Tanzania Journal of Science 51(1): 182-195, 2025
ISSN 0856-1761, e-ISSN 2507-7961

From Waste to Wealth: Sisal By-product Opportunities in Tanzania

Neema Msuya* **and Abraham Temu**

Department of Chemical and Process Engineering, College of Engineering and Technology

University of Dar es Salaam, P.O. Box 35131, Dar es Salaam, Tanzania

**Corresponding Author: nmsuya@udsm.ac.tz, nmmsuya@gmail.com*

Received 13 Nov 2024; Revised 3 Mar 2025; Accepted 25 March; Published 14 April 2025

https://dx.doi.org/10.4314/tjs.v51i1.13

Abstract

Sisal fibre production process in Tanzania is highly inefficient, utilizing only 2% of the plant leaving 98% waste including; damaged leaves, boles, roots, poles, decortication by-products and short fibres. These wastes contain valuable components like sugars, protein, volatile solids, carbon, and other organic matter, which can be repurposed into high-valuable products. This review examines the current state of sisal production and waste management in Tanzania, emphasising innovative strategies to transform sisal waste into valuable resources. While extensive research has identified potential products from sisal waste, such as acids, bioplastics, biofuels, or animal feed, commercialization efforts remain limited. The technical and economic barriers to commercialization include variability in waste quality and composition, as well as the initial costs of building the infrastructure and machinery needed to convert sisal waste into valuable products. It is essential to conduct comprehensive studies on the quantities and composition of sisal waste across Tanzania; the scalability of waste valorisation processes and marketing of the products from sisal waste. Such studies will enable informed decisions for specific policy changes, fostering industrial investments through collaboration between researchers, industry, and government. This will drive commercialization, unlocking its economic potential by creating new industries, job opportunities and reducing environmental impact.

Keywords: Sisal waste; Waste valorisation; Lignocellulose; Non-fibre products; commercialization

Introduction

Sisal is among marginal land crops that may grow in arid places and requires less maintenance because it can withstand many agro-ecological conditions (Mwaniki 2018). The plant consists of leaves, boles, poles and roots. The current worldwide annually demand for sisal fibre is projected to be 400,000 tonnes, whereas the production is roughly 250,000 tonnes. Tanzania was the second sisal producer in 2019, producing 15% of the world's production of 220,363 tonnes of sisal fibre after Brazil which produced 39% (Colley et al. 2021). In 2022/2023 fiscal year Tanzania produced more than 56,732.7 tonnes of sisal fibre, an increase of more than 17.3% compared to the 48,359.49 tonnes produced in 2021/2022 (URT 2024).

The semi-arid climate and hot regions such as Lindi, Morogoro, Mtwara, Shinyanga, Singida and Tanga favours the plant. Other leading sisal growing regions in Tanzania are Arusha, Kilimanjaro, Pwani and Mwanza (Terrapon-Pfaff et al. 2012, Nylander 2024). Tanzania produces two varieties: hybrid 11648, which accounts for about 80% of the production, and agave sisalana (Monja-Mio et al. 2019, Nerini et al. 2016). The agave sisalana specie, introduced in 1893 from Mexico, is primarily grown in waterlogged soils but is less tolerant to drought (Colley et al. 2021, Saxena et al. 2011). Agave sisalana is currently grown in Lindi, Mwanza, Shinyanga, Simiyu and Singida. In comparison to agave sisalana, the Hybrid 11648 has demonstrated superior performance in terms of fibre yield, leaf count, and life cycle. The agave sisalana specie has short life span (7 – 8 years before poling) and fewer leaves (250 leaves per plant) than hybrid 11648, which has more leaves (500 – 600 leaves) and a life span of 12 -15 years before poling (Monja-Mio et al. 2019). However, agave sisalana produces far better, stiffer fibres.

The traditional focus of the sisal industry has been on fibre production from sisal leaves, leaving a gap for the sustainable use of the entire plant. Sisal fibre production is highly wasteful utilizing only 2% of the plant (Mshandete et al. 2013, Msuya et al. 2018a). The remaining 98% which includes roots, leaves, stems, and short fibres, becomes waste that is often discarded or burned, releasing harmful particulate matter and carbon dioxide that worsens air quality and contributes to climate change and hence environmental challenges (Kivaisi and Mshandete 2017). Valorising sisal waste is crucial because it reduces environmental pollution such as emission concerns when burned in the farms and may yield valuable commercial products (den Doop 1949, Zhang et al. 2014). Production of value-added products, such as biodegradable materials, animal feed, biofuels, and biodegradable packaging, can lead to new industries, job opportunities for women and youth in rural areas, and income for local communities, thus fostering rural development and contributing to Tanzania's economic growth (Virgin et al. 2022, Konyo 2024).

Several technologies can be applied to sisal waste valorisation in Tanzania, including biomass gasification, biochar production, composting, animal feed and biochemical production (Fertahi et al. 2023, Ogbu and Okey 2023, Haque et al. 2023, Siwal et al. 2022, Wang et al. 2022). Though the investment costs for these technologies can be considerable, biomass gasification to generate electricity or produce biofuels, for example, require expensive initial setups like gasifiers, turbines, and cleaning systems (Sansaniwal et al. 2017). However, operating a biomass gasification plant from biomass waste is relatively cost-effective (Heidenreich and Foscolo 2015), since waste such as sisal waste is often discarded, lowering the input cost. Additionally, syngas production offers a stable energy source for rural areas, reducing reliance on imported fuels. Electricity generated from waste or converting syngas into biofuels for local transport or industry can provide long-term economic benefits (Demirbas et al. 2011, Kabeyi and Olanrewaju 2022). The energy can be supplied to local grids or used in off-grid communities, making it both economically viable and environmentally beneficial (Kusekwa 2011). The abundance of sisal waste in Tanzania further reduces the need for expensive raw materials.

The economic feasibility of sisal waste like other waste valorisation technologies in Tanzania depends largely on the technology chosen, scale of implementation, and available infrastructure (Doukali 2023). While low-cost options, such as biomass gasification, animal feed production, and composting, can have significant local impact, higher investment options like biochemical production and biodegradable packaging, may offer substantial long-term returns (Ashokkumar et al. 2022). The diverse range of technologies available ensures solution suitable for different scales of operation, offering both local and international revenue opportunities (Andoni et al. 2019, Schramade 2017). The key to success will lie in selecting technologies that align with the country’s economic, environmental, and social goals, supported by effective business planning, access to financing, and research and development.

