45
<b>NPV (US\$ million)</b>	227.09	-103.83	-289.27	-120.68	202.78	-71.8	98.18
<b>IRR</b>	18%	n/a	n/a	n/a	17%	n/a	14%
<b>PI</b>	2.8	n/a	n/a	n/a	5.69	n/a	3.15

Morakile *et al.* (2022:1) investigated six biorefineries for producing levulinic acid, glutamic acid and xylitol. Different combinations of these products were considered for simultaneous production. The six scenarios that were investigated are scenario 1 – glutamic acid only from 1G feedstock, scenario 2 - levulinic acid only from 1G feedstock, scenario 3 – glutamic acid from 1G and 2G feedstock, scenario 4 – levulinic acid from 1G and 2G feedstock, scenario 5 – glutamic acid and xylitol from 1G and 2G feedstock and scenario 6 – levulinic acid and xylitol from 1G and 2G feedstock.

The product prices used in their study were for glutamic acid, US\$ 3600/tonne; levulinic acid, US\$ 2750/tonne; and Xylitol, US\$ 3900/tonne. Scenario 1 (glutamic acid from 1G) performed

the best with an IRR of 59.78%, followed by scenario 3 (glutamic acid from 1G and 2G feedstock) with an IRR of 36.37% and scenario 5 (glutamic acid and xylitol) with an IRR of 35.06% (Morakile *et al.*, 2022:9).

**Table 13: Input variables obtained from the study by Morakile *et al.* (2022:1) Morakile *et al.* (2022:1)**

Descriptor	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Cost year: 2018	1G Glutamic acid only	1G Levulinic acid only	1G2G Glutamic acid only	1G2G Levulinic acid only	1G2G Glutamic acid and xylitol	1G2G Levulinic acid and xylitol
TCI (US\$ million)	144.48	113.1	715.17	470.5	711.62	451.4
TCOP (US\$ million/year)	54.6	43	115.3	110.2	137.53	127.3
Glutamic acid production (t/hour)	11.1	0	26.1	0	21.4	0
Levulinic acid production (t/hour)	0	7.2	0	18.5	0	4.2
Xylitol production (t/hour)	0	0	0	0	6.4	11.1
Electricity production (MWh/hour)	0	0	12.2	12.2	12.4	18.6

Results for the CBA are presented in Table 14 and indicate that scenario 2 (IRR of 37%) for levulinic acid only from 1G feedstock, scenario 4 (IRR of 29%) for levulinic acid only from 1g and 2G feedstock and scenario 1 (IRR of 25%) for glutamic acid only from 1G feedstock ranked as the top three options for production. This is in contrast with the findings by Morakile *et al.* (2022:1), as the levulinic acid scenarios generally performed better.

This contrast is attributed to the changes in prices. In this study, glutamic acid was US\$2200/tonne compared to US\$ 3600/tonne in the study by Morakile *et al.* (2022:1). The decreased price reduced the product earning potential. Similarly, this study used a higher levulinic acid price of US\$ 3700/tonne than US\$ 2750/tonne. This resulted in the more robust performance of the levulinic acid scenarios. The price for xylitol used in this study (US\$ 3000/ton) is lower than that used by Morakile *et al.* (2022:1), which was US\$ 3900/tonne. The reduced xylitol price did not enhance the performance of the xylitol scenarios.

**Table 14: Results obtained from the CBA using the base model for glutamic acid, levulinic acid, xylitol, and electricity production**

Descriptor	Scenario 1 1G Glutamic acid only	Scenario 2 1G Levulinic acid only	Scenario 3 1G2G Glutamic acid only	Scenario 4 1G2G Levulinic acid only	Scenario 5 1G2G Glutamic acid and xylitol	Scenario 6 1G2G Levulinic acid and xylitol
TCI (US\$ million) in 2023	204.85	160.36	1014.01	667.10	1008.97	640.02
<b>Costs in 2026</b>						
TCOP (US\$ million/year)	96.57	76.05	203.93	194.91	243.25	22.15
<b>Sales 2026</b>						
Glutamic acid (US\$ million/year)	88.97	0	209.19	0	171.52	0
Levulinic acid sales (US\$ million/year)	0	96.18	0	247.13	0	96.18
Xylitol sales (US\$ million/year)	0	0	0	0	33.26	57.68
Electricity sales (US\$ million/year)	0	0	6.73	6.73	6.84	10.26
<b>Costs 2048</b>						
TCOP (US\$ million/year)	529.78	417.22	1118.74	1069.26	1334.44	1235.18
<b>Sales 2048</b>						
Glutamic acid (US\$ million/year)	909.91	0	2139.51	0	1754.23	0
Levulinic acid sales (US\$ million/year)	0	983.68	0	2527.52	0	983.68
Xylitol sales (US\$ million/year)	0	0	0	0	1739.56	3017.05
Electricity sales (US\$ million/year)	0	0	24.47	24.47	24.87	37.3
NPV (US\$ million)	374.71	689.98	650.67	1600.23	924.61	1132.45
IRR	25%	37%	18%	29%	18%	21%
PI	19.29	44.03	7.42	24.99	10.16	18.69

Özüdoğru *et al.* (2019:259) conducted TEAs for three scenarios: scenario 1 – xylitol with electricity, scenario 2 – citric acid with electricity, and scenario 3 – glutamic acid with electricity. Scenario 3 performed the best, with an IRR of 31.5% and a glutamic acid selling price of US\$ 3625/tonne. Scenario 1 followed with an IRR of 12.3% and a xylitol selling price of US\$ 3000/tonne. Scenario 2 was eliminated as it had a negative NPV at a citric acid selling price

of US\$ 680/tonne. Table 15 presents the input values obtained from the study by Özüdoğru *et al.* (2019:264).

**Table 15: Input variables obtained from the study by Özüdoğru *et al.* (2019:264)**

Descriptor	Scenario 1	Scenario 2	Scenario 3
Cost year: 2016	Xylitol only	Citric acid only	Glutamic acid only
TCI (US\$ million)	220.1	351.6	421.9
TCOP (US\$ million/year)	79.3	60	109.1
Glutamic acid production (t/hour)	0	0	12.6
Citric acid production (t/hour)	0	14.9	0
Xylitol production (t/hour)	5.8	0	0
Electricity production (MWh/hour)	2.3	7.97	11.42

When applying the input variables used by Özüdoğru *et al.* (2019:264) to the model in this study, it was found that none of the scenarios was feasible as they all produced negative NPVs, as shown in Table 16. This performance is attributed to the higher TCIs required in the year 2023 as compared to the original TCIs in 2016.

The glutamic acid prices used in this study also reduced the product viability due to the reduction in glutamic acid price (US\$ 3625/tonne to US\$ 2200/ton). Although xylitol remained at US\$ 3000/tonne for both products, the sales did not outperform the costs in the project life. Although the citric acid price increased in this study to US\$ 972/tonne from US\$ 680/tonne, sales could not outperform costs.

**Table 16: Results obtained from the CBA using the base model for xylitol, citric acid, glutamic acid, and electricity production**

Descriptor	Scenario 1	Scenario 2	Scenario 3
	<b>Xylitol only</b>	<b>Citric acid only</b>	<b>Glutamic acid only</b>
<b>TCI (US\$ million) in 2023</b>	353.61	564.88	677.82
<b>Costs in 2026</b>			
<b>TCOP (US\$ million/year)</b>	160.13	121.16	220.30
<b>Sales 2026</b>			
<b>Glutamic acid (US\$ million/year)</b>	0	0	100.99
<b>Citric acid sales (US\$ million/year)</b>	0	52.29	0
<b>Xylitol sales (US\$ million/year)</b>	30.14	0	0
<b>Electricity sales (US\$ million/year)</b>	1.27	4.39	6.29
<b>Costs 2048</b>			
<b>TCOP (US\$ million/year)</b>	254.73	664.66	1208.57
<b>Sales 2048</b>			
<b>Glutamic acid (US\$ million/year)</b>	0	0	1032.87
<b>Citric acid sales (US\$ million/year)</b>	0	534.78	0
<b>Xylitol sales (US\$ million/year)</b>	1576.48	0	0
<b>Electricity sales (US\$ million/year)</b>	4.62	15.98	6.29
<b>NPV (US\$ million)</b>	-558.34	-664.11	-824.46
<b>IRR</b>	n/a	n/a	n/a
<b>PI</b>	n/a	n/a	n/a