Waste from Sisal Plant

Sisal, a hardy plant known for its durable fibres, generates substantial waste during cultivation and processing. This review examines the types of waste, their composition, and potential uses. Different researches published on sisal production and waste utilization were reviewed. The waste from sisal plant includes damaged leaves, boles, decortication waste, roots, poles and spinning waste. These wastes are made up of liquid or solid part except the last one. The composition of sisal waste varies based on several factors, including soil conditions, climate, agronomic practices, the plant's age, and the processing method. In addition, the amount of waste produced depends on the farming and fibre production technology and capacity. Sisal decortication technologies include manual, mechanical, wet, dry, biological, chemical, ultrasonic and a combination of those (Ahmad et al. 2017). Manual and mechanically rotating cylinder (raspador) type of decorticators are more common in Tanzania. But there is no documentation of which technology is dominant. Although the latter technology is efficient and produces high quality fibres, it needs a lot of washing water, hence producing substantial amount of wastewater, which is environmentally unfriendly. Modern plants require less water and have solid-liquid wastes separator, which impacts waste composition.

Type of Waste from Sisal Plant

Sisal leaves decortication waste

The leaf is typically composed of 4% fibre, 0.75% cuticle, 8% dry matter and 87.25% liquid (Sannapapamma et al. 2020). The fibres are used in the manufacture of different valuable products including ropes, anchors, cordage, and handicrafts that are applied in marine, automotive, renewable energies and construction materials (Warra and Prasad 2024). Sisal fibres are obtained from leaves by a mechanical method known as decortication process as described by Srinivasakumar et al. (2013). This process is generally water intensive and generates large amounts of residues. Since sisal fibres are only 4% of the wet sisal leaf mass fed in the decortication process, the remaining 96% of solid (bagasse) and liquid (juice) are usually discarded as waste (Daher et al. 2023, Apolinário et al. 2014).

Sisal boles

The sisal bole is the stem part of the sisal plant holding the leaves and the roots and it is traditionally counted as waste (Msuya et al. 2018a, Mshandete et al. 2013). Studies show that for each tonne of sisal fibre produced from sisal leaves; about 24 tonnes of leaf residues (sisal pulp), 100 m^3 of wastewater, and 4.7 tonnes of sisal boles are generated (Terrapon-Pfaff et al. 2012). Each bole uprooted at the end of sisal plant life will have a pole and roots. According to Naik et al. (2016), the average weights of sisal bole, pole and roots are 38.38 kg, 21.4 kg and 29.98 kg, respectively. Thus, the tonnage of sisal bole generated per tonne of fibre produced corresponds to 2.6 tonnes of sisal poles and 3.7 tonnes of sisal roots.

Short and damaged fibres, poles and roots

Short and damaged fibres are produced during decortication process and typically account for 10-20% of the total fibres produced (Anandjiwala and John 2010). Sisal poles (the thicker, central parts of the sisal plant) and roots remain after the leaves are harvested for fibre extraction. A study of the typical composition of poles and roots of a sisal plant is necessary. Despite technological improvements in sisal fibre production and use, the amount of these wastes continues increasing with increase in fibre production. As efforts to increase sisal fibre production in Tanzania grow, exceeding 40,000 tonnes over just five years (Figure 1) due to the expanding market, more waste will be accumulated. These wastes are biodegradable and resilient, appropriate for various end uses. Beside production of various chemicals and fuels, sisal wastes can be used in construction and landscaping (Mazo et al. 2024).

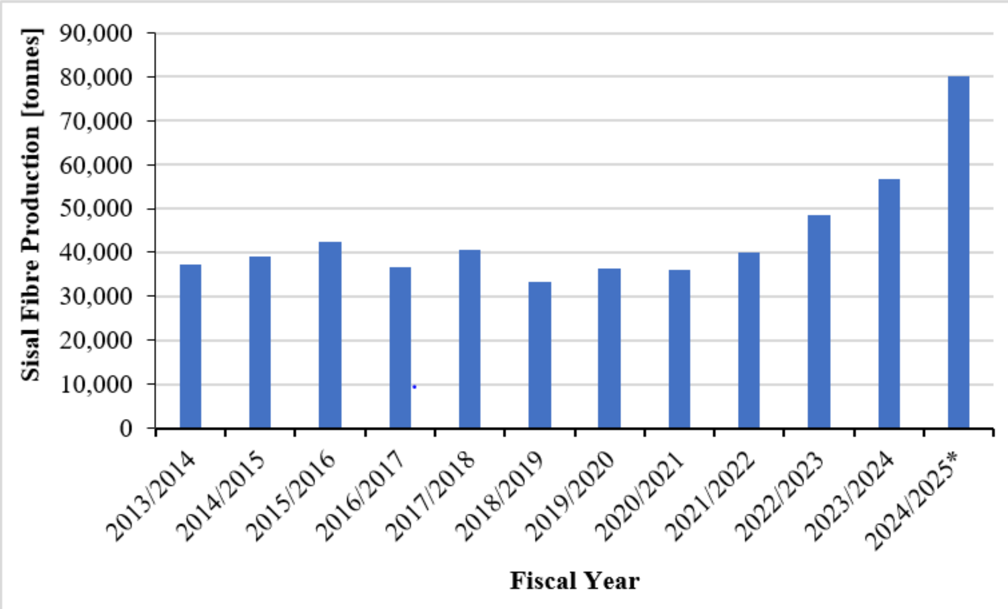

Figure 1: Sisal fibre production in Tanzania. Data source: (URT 2024)

Composition of Waste from Sisal Plant

Understanding the composition of sisal waste which includes; fibres, leaves, boles, poles, and roots, is crucial for effective valorisation. The components of sisal waste aforementioned differ in fibre content, chemical composition, and structural characteristics. Recognizing these differences is essential for determining the potential environmental impact and selecting the most appropriate technologies for processing the waste. Mshandete et al. (2013) investigated the feasibility of utilizing fresh sisal boles waste (SBW) and residual leaf stubs (RLS). The volatile solids, total carbon, and total organic matter in all fractions investigated ranged from 93% to 98%, 49% to 55%, and 91% to 98% on a dry weight basis, respectively. The total sugar contents in the investigated solid and liquid fractions of the wastes ranged between 8-27% and 30-35 mg/l, respectively (Mshandete et al. 2013). Table 1 shows the composition of waste from sisal plants as gathered from various literatures. The composition of sisal waste in terms of crude protein, cellulose, hemicellulose and total sugars highlights its potential for conversion into valuable products, such as animal feeds, biofuels and packaging materials. More research is needed on sisal poles and roots on their composition and potential for production of valuable products.