Pachón *et al.* (2018:1) conducted a study for two coproduction scenarios with sugar, scenario 1 – lactic acid and scenario 2 - lactic acid and furfural. Electricity was also considered in both coproduction scenarios. Scenario 2 performed better between the two scenarios, with an NPV of US\$ 158.76 million compared to the NPV of scenario 1, which is US\$ 131.81 million. The furfural and lactic acid prices were US\$ 1200/tonne and US\$ 2000/tonne, respectively (Pachón *et al.*, 2018:9).

**Table 17: Input variables obtained from the study by Pachón *et al.* (2018:9)**

Descriptor	Scenario 1	Scenario 2
<b>Cost year: 2010</b>	<b>Lactic acid</b>	<b>Lactic acid and furfural</b>
<b>TCI (US\$ million)</b>	509.71	568.62
<b>VOC (US\$ million/year)</b>	45.88	36.98
<b>FOC (US\$ million/year)</b>	9.31	10.46
<b>Furfural production (t/hour)</b>	0	2.5
<b>Lactic acid production (t/hour)</b>	7.7	6.4
<b>Electricity production (MWh/hour)</b>	3.64	2.15

When applying the input values to the model in this study, the NPVs for both scenarios returned negative values, indicating that these scenarios are not feasible. This is attributed to the high TCI in 2023 instead of the TCI calculated initially for 2010. Note that the price for furfural in this study was US\$ 3250/tonne and for lactic acid was US\$ 1193.33. The lower lactic acid price and higher TCI and operating costs in the production years reduced the feasibility of scenarios. The increased furfural price did not enhance the feasibility of scenario 2 as it was the least produced product in the product mix.

**Table 18: Results obtained from the CBA using the base model for lactic acid, furfural, and electricity production**

Descriptor	Scenario 1	Scenario 2
	Lactic acid	Lactic acid and furfural
<b>TCI (US\$ million) in 2023</b>	1235.85	1378.70
<b>Costs in 2026</b>		
<b>VOC (US\$ million/year)</b>	143.95	116.03
<b>FOC (US\$ million/year)</b>	21.61	24.30
<b>Sales 2026</b>		
<b>Furfural sales (US\$ million/year)</b>	0	29.33
<b>Lactic acid sales (US\$ million/year)</b>	33.17	27.57
<b>Electricity sales (US\$ million/year)</b>	2.01	1.19
<b>Costs 2048</b>		
<b>VOC (US\$ million/year)</b>	789.69	636.56
<b>FOC (US\$ million/year)</b>	78.61	88.38
<b>Sales 2048</b>		
<b>Furfural sales (US\$ million/year)</b>	0	300.02
<b>Lactic acid sales (US\$ million/year)</b>	339.29	282.01
<b>Electricity sales (US\$ million/year)</b>	7.3	4.32
<b>NPV (US\$ million)</b>	-1891.1	-1454.25
<b>IRR</b>	n/a	n/a
<b>PI</b>	n/a	n/a

Ratshoshi *et al.* (2021:1871) conducted a study of six scenarios to produce PLA and PBS from different configurations of feedstock. These scenarios are scenario 1 – PLA from 1G feedstock, scenario 2 – PLA from 2G feedstock, scenario 3 – PLA from 1G2G feedstock, scenario 4 – PBS from 1G feedstock, scenario 5 – PBS from 2G feedstock, scenario 6 – PBS from 1G2G feedstock.