Table 1: Composition of some waste from sisal plants

Parameter	Decortication waste		Sisal boles		References
	Liquid	Solids	Leachate	Biomass	
pH	5.60	-	5.23	-	(Sharma and Varshney
Total sugars (g/L.)	1.11	-	30.15	8.45	2012);
Crude protein (% by wt.)	11.56	-	6.38	5.31	(Msuya et al. 2018a);
Ash content (% by wt.)	1.5-4.0	3.15	3.97-5.80	4.28-5.80	(Lima et al. 2013);
Total solids, (% by wt.)	10.07	37.01	9.72	36.05	(Guerra et al. 2021,

Total nitrogen (mg/L)	2.14	0.27	1.02	0.85	Mshandete et al. 2013);
Total Organic matter (% by wt.)	87.53	97.87	97.94	98.66	(Konyo et al. 2023)
Cellulose (% by wt.)	-	-	-	6.48	
Hemicellulose (% by wt.)	11.26	11.26	6.41	8.14	
Lignin (% by wt.)	4.5	6.6	-	5.00	

Alternative Uses of Sisal Plant Wastes

Literature has documented various studies on the utilization of sisal waste, including sisal decortication wastes and boles, but scanty on sisal poles and roots. More efforts to boost sisal fibre production and profitability through smallholder sisal farmers (Beleko and Urassa 2022) will result in increased waste and environmental pollution. Therefore, it is critical to address potential use of these waste products by valorising the entire sisal plant.

Potential use of Sisal Leaves and Decortication Waste

Sisal leaf processing generates solid and liquid decortication waste. Additionally, fibres that do not meet the required grades are classified as waste. The liquid waste ends up in stream and other water bodies while the solid waste is normally disposed of by burning or dumping on land and leaving it to rot thereby generating greenhouse gases such as methane (Msuya et al. 2018a). Attempts to mitigate the polluting effects of sisal decortication waste have been made by investigating the possibility of producing profitable products. Researched products are biogas (Srinivasakumar et al. 2013, Kiairie 2019, Peter et al. 2019, Arisutha et al. 2014); manure (Mridha et al. 2023), animal feed (poultry and fish), pectin (Santos et al. 2013), alcohol (Lima et al. 2013), hecogenin (Joshi et al. 2023), chemicals such as pectin, mannitol and succinic acid (Santos et al. 2015), simple sugars (De Paula et al. 2012) protein oyster mushrooms and pulp and paper (Bosco et al. 2022) and protein black soldier fly (Konyo et al. 2023). However, thorough proximate and ultimate analyses of the decortication waste, which are important in knowing the potential for specific end products, are still lacking. Some specific end-products are highlighted below.

Biogas production

Biogas is an alternative green energy resource that is clean, environmentally friendly, renewable, and may be generated in digesters filled with feedstocks (Korbag et al. 2020). This has attracted the most attention in research and at the production level in Tanzania (Magoggo 2011). The world's first biogas power plant (1,700 m^3) employing sisal waste and bacteria from cow dung (methanogenic bacteria) was commissioned at Hale, Tanga in 2007 (Srinivasakumar et al. 2013, Yhdego 2021). The methanogenic bacteria convert the sisal waste to produce methane (CH4) and other gases such as carbon dioxide (CO_2), Hydrogen Sulphide (H_2S) and oxygen (O_2) (Oudshoorn 1995). The biogas can be used to generate electricity, used as fuel for transport, cooking and lighting, or for powering farm machinery. The process effluent contains significant amounts of nitrogen, potassium, and calcium, which can be used as fertilizer and nutrient-rich animal feed. However, there is lack of information on efficiency of the biodigester and the concentrations of its effluent for suitability as animal feed or biofertilizer.

According to Oudshoorn (1995) one tonne of sisal pulp can generate 54.3 m^3 of biogas by methanogenesis. But pilot plant designed by Rajabu and Manyele et al. (2015) to produce biogas from sisal decortication waste increased the biogas yield from 0.157 m^3/kg to 0.386 m^3/kg (146% increase) when sisal decortication waste was reduced in size to 2 mm and digested at 40˚C than when the feedstock was untreated with large particle sizes and operating at atmospheric condition. Yet, they did not provide information on the microorganisms in the inoculum and the effect of agitation. Kivaisi and Mshandete (2017) on the other hand, suggested that physical and biological pre-treatments of decortication waste increased methane yield by 23-30%, while co-digestion with fish waste increased methane yields by 59-94%. But neither did they discuss the effect of digester design, particle size nor the techno-economic analysis and the possible commercialization of the products.

In another study by González (2017) reported that using a Combined Heat and Power (CHP) unit Mkumbara Sisal Estate in Tanga region could produce about 1,200,000 m^3 of biogas per year that would generate around 2,340 MWh of electricity. Although this is only for one estate, there is a potential to integrate this to all sisal estates to reduce production costs and contribute to the national electricity grid. However, the study did not discuss details of design, sustainability of supply of feedstock and its economic viability. Sisal leaves are known to contain wax (0.38%) and hecogenin (0.10%) (Srinivasakumar et al. 2013). Hecogenin is a pharmaceutical raw material for the manufacture of corticosteroids, which are currently imported into Tanzania.

Mushroom cultivation and protein source

Mushrooms have an important role in organic soil growth and development, solid waste management, and soil mineral replenishment. Muthangya et al. (2013) studied the pre-treatment effect of saline sisal decortication waste for mushroom production when soaked in hot and cold water. The study indicates that saline sisal decortication waste can be utilized for commercial mushroom production with a yield of more than 40%. In another study, do Carmo et al. (2014) found that sisal decortication waste can be efficiently bio converted into nutrient rich oyster mushrooms with 29.0% crude protein and 2.2% fat. The high protein and fat content of black soldier fly (BSF) makes it one of the most promising insect species for commercial production in poultry feed composition (Abd El-Hack et al. 2020).

Konyo et al. (2023) used sisal decortication waste as a substrate for the growth of the black soldier fly (BSF) and found that it had a better reduction of the waste by 52%. The harvested BSF larvae contained crude protein 53% and other mineral nutrients which are sufficient for poultry and fish feed requirements. Mhaiki et al. (2013) and Msuya et al. (2024) isolated yeast cells from sisal bole juice as source of microorganism for fermentation but the yeast can also be a source of protein for animal feed. Strains isolated from specific regions have high adaptation to their own climatic conditions and substrate, making their use in production processes more interesting (Šimonovičová et al. 2021, Jacobus 2021).