Ratshoshi *et al.* (2021:1882) used the minimum selling price (MSP) that would ensure a viable solution as a measure. The MSP for scenario 3 was US\$ 2965/tonne and produced the best option for PLA production. The MSP for Scenario 4 was US\$ 2980/tonne and was the best price for PBS, ultimately coming second in the analysis. Ratshoshi *et al.* (2021:1871) did not

indicate electricity sales in their study. Table 19 presents the input variables from Ratshoshi *et al.* (2021:1882) used in this study.

**Table 19: Input variables obtained from the study by Ratshoshi *et al.* (2021:1871)**

Descriptor	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Cost year: 2018	1G PLA	2G PLA	1G2G PLA	1G PBS	2G PBS	1G2G PBS
TCI (US\$ million)	361	524.3	590.9	309.8	456.4	420.9
TCOP (US\$ million/year)	74.33	63.64	101.28	65.112	52.08	45.15
PLA production (t/hour)	10	10.3	16.80	0	0	0
PBS production (t/hour)	0	0	0	9.5	4.5	8.4

Table 20 presents the results obtained using the input variables extracted from the study by Ratshoshi *et al.* (2021:1871) into the baseline model and conducting the CBA. Scenario 4 (IRR of 29%), scenario 6 (IRR of 24%), and scenario 3 (IRR of 22%) were the best-performing scenarios. Scenario 4 is the optimal scenario for this study as it has the highest IRR. The prices used in this study for PLA and PBS are US\$ 3546.67/tonne and US\$ 4650/tonne, respectively.

**Table 20: Results obtained from the CBA using the base model for PLA and PBS production**

Descriptor	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
	1G PLA	2G PLA	1G2G PLA	1G PBS	2G PBS	1G2G PBS
<b>TCI (US\$ million) in 2023</b>	511.85	743.38	837.81	439.25	647.11	596.78
<b>Costs in 2026</b>						
<b>TCOP (US\$ million/year)</b>	131.47	112.56	179.13	115.16	92.11	79.85
<b>Sales 2026</b>						
<b>PLA (US\$ million/year)</b>	128.05	131.89	215.12	0	0	0
<b>PBS sales (US\$ million/year)</b>	0	0	0	159.49	75.55	141.02
<b>Costs 2048</b>						
<b>TCOP (US\$ million/year)</b>	721.22	617.51	982.70	631.78	505.33	438.07
<b>Sales 2048</b>						
<b>PLA (US\$ million/year)</b>	1309.61	1348.90	2200.14	0	0	0
<b>PBS sales (US\$ million/year)</b>	0	0	0	1631.16	772.66	1442.29
<b>NPV (US\$ million)</b>	410.88	420.63	1050.34	1081.89	-178.30	953.71
<b>IRR</b>	19%	17%	22%	29%	n/a	24%
<b>PI</b>	9.03	6.66	13.54	25.63	n/a	16.98

Kapanji *et al.* (2021:1) analysed two scenarios: scenario 1 – levulinic acid and furfural and scenario 2 - levulinic acid, furfural and gamma valerolactone (GVL). Electricity sales were also considered in these scenarios. In their scenario 1 the price for furfural was taken as US\$ 1207/tonne and for levulinic acid US\$ 905/tonne. The price for levulinic acid was US\$ 6500/tonne, and the price of GVL was US\$ 993/tonne and for furfural US\$ 1207/tonne. This price difference was based on the configuration of the plant and whether it produced high-volume low-value products or high-value low-volume products (Kapanji *et al.*, 2021:3). Scenario 2 performed the best with an IRR of 23% and NPV of US\$ 253 million. Scenario 1 had an IRR of 17.4% and an NPV of US\$ 139 million (Kapanji *et al.*, 2021:7). Table 19 presents the input values obtained from the study by Kapanji *et al.* (2021:5,6).