Bioethanol and bio-oil production

Bioethanol, which is produced through the conversion of biomass resources such as sisal, is utilized in a variety of industries to catalyse the synthesis of petrochemicals and fuels (Anekwe et al. 2023). Sisal decortication waste was indicated as a possible feedstock to produce bioethanol with maximum production of 0.27 g/g attained in 60 hours when Candida tropicalis CCT 1516 was employed in the fermentation process (Damião et al. 2018). However, the researchers did not cover the effect of the production process conditions and the quality of the bioethanol produced as well as the scaling up of the production process and commercialization of the product. Cunha et al. (2024) studied the pyrolysis of composted sisal residue to produce bio-oil at 450°C and 550°C. Results show that composting helped reduce the oxygenated bio-oil species by approximately 44%–75%. At both temperatures, large concentrations of hydrocarbons (alkanes and alkenes) were produced (>160% increase), concentrations of ketones, aldehydes, and phenolic were reduced (>50%) and esters, furans, and acetic acid were eliminated in the composted biomasses (Cunha et al. 2024). Pereira et al. (2022) used sisal residues in a fluidized bed reactor to produce bio-oil with distinct characteristics compared to other biomasses. By varying the nitrogen flow rate, biomass mass flow, temperature, and pressure in a fluidized bed reactor obtained bio-oil composition that was intensely dependent on the process parameters. The best results were achieved at the lowest pressure (test LLP) condition, which showed high bio-oil yield and improved composition consisting mainly of alkylphenols (16.05 wt %), aromatics (6.09 wt %) and catechols (8.72 wt %) (Pereira et al. 2022).

Pulp and paper and bio-composites

The potential and special papermaking properties of certain sisal species have long been used by producers of specialty papers such as cigarette, bank note, filter and Bible paper. Short and damaged fibres left after fibre extraction is mainly used for making paper/paperboards, hecogenin (a cortico steroid), wax and biogas (Li et al. 2020). Bosco et al. (2022) found that short sisal fibre wastes from spinning processes have a promising potential for paper pulp production compared to other non-wood raw material. Through soda pulping techniques waste sisal fibres as short as 1 mm achieved pulping required performance after 240 minutes under maximum temperature 140◦C. However, both studies do not provide optimal fibre length and operating conditions for best quality pulp.

Guerra et al. (2021) showed that acid and alkali pretreatment of sisal waste increase cellulose content. The X-ray diffraction pattern and thermal characterization showed a crystallinity degree increase and thermal stability improving, respectively, hence a better candidate for composite production. Melo et al. (2019) found that sisal fibre powder can be used as reinforcement in composites. Natural fibre reinforced polymer composites are more attractive structural materials due to their high specific strength, lightweight and biodegradability properties. However, one of the serious problems of plant fibres is their strong polar character, which creates many problems of incompatibility with most thermosetting and thermoplastic matrices (Ndazi et al. 2006).

Potential use of Sisal Boles Waste

Sisal boles are normally slashed and burned on the farm thus causing environmental emission concerns (Mshandete et al. 2013, Ngonyani 2010). The boles composed of various materials that can be used in production of sugars, membranes, inulin, acids (citric, lactic, etc.) and polymers, bioethanol and bio-oil and protein. Efforts to utilize these boles have been done through research to analyse the potential of producing different valuable products. However, thorough proximate and ultimate analyses of the boles, which are important in knowing the potential for specific end products, are still lacking. Some specific end-products are highlighted below.

Sugars and membranes from juice and bagasse

The boles contain high total sugar content in the juice of up to 30% (m/v) that can be extracted and fermented to produce valuable products to increase income to the sisal industry (Msuya et al. 2018a). The sisal bagasse, a lignocellulose has about 60% carbohydrates that can be pre-treated to produce sugars than can be used as feedstock for various products. Xavier et al. (2023) reported production of 90% pure cellulose acetate membranes using alkaline and acid pre-treatments of the sisal bagasse. The membrane produced is suitable for removing inhibitors from the fermentation process.

Inulin production

Inulin is a naturally soluble dietary fibre, a reserve biopolysaccharide in plants (Afoakwah 2023). Inulin is becoming increasingly popular due to its purported immunomodulatory, antioxidant, anticancer, hepatoprotective, hypoglycaemic, and gastrointestinal protective properties (Du et al. 2023). Industrially inulin is currently derived from Jerusalem artichoke tubers (Zhang et al. 2022) and chicory roots (Kardamanidis et al. 2024, Singh et al. 2025). Sisal boles waste a lignocellulosic material has the potential to produce inulin (Apolinario et al. 2017) using different extraction methods. Elisante and Msemwa et al. (2010) used dry ‘baking’ extraction method to extract inulin from sisal boles as a feedstock for bioethanol production. Majaliwa et al (2023) used an ultrasonic extractor in a wet extraction to produce inulin (18%) from sisal boles waste at 80°C and 90 minutes.

Acids and Polymers

Ngonyani (2020) used sisal inulin as a feedstock to produce citric acid with a high yield of 46.66%. Besides citric acid, lactic acid can also be produced from sisal bole juice. Lactic acid (2-hydroxy propanoic acid) is the simplest hydroxyl acid with an asymmetric carbon atom that was traditionally used in food, pharmaceutical, cosmetic and leather tanning industries (Nikolaivits et al. 2021). Lactic acid is also used as a building block for renewable and biodegradable plastics (Msuya et al. 2022). Recent research has shown encouraging results in reducing the cost of producing Lactic acid using various biomass sources, such as horse chestnut (Çetin 2022), lignocellulosic biomass (Zu et al. 2024, Choi et al. 2024) and coffee waste (Kim et al. 2024).

Lactic acid can also be produced from sisal bole waste. Msuya et al. (2018b) utilized different concentrations of sugar from sisal boles juice for production of Lactic acid (LA) using Lactic Acid Bacteria (LAB). The study focused on analysing the effect of initial sugar concentration, process temperature and initial medium pH on the produced lactic acid concentration, yield and productivity. Maximum condition for production of LA occurred at a temperature of 37°C, initial pH of 6 and initial sugar concentration of 120 g/L which corresponded with the highest LA concentration of more than 24 g/L and a yield of 93% (Msuya et al. 2018b). It was possible to produce lactide from lactic acid with a conversion rate of 99% over 2 hours at a system temperature of 180ºC, regardless of the catalyst ratio used (Msuya et al. 2022, Çetin 2022).

Bioethanol and bio-oil production

Sisal bole bagasse is a lignocellulose which can be used for second generation bioenergy such as biogas, briquettes and bioethanol. In addition, bagasse can be pyrolyzed to produce bio-oil, or gasified to produce syngas or pre-treated to produce pulp and paper and other chemicals. Elisante and Msemwa et al. (2010) extracted the inulin from sisal boles as a feedstock for bioethanol production. More studies on the optimal conditions that affect the production of high yield ethanol are necessary. Other products that are still in research from lignocellulosic sisal bole bagasse include furfural, biogas, briquettes, bio-oil and bioethanol. In addition, all products from the sisal decortication waste can also be produced from sisal bole

Unlocking the Commercial Potential of Valorisation of Sisal Waste in Tanzania

The sisal industry has traditionally focused on fibre production from sisal leaves, leaving a gap in the sustainable use of the entire plant. Currently, only 2% of the plant is used for fibre production, while the remaining 98%, including leaves, stems, and fibres, is often discarded or burned, releasing harmful particulate matter and carbon dioxide that worsens air quality and contributes to climate change. However, these wastes materials can be transformed into valuable products as shown in Figure 2. For instance, waste from sisal decortication, containing fibres, can be used in construction materials, composted for biofertilizer production, or anaerobically digested to produce biogas. Sisal boles juice can be used to isolate microorganisms or fermented for biofuels production and biopolymers for packaging. The bagasse from sisal boles, on other hand, can be used for briquetting, gasification, or pyrolysis to generate alternative energy. Poles and roots have the potential as construction materials, and for chemicals and fuel production.

Despite promising research, commercialization of these valuable products has been limited. With Tanzania's fibre production increasing by more than 40,000 tonnes in five years (Figure 1), and the Tanzania Sisal Board aiming to reach 120,000 tonnes by 2025/2026, the potential for sisal waste accumulation and its valorisation continues to grow. Valorising sisal waste is crucial to reduces environmental pollution and unlock its commercial potential. Producing value-added products like biodegradable materials, animal feed, biofuels, and packaging can create new industries, provide job opportunities for women and youth in rural areas, and generate income streams for local communities, fostering rural development and contributing to Tanzania's economic growth.

Sisal waste valorisation aligns with several global sustainability goals. By promoting the efficient use of agricultural by-products, Tanzania can help reduce poverty (SDG 1), advance clean energy (SDG 7), and improve food security and mitigating climate change (SGD 2, 8, 9 and 12). It also supports the transition to a circular economy, where waste is minimized and resources are reused, thus creating positive environmental, economic, and social impacts (Tawo and Mbamalu 2025).

Despite these benefits, several barriers can hinder the shift to sisal waste valorisation. These barriers include technological, financial, regulatory, and social aspects. Technological solutions and innovations should focus on affordable, small-scale, modular systems that integrated into existing sisal farming and processing operations, minimizing capital costs while maintaining high efficiency. Compact biomass gasification units or small-scale pyrolysis systems, for example, would allow local farmers and small businesses to participate without requiring large investments. Additionally, biotechnological innovations, such as enzymatic pre-treatment of sisal fibre for biofuels or biocomposites, can improve the efficiency and value of the waste. Integrating renewable energy sources, like solar or wind power, with waste processing can make valorisation more energy-efficient and sustainable.

Financial solutions and innovations should include government subsidies, tax incentives, and grants to support businesses adopting environmentally sustainable technologies. Partnerships between the private sector, government, and NGOs can mobilize resources and facilitate technology transfer.

The Tanzanian government should implement clear policies to encourage the valorisation of agricultural waste, particularly sisal. These policies could include tax incentives for businesses adopting waste valorisation technologies, subsidies for renewable energy production from agricultural waste, and waste management regulations that promote recycling and repurposing of sisal waste.

The question will be the availability of raw material in terms of the specific product to be produced. The availability of specific waste types determines the feasibility of producing certain products. The waste treatment methods depend on its composition and its distinctive characteristics. The cost-effectiveness of utilizing and processing sisal waste remains a critical consideration.

It is necessary to conduct comprehensive research that will thoroughly document the composition of the entire sisal plant, plantation biomass and the country's production capacity. The study should also focus on the scalability of waste utilization process and building markets for products from sisal waste. The estimates on plantation biomass of the sisal plant can be used in assessing the role of sisal plantations specifically on the regional carbon storage (Vuorinne et al. 2021) which is also the major area of concern worldwide. The proposed research will include the sisal poles and roots composition and their potential for production of valuable products. The financial potential of different valorisation processes (cost-benefit analysis), environmental impact reduction metrics (e.g., pollution levels before and after waste valorisation) is another area of concern. This will pave the way to industries and investors on the clear path to take in industrial production of different products from sisal waste and its economic benefits.

It is essential to allocate resources towards research and development to improve the quality and functionality of products made from sisal waste. Additionally, it is important to broaden the range of market uses for these products. This will contribute to the growth of product development and market expansion. Engaging in collaboration with designers and manufacturers can reveal novel applications, thereby portraying these products as environmentally friendly alternatives. Implementing training programs to provide local communities with the knowledge needed to properly handle sisal waste can lead to economic benefits. Additionally, promoting local enterprises that transform waste into valuable goods can further contribute to these benefits. Furthermore, supporting the adoption of techniques that convert sisal waste into valuable resources not only decreases the need for landfills and minimizes pollution, but also incorporates waste into other applications like soil stabilization. This, in turn, promotes the implementation of sustainable land management practices. Tanzania could develop a fully integrated circular economy model for the sisal industry, where sisal waste is no longer seen as a burden but rather a valuable resource. Sisal farms and processing plants would adopt sustainable practices to maximize the utility of every part of the plant. Fibre would be extracted for use in traditional products like ropes, while waste materials, such as leaves, pulps, and stems, would be transformed into high-value products such as bioplastics, biofuels, compost, and animal feed. To create economic opportunities, a network of small- to medium-scale processing units could be established across rural areas, enabling local farmers and entrepreneurs to transform sisal waste into value-added products. The alternative routes for production of valuable products from sisal plant wastes are summarised in Figure 2.