**Table 21: Input variables obtained from the study by Kapanji *et al.* (2021:5,6)**

Descriptor	Scenario 1	Scenario 2
<b>Cost year: 2016</b>	<b>Levulinic acid and furfural</b>	<b>Levulinic acid, furfural, and GVL</b>
TCI (US\$ million)	218.90	220.6
VOC (US\$ million/year)	17.40	32.5
FOC (US\$ million/year)	7.5	8.2
Furfural production (t/hour)	3.4	3.3
Levulinic acid production (t/hour)	7.2	7.7
Gamma valerolactone production (t/hour)	-	6.8
Electricity production (MWh/hour)	12.2	13

Table 22 presents the results produced when the input variables extracted from the study by Kapanji *et al.* (2021:5,6) were used in the baseline model of this study. The CBA results indicate that scenario 1 had the greatest IRR of 37%, and scenario 2 had an IRR of 34%. The change in the better-performing scenario is attributed to using a single price for levulinic acid of US\$ 3700/tonne. The prices for furfural and GVL in this study are listed as US\$ 3250/tonn and US\$ 1000/tonne, respectively (Alonso *et al.*, 2017). The higher furfural output and lower operating costs ensured that scenario 1 performed better even though GVL's price increased by US\$ 7/tonne in this study.

**Table 22: Results obtained from the CBA using the base model for levulinic acid, furfural and GVL production**

Descriptor	Scenario 1	Scenario 2
	<b>Levulinic acid and furfural</b>	<b>Levulinic acid, furfural and GVL</b>
TCI (US\$ million) in 2023	351.68	354.42
<b>Costs in 2026</b>		
VOC (US\$ million/year)	35.14	65.63
FOC (US\$ million/year)	12.55	13.72
<b>Sales 2026</b>		
Furfural sales (US\$ million/year)	39.89	38.72
Levulinic acid sales (US\$ million/year)	96.18	102.86
GVL sales (US\$ million/year)	0	17.24
Electricity sales (US\$ million/year)	6.73	7.17
<b>Costs 2048</b>		
VOC (US\$ million/year)	192.75	360.02
FOC (US\$ million/year)	43.03	49.89
<b>Sales 2048</b>		
Furfural sales (US\$ million/year)	408.02	396.02
acid sales (US\$ million/year)	983.68	1051.99
GVL sales (US\$ million/year)	0	901.94
Electricity sales (US\$ million/year)	24.47	26.07
NPV (US\$ million)	1418.47	1245.19
IRR	37%	34%
PI	41.33	36.13

Morakile (2021:101) conducted a TEA for four scenarios, namely, scenario 1 – succinic acid from 1G feedstock, scenario 2 – succinic acid from 2G feedstock, scenario 3 – succinic acid from 1G2G feedstock and scenario 4 – succinic acid and xylitol from combined 1G2G feedstock. Scenario 1 performed the best with an IRR of 58.3% and a succinic acid MSP of US\$ 1220/tonne, followed by scenario 3 (IRR of 32.8%, succinic acid MSP of US\$ 1745/ton), scenario 4 (IRR of 26.4%, succinic acid MSP of US\$ 1888/ton) and scenario 2 (IRR of 23.1%, succinic acid MSP of US\$ 2237/ton). Morakile (2021:102) used a US\$ 3900/tonne price for xylitol. Table 23 presents the input values obtained from the study by Morakile (2021:101).

**Table 23: Input variables obtained from the study by Morakile (2021:101)**

Descriptor	Scenario 1	Scenario 2	Scenario 3	Scenario 4
<b>Cost year: 2018</b>	<b>1G Succinic acid only</b>	<b>2G Succinic acid only</b>	<b>1G2G Succinic acid only</b>	<b>1G2G Succinic acid and xylitol</b>
<b>TCI (US\$ million)</b>	137.16	545.82	600.96	557.72
<b>TCOP (US\$ million/year)</b>	56.39	77.4	134.34	134.4
<b>Succinic acid production (t/hour)</b>	15.3	20.2	34.1	18.5
<b>Xylitol production (t/hour)</b>	0	0	0	5.6
<b>Electricity production (MWh/hour)</b>	0	12.4	14.1	13.9

Table 24 presents the results obtained from the CBA for succinic acid and xylitol production. In this study, scenario 1 (IRR of 32%) performed the best, followed by scenario 3 (IRR of 21%) and scenario 2 (IRR of 17%). This study's succinic acid price was US\$ 1934/tonne, and xylitol was US\$ 3000/tonne. As with the study by Morakile (2021:101), this study had similar rankings of performance for scenario 1 and scenario 3. Scenario 4 produced a negative NPV and is unfeasible. This is attributed to the reduced xylitol price used in this study.