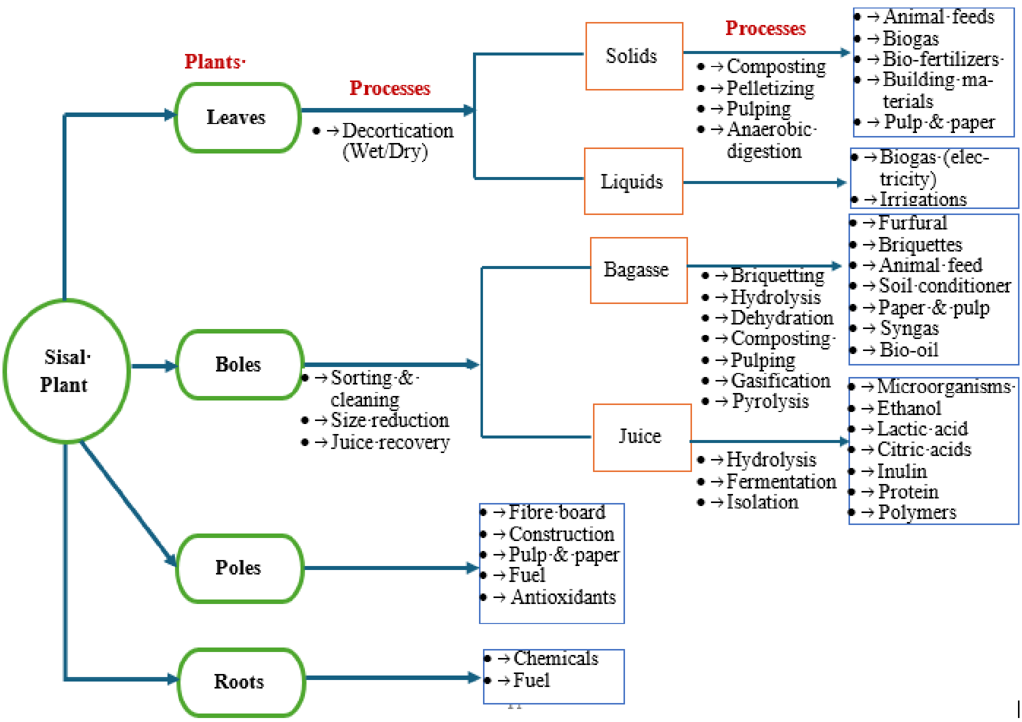

Figure 2: Alternative uses of sisal waste.

Conclusions and Future Research

Sisal fibre production is a high waste process that generates significant waste such as damaged leaves, boles, decortication waste, roots and poles. The composition of sisal waste varies based on several factors, including soil conditions, climate, agronomic practices, the plant's age, and the processing method. Despite improvements in sisal fibre production and use technology, the amount of these wastes continues to rise in tandem with increased fibre production. Consequently, efforts to boost sisal fibre production and profitability through smallholder sisal farmers may result in increased waste and environmental pollution. To address these concerns, the valorisation of sisal waste is crucial as not only help mitigate environmental pollution but also present opportunities for production of useful and commercially viable products. In addition to being used in production of various chemicals and fuels, sisal wastes can be used in construction and landscaping.

While literature has extensively explored the utilization of sisal decortication wastes and boles, research on the potential of sisal poles and roots remains limited. Despite research that has been done on valuable products from sisal waste, little has been done on the commercialization of these products. It is therefore recommended comprehensive research be conducted to document the quantity and quality of sisal wastes produced in Tanzania, which may save as feedstock for various products. This research should include the analysis of ultimate and proximate composition of roots and poles, as well as vitamins and minerals analysis of various parts of the plant Other important data is on plantation biomass (a breakdown of waste generation per plantation), production capacity within the country., and the environmental impact reduction metrics (e.g., pollution levels before and after waste valorisation). Further studies should also focus on the scalability and the financial potential of waste valorisation processes and marketing of the products from sisal waste. Such studies will provide a clear guidance for industries and investors, helping them pursue the industrial production of sisal waste-derived products and realize the associated economic benefits. The Tanzanian government should implement clear policies to encourage the valorisation of agro-waste, particularly sisal. These policies could include tax incentives for businesses adopting waste valorisation technologies, subsidies for renewable energy production from agricultural waste, and waste management regulations that promote recycling and repurposing of sisal waste.

References

Abd El-Hack ME, Shafi ME, Alghamdi WY, Abdelnour SA, Shehata AM, Noreldin AE, Ashour EA, Swelum AA, Al-Sagan AA and Ragni M 2020 Black soldier fly (Hermetia illucens) meal as a promising feed ingredient for poultry: A comprehensive review. *Agriculture*. 10(8): 339.

Afoakwah NA, Zhao Y and Dong Y 2023 Biological functionality and characteristics of Jerusalem artichoke (Helianthus tuberosus L.) tuber extracts. *Acta Alimentaria*. 52(1): 12-26.

Ahmad T, Mahmood HS, Ali Z, Khan MA and Zia S 2017 Design and Development of a Portable Sisal Decorticator. *Pakistan J. Agric. Res*. 30(3): 209-217.

Anandjiwala RD and John M 2010 Sisal-cultivation, processing and products. In: Jörg Müssig (Ed) Industrial Applications of Natural Fibres: Structure, Properties and Technical Applications (pp. 181-195), John Wiley & Sons.

Anekwe IMS, Isa YM and Oboirien B 2023 Bioethanol as a potential eco-friendlier feedstock for catalytic production of fuels and petrochemicals. *J. Chem. Technol. Biotechnol*. 98(9): 2077-2094.

Andoni M, Robu V, Flynn D, Abram S, Geach D, Jenkins D and Peacock A 2019 Blockchain technology in the energy sector: A systematic review of challenges and opportunities. *Renew. Sustain. Energy Rev*. 100: 143-174.

Apolinario AC, de Carvalho EM, de Lima Damasceno BPG, da Silva PCD, Converti A, Pessoa JrA and da Silva JA 2017 Extraction, isolation and characterization of inulin from Agave sisalana boles. *Ind. Crop Prod*. 108: 355-362.

Apolinário AC, do Nascimento ML, de Luna Vieira JP, Melo CDO, Santos FF, de Lima Damasceno BPG and da Silva JA 2014 Physico-chemical quality parameters of herbal products from Agave sisalana. *Nat. Prod. Res*. 28(22): 1992-1999.

Arisutha S, Baredar P, Deshpande DM and Suresh S 2014 Evaluation of methane from sisal leaf residue and palash leaf litter. *J. Inst. Eng. (India)*. Series E 95: 105-110.

Ashokkumar V, Flora G, Venkatkarthick R, SenthilKannan K, Kuppam C, Stephy GM and Ngamcharussrivichai C 2022 Advanced technologies on the sustainable approaches for conversion of organic waste to valuable bioproducts: Emerging circular bioeconomy perspective. *Fuel*. 324: 124313.

Beleko AH and Urassa, JK 2022 Socio-economic determinants of smallholder farmers sisal productivity and profitability: a case of Korogwe District, Tanzania. *Tanzan. J. Agric. Sci*. 21(1): 113-125.

Bosco M, Mbise E and Minja RJ 2022 Production of Paper Pulp Using Sisal Fiber Waste from Sisal Spinning Processes. *Tan. J. Eng. Technol*. 41(2): 151-157

Çetin ZB 2022 *Production of lactic acid by simultaneous saccharification and fermentation of horse chestnut shell by using lactobacillus casei*. Master's thesis, Middle East Technical University, Ankara, Turkey.

Choi B, Rangel AT, Kerkhoven EJ and Nygård Y 2024 Engineering of Saccharomyces cerevisiae for enhanced metabolic robustness and L-lactic acid production from lignocellulosic biomass. *Metabolic Eng*. 84: 23-33.

Colley TA, Valerian J, Hauschild MZ, Olsen SI and Birkved M 2021 Addressing nutrient depletion in Tanzanian sisal fibre production using life cycle assessment and circular economy principles, with bioenergy co-production. *Sustainability*. 13(16): 8881.

Cunha FS, Lima SB, Pires CAD and de M 2024 Upgrade of bio-oil produced from the sisal residue composting. *GCB Bioenergy*. 16(3): e13129.

Daher CC, Barreto SMAG, de Brito Damasceno GA, de Santana Oliveira A, Leite PIP, Reginaldo FPS and Ferrari M 2023 Use of sisal industrial waste (Agave sisalana Perrine) in sustainable and multifunctional cosmetic products. *Int. J. Cosmetic Sci*. 45(6): 815-833.

Damião Xavier F, Santos Bezerra G, Florentino Melo Santos S, Sousa Conrado Oliveira L, Luiz Honorato Silva F, Joice Oliveira Silva A and Maria Conceição M 2018 Evaluation of the simultaneous production of xylitol and ethanol from sisal fibre. *Biomolecules.* 8(1): 2. https://doi.org/10.3390/biom8010002.

De Paula MP, Lacerda TM, Zambon MD and Frollini E 2012 Adding value to the Brazilian sisal: acid hydrolysis of its pulp seeking production of sugars and materials. *Cellulose*. 19: 975-992.

Demirbas MF, Balat M and Balat H 2011 Biowastes-to-biofuels. *Energy Convers. Manag*. 52(4): 1815-1828.

den Doop JEA 1949 Prospects for the Utilization of Sisal Waste. *East African Agric. J.* 15(1): 15-24.

do Carmo CO, da Silva RM, de Souza Rodrigues M and Soares AC 2014 Bioconversion of sisal agro-industrial waste into high protein oyster mushrooms. *Bioresour. Technol. Rep*. 14: 100657. https://doi.org/10.1016/j.biteb.2021.100657.

Doukali I 2023 *Enhancing Circular Economy and Waste Management in Zanzibar: By leveraging young entrepreneurship and innovation*. M.Sc. Thesis. Linnaeus University.

Du M, Cheng X, Qian L, Huo A, Chen J and Sun Y 2023 Extraction, physicochemical properties, functional activities and applications of inulin polysaccharide: a review. *Plant Foods Hum. Nutr.*. 78(2): 243-252.

Elisante E and Msemwa V 2010 Dry method for preparation of inulin biomass as a feedstock for ethanol fermentation. *African Crop Sci. J*. 18(4).

Fertahi S, Elalami D, Tayibi S, Taarji N, Lyamlouli K, Bargaz A and Barakat 2023 The current status and challenges of biomass biorefineries in Africa: A critical review and future perspectives for bioeconomy development. *Sci. Total Environ*. 870: 162001.

González VC 2017 *Techno-economic analysis of the benefits of anaerobic digestion at a rural sisal processing industry in Tanzania*. Master's Thesis, KTH Royal Institute of Technology.

Guerra GN, Cabral Albuquerque EC, Campos LM and Pontes LA 2021 Chemical and physicochemical characterization of alkali pretreated and in natura sisal solid waste. *J. Natural Fibers*. 18(2): 203-212.

Haque F, Fan C and Lee YY 2023 From waste to value: Addressing the relevance of waste recovery to agricultural sector in line with circular economy. *J. Clean. Prod*. 415: 137873.

Heidenreich S and Foscolo PU 2015 New concepts in biomass gasification. *Prog. Energy Combust. Sci*. 46: 72-95.

Jacobus AP, Gross J, Evans JH, Ceccato-Antonini SR and Gombert AK 2021 Saccharomyces cerevisiae strains used industrially for bioethanol production. *Essays in Biochem*. 65(2): 147-161.

Joshi S, Joshi T and Mishra A 2023 Bioactives and Pharmacology of Agave sisalana Perrine. *Phytochem. Comp. Pharm. Med. Plants.* 2:135

Kabeyi MJB and Olanrewaju OA 2022 Biogas production and applications in the sustainable energy transition. *Journal of Energy*. 2022(1): 8750221.

Kardamanidis A, Misailidis N, da Gama Ferreira R and Petrides D 2024 Inulin Production from Chicory Roots.

Kiarie E 2019 Biogas as a Potential Alternative Source of Energy for Industrial Sector: Case Study of Kilifi Sisal Plantation Biogas Plant. *Int. J. Adv. Res. Public*. 3(7): 30-38.

Kim S, Kim JC, Kim YY, Yang JE, Lee HM, Hwang IM, Park HW and Kim HM 2024 Utilization of coffee waste as a sustainable feedstock for high-yield lactic acid production through microbial fermentation. *Sci. Total Environ*. 912: 169521.

Kivaisi A and Mshandete A 2017 Exploring Technological Strategies for Valorization of Solid Sisal Waste: A Research Review. *Tanzan. J. Sci.* 43(1): 47-61.

Konyo AA, Machunda R, Pasape L and Mshandete A 2023 The Potential of Valorized Sisal Decorticated Waste in Rearing of Black Soldier Fly. *Recycling*. 8(1):1.

Konyo, A 2024 *Valorisation of solid sisal leaves decortication wastes using black soldier fly (hermetia illucens l.) larvae*. Doctoral dissertation, Nelson Mandela-African Institute of Science and Technology, Tanzania.

Korbag I, Omer SM, Boghazala H and Abusasiyah MA 2020 Recent Advances of Biogas Production and Future Perspective. *In: Biogas: Recent Advances and Integrated Approaches,* 1st ed. (pp. 1-3), London, United Kingdom.

Kusekwa MA 2011 A review on the renewable energy resources for rural application in Tanzania. *In: Renewable Energy-Trends and Applications* (pp. 41-72). Books on Demand.

Li M, Pu Y, Thomas VM, Yoo CG, Ozcan S and Deng Y 2020 Recent advancements of plant-based natural fiber–reinforced composites and their applications. *Composites Part B: Engineering*. 200: 108254.

Lima CS, Conceição MM, Silva FL, Lima EE, Conrado LS and Leão DA 2013 Characterization of acid hydrolysis of sisal. *Applied Energy*. 102: 254-259.