**Table 24: Results obtained from the CBA using the base model for succinic acid and xylitol production**

Descriptor	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	<b>1G Succinic acid only</b>	<b>2G Succinic acid only</b>	<b>1G2G Succinic acid only</b>	<b>1G2G Succinic acid and xylitol</b>
<b>TCI (US\$ million) in 2023</b>	194.47	773.89	852.07	790.77
<b>Costs in 2026</b>				
<b>TCOP (US\$ million/year)</b>	99.74	136.97	237.60	237.71
<b>Sales 2026</b>				
<b>Succinic acid (US\$ million/year)</b>	106.83	141.04	238.1	129.17

Descriptor	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	1G Succinic acid only	2G Succinic acid only	1G2G Succinic acid only	1G2G Succinic acid and xylitol
Xylitol sales (US\$ million/year)	0	0	0	25.35
Electricity sales (US\$ million/year)	0	6.84	7.78	7.66
<b>Costs 2048</b>				
TCOP (US\$ million/year)	547.15	751.39	1303.49	1304.07
<b>Sales 2048</b>				
Succinic acid (US\$ million/year)	1092.62	1442.54	2435.18	1324.14
Xylitol sales (US\$ million/year)	0	0	0	1326.02
Electricity sales (US\$ million/year)	0	24.87	28.28	27.88
NPV (US\$ million)	627.49	379.99	960.82	-630.67
IRR	32%	17%	21%	n/a
PI	33.27	5.91	12.28	n/a

## 2.6.9 Summary

Table 25 offers a selection of the best-performing scenarios of each of the TEAs that were investigated. These TEAs offer products for co-production with sugar, such as lactic acid, furfural, levulinic acid, PBS and succinic acid. The scenario to produce levulinic acid and furfural is the best-performing multiproduct production option from the various options investigated.

**Table 25: Successful products for specific scenarios from the CBA**

TEA	Mandegari, Farzad, van Rensburg, <i>et al.</i> (2017)	Ntimbani <i>et al.</i> (2021)	Morakile <i>et al.</i> (2022)	Ratshoshi <i>et al.</i> (2021)	Kapanji <i>et al.</i> (2021)	Morakile (2021)
Scenario	Scenario 2: Lactic acid	Scenario 1: furfural production	Scenario 2: 1G Levulinic acid	Scenario 4: 1G PBS	Scenario 1: Levulinic acid and furfural	Scenario 1: 1G Succinic acid
NPV (US\$ million)	220.04	227.09	689.98	1081.89	1418.47	627.49
IRR	15%	18%	37%	29%	37%	32%

## 2.6.10 Sensitivity analysis

For the sensitivity analysis, the best three scenarios were subjected to a sensitivity analysis measuring the effects of changes in co-product selling prices. For continuity, the selling price of electricity was left unchanged. Table 26 presents the sensitivity analysis of the two single-

product scenarios and the effect of changing the co-product price. As indicated in the table, the selling price was adjusted by increasing and decreasing the price.

**Table 26: Sensitivity analysis of single product scenarios**

TEA	Morakile <i>et al.</i> (2022)			Morakile (2021)		
Scenario	Scenario 2: 1G Levulinic acid			Scenario 1: 1G Succinic acid		
Item	NPV (US\$ million)	IRR	Selling price (US\$/ton)	NPV (US\$ million)	IRR	Selling price (US\$/ton)
Price unchanged	689.98	37%	3700	627.49	32%	
Product selling price increase by	Levulinic acid			Succinic acid		
5%	762.54	39%	3885	708.09	34%	2030.7
15%	907.66	43%	4255	869.28	38%	2224.1
25%	1052.78	46%	4625	1030.47	41%	2417.5
40%	1270.45	51%	5180	1272.25	46%	2707.6
50%	1415.57	55%	5550	1433.44	49%	2901
Product selling price decrease by						
5%	617.42	35%	3515	546.90	30%	1837.3
15%	472.30	31%	3145	385.71	26%	1643.9
25%	327.18	26%	2775	224.52	21%	1450.5
40%	109.50	18%	2220	-17.27	n/a	1160.4
50%	-35.62	n/a	1850	-178.46	n/a	967

From Table 26, decreasing the price of levulinic acid by 40% is still feasible, yet further reductions result in a negative NPV at the reduced selling price by 50%. This then makes the project unfeasible. Similarly, when decreasing the price of succinic acid, the NPV becomes negative when the price is decreased by 40%. This illustrates that both these products can have reduced prices up to a point, but after that, these projects become unfeasible.

Table 27 presents the sensitivity analysis of the multiple co-product scenario. It was found that reductions of up to 50% in either co-product selling prices or both simultaneously still provided positive NPS and healthy IRRs. This indicates that should the selling prices decrease, this project would maintain its feasibility even when cutting the co-product selling prices by half. Given this finding, the researcher concludes that manufacturing levulinic acid and furfural as co-products from sugar is the optimal solution. This would require the construction of plant and equipment in line with the proposed configuration set out by Kapanji *et al.* (2021) for this specific scenario.

**Table 27: Sensitivity analysis of a multiple-product scenario**

<b>TEA</b>	<b>Kapanji et al. (2021)</b>							
<b>Scenario</b>	Scenario 1: Levulinic acid and furfural							
<b>Item</b>	<b>NPV (US\$ million)</b>	<b>IRR</b>	<b>Selling price (US\$/ton)</b>					
<b>Price unchanged</b>	1418.47	37%	3700					
<b>Product selling price decrease by</b>	<b>Levulinic acid</b>			<b>Furfural</b>			<b>Both co-products</b>	
<b>5%</b>	1491.03	38%	3885	1448.57	38%	3412.5	1521.13	39%
<b>15%</b>	1636.15	40%	4255	1508.76	38%	3737.5	1726.44	41%
<b>25%</b>	1781.27	42%	4625	1568.96	39%	4062.5	1931.76	44%
<b>40%</b>	1998.95	44%	5180	1659.25	40%	4550	2239.73	47%
<b>50%</b>	2144.07	46%	5550	1719.44	41%	4875	2445.04	49%
<b>Product selling price decrease by</b>	<b>Levulinic acid</b>			<b>Furfural</b>			<b>Both co-products</b>	
<b>5%</b>	<b>1345.91</b>	36%	3515	1388.38	37%	3087.5	1315.82	36%
<b>15%</b>	<b>1200.80</b>	34%	3145	1328.18	36%	2762.5	1110.50	33%
<b>25%</b>	<b>1055.68</b>	32%	2775	1267.99	35%	2437.5	905.19	30%
<b>40%</b>	<b>838.0</b>	29%	2220	1177.70	34%	1950	597.22	25%
<b>50%</b>	<b>692.88</b>	27%	1850	1117.50	33%	1625	391.91	21%

## **CHAPTER 3 CONCLUSION AND RECOMMENDATIONS**

### **3.1 Key findings**

This research and investigation into feasible products for co-production with sugarcane in a South African context has found that levulinic acid, succinic acid and furfural are the top three co-products for manufacturing consideration. This is based on the superior IRR and NPV values these products returned in the cost-benefit analyses.

The sensitivity analysis that was conducted on these three products also returned favourable results, with the co-production of levulinic acid and furfural performing exceptionally well, wherein both products could sustain a reduction of 50% in selling price and still provide an IRR of 21% and a NPV of US\$ 391.91million for a specific production scenario.

Note that the production of these products is aligned with chemical processes designed by other researchers. Production would thus require adherence and implementation to their designed factory configurations at an existing South African sugar mill that can process at least 300 tonnes of sugar cane per hour.

### **3.2 Achievement of objectives**

The researcher has addressed the secondary research objectives listed below as described:

- SO1 – A literature review was conducted of the sugar industry which included a PESTEL analysis and a Five Forces Framework analysis.
- SO2 – A literature review was conducted of alternative products for co-production with sugar from sugarcane as found in academic and online resources.
- SO3 – Co-products were selected for further evaluation by process of elimination based on specific criteria set out in section 0.
- SO4 – A cost-benefit analysis was executed on preferred potential co-products resulting in the identification of viable co-products for production with sugar.

The researcher believes that addressing these secondary objectives and identifying the co-production of levulinic acid and furfural has addressed this study's primary objective, which was to determine the feasibility of co-production of selected products from sugarcane in the South African sugar industry. By doing this, the researcher believes this work has added to the body of knowledge of feasible co-products for manufacture from sugarcane.

### **3.3 Practical application**

In practice, this study may be used as a baseline for further research and planning into co-production viability for South African sugar mills. It has sifted over thirty products to identify three products. It offers a unique strategy utilising historic TEAs of others in historic economic conditions and reconciling those findings with current economic conditions in post-COVID-19, July 2021 unrest and KZN floods' economic conditions.

This study provides sugar milling companies, entrepreneurs, and industrialists with a baseline scenario that may inform the application of an FEL (front-end loading) project process, offering preliminary findings. This could ultimately reduce time spent in the specific FEL-0 phase and assist project managers in planning to execute such an FEL project.

### **3.4 Theoretical application**

This study highlights specific scenarios (designed by others) that theoretically have been proven successful in the past but, in some instances, may not be feasible today due to the current economic climate and increased cost of construction.

This study has also offered a model for application in future studies and provided a strategy for those without an engineering background to apply cost-benefit analysis methodology to projects initially evaluated through an engineering lens.

### **3.5 Managerial implications**

The researcher recommends conducting further research on the preferred scenario and co-products. This may be in the form of a detailed feasibility study with the engagement of engineering consulting firms to execute FEL 1, FEL 2 and FEL 3. This should, however, be done in conjunction with the authors and researchers of the original TEAs. An environmental impact assessment is also required and must be considered. Legal and regulatory requirements in South Africa must be investigated for project execution.

From a business management point of view, the sugar mills must identify customers and key markets, delivery channels, key partners, and the value proposition. They should consider the application of a business model canvas, which is a business model composed of nine components named here: customer relationships, customers, revenue, channels, key resources, costs, key partners, key activities and value proposition (Hong & Fauvel, 2013:28).

### **3.6 Limitations**

This study has relied on TEAs by others who have made assumptions about factory capital and operational costs. These costs have been adjusted to match the current year (2023) using historical and best-estimated future interest rates. This is, at best, an estimate of the future performance of the costs for construction and operations.

The selling prices of co-products were extracted from various internet resources, often indicating live prices on the day. These products do not exist in isolation but are affected by changes in the global economy, as shown by the impact of COVID-19 and the ongoing war between Russia and Ukraine. Prices could rise today and fall tomorrow, which is the nature of business.

### **3.7 Suggestion for further research**

Over thirty products were identified in this research, and many were eliminated based on the availability of TEAs in a South African context. This requires further research and execution of TEAs to scrutinize the remaining products to understand their place in future developments better.

Using biogas as an example can reduce the use of bagasse, ultimately increasing feedstock levels for the co-production of alternative chemicals. This, however, should be considered in a TEA based on the South African context. Combinations of co-products different to those in existing TEAs may also be considered for further research.

### **3.8 Trustworthy**

The researcher is convinced that this study and its findings are trustworthy as they consider current economic conditions. Information gathered from academic resources is from reputable sources. The strategy presented in this study to conduct CBAs using input data from other researchers may also be applied to other industries. This should be done for other industries, considering the effects of inflation and changing economic conditions.

### **3.9 Closing argument**

In a struggling sugar industry, there is hope. With TEAs conducted by others and the findings of this study, the researcher believes that the industry should adopt co-production of niche chemicals to ensure a sustainable future for the sugar industry.

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