Magoggo JP 2011 Cleaner Integral Utilization of Sisal Waste for Biogas and Biofertilizer. Common Fund for Commodities: Project completion report UNIDO CFC: CFC/FIGHF/13. Tanga, Tanzania.

Majaliwa N, Kussaga J, Mabiki F, Kilima B and Manyete F 2023 Optimization of Inulin Extraction from sisal wastes using response surface Methodology. *Tanzan. J. Agric. Sci*. 22 (special issue):122-133.

Mazo GDS, Fracasso JAR, da Costa LTS, Farias Ximenes V, Zoppe NA, Viel AM and dos Santos L 2024 Development of an Antioxidant, Anti-Aging, and Photoprotective Phytocosmetic from Discarded Agave sisalana Perrine Roots. *Cosmetics*. 11(3): 104.

Melo KMDe, Dos Santos TF, Santos CM, Fonseca RTDa, Lucena NDDe, Medeiros JIDe and Aquino MSDe 2019 Study of the reuse potential of the sisal fibers powder as a particulate material in polymer composites. *J. Mater. Res. Technol*. 8(5): 4019-4025.

Mhaiki CJN, Masanja E, Katima JHY, Rajarao G, Dalhammar G 2013 Isolation and Characterization of Micro-organisms with Industrial Importance from Sisal Bole Rots. *Tanzan. J. Eng. Technol*. 34(1): 26-35.

Monja-Mio KM, Herrera-Alamillo MA, Sánchez-Teyer LF and Robert ML 2019 Breeding strategies to improve production of Agave (Agave spp.). *Adv. Plant Breed: Strateg. Ind. Food Crop*. 6: 319-362.

Mridha N, Ray DP, Singha A, Das A, Bhowmick M, Ghosh RK and Das A 2023 Composting of Natural Fibre Wastes for Preparation of Organic Manures and Bio-enhancers. *Econ. Affairs*. 68(02): 1121-1128.

Mshandete AM, Kibazohi O and Kivaisi AK 2013 Tanzania sisal industry: Auditing and characterization of sisal post-harvest wastes as a bio-resource for bio-refining. *Int. J. Pure Applied Sci. Technol*. 14(2): 84.

Msuya N, Katima JHY, Minja RJA, Masanja E and Temu AK 2018a Characterization of Sisal Boles for Production of Polylactic Acid (PLA). *Am. J. Chem*. 8(2): 36-40.

Msuya N, Katima JHY, Masanja E, Minja RJA and Temu AK 2018b Lactic Acid Production from Sisal Boles Juice by Lactobacillus Delbrueckii Sp. Delbrueckii. *Am. J. Chem*. 8(3): 57-64.

Msuya N, Temu AK and Minja RJ 2022 Effect of Temperature, Catalyst Concentration and Time, on Polylactic Acid Production from Sisal Boles Juice by Ring Open Polymerization. *Tanzan. J. Eng. Technol*. 41(2): 70-81.

Msuya, N, Andrew, SP and Temu, AK 2024 Isolation and Characterization of Yeast from Sisal Boles for Bioethanol Production. *Tanz. J. Sci*. 50(3): 628-638.

Muthangya M, Hashim SO, Amana JM, Mshandete AM and Kivaisi AK 2013 Optimization of Pleurotus mushroom cultivation on saline sisal solid waste. *World Appl. Sci. J*. 23(9): 1146-1150.

Mwaniki AM 2018 Factors affecting sisal cultivation and adoption in Kiomo division, Kitui County, Kenya. Dissertation, South Eastern Kenya University, Kenya.

Naik RK, Dash RC, Behera D and Goel AK 2016 Studies on Physical Properties of Sisal (Agave Sisalana) Plant Leaves. *Int. J. Agric. Sci*. 8(48): 2004-2007.

Ndazi B, Tesha JV and Bisanda ET 2006 Some opportunities and challenges of producing bio-composites from non-wood residues. *J. Mater. Sci*. 41: 6984–6990.

Nerini FF, Andreoni A, Bauner D and Howells M 2016 Powering production. The case of the sisal fibre production in the Tanga region, Tanzania. *Energy Policy*. 98: 544-556.

Ngonyani CJ 2010 *Utilization of sisal bole juice-inulin as an Alternative chemical feedstock in citric acid Production*. PhD thesis, University of Dar es Salaam, Dar es Salaam, Tanzania.

Nikolaivits E, Pantelic B, Azeem M, Taxeidis G, Babu R, Topakas E and Nikodinovic-Runic J 2021 Progressing plastics circularity: A review of mechano-biocatalytic approaches for waste plastic (re) valorisation. *Front. Bioeng. Biotechnol*. 9: 696040.

Nylander L 2024 *Corporate Commitments and Human Capabilities: A Thematic Analysis of Corporate Social Responsibility in the Tanzanian Sisal Industry using Nussbaum's Capabilities Independent*. Thesis basic level, Linnaeus University.

Ogbu CC and Okey SN 2023 Agro-industrial waste management: the circular and bioeconomic perspective. In: Fiaz Ahmad and Muhammad Sultan (Ed) *Agricultural Waste-New Insights*. https://www.intechopen.com/chapters/85597.

Oudshoorn L, Lemmens AMC, Lapperre PE and Prasad KK 1995 Biogas from sisal waste: a new opportunity for the sisal industry in Tanzania. *Energy Sustain. Dev*. 2(4): 46-49.

Pereira LG, Heeres HJ, Lima SB and Pires CAM 2022 Development of process-product relations for the pyrolysis of sisal residue. *J. Anal. Appl. Pyrolysis*. 165.

Peter EA, Hudson N and Evans C 2019 Ameliorating Sisal Leaf Wastes in Purveying Plant Macronutrients. *Int. J. Res. Anal. Rev. (IJRAR)*. 6(4): 87-93.

Rajabu YR and Manyele SV 2015 Performance Improvement for Sisal Waste Anaerobic Biodegradation by Digester Redesign and Feed Size Reduction. *Engineering*. 7(9): 553-566.

Sannapapamma KJ, Mariyappanavar S, Sangannavar VV, Jamadar D, Vastrad JV and Byadagi SA 2020 Development and quality assessment of handmade papers using underutilized agro based natural fibres. *J. Pharmacog. Phytochem*. 9(2): 1410-1417.

Sansaniwal SK, Rosen MA and Tyagi SK 2017 Global challenges in the sustainable development of biomass gasification: An overview. *Renew. Sustain. Energy Rev.* 80: 23-43.

Schramade W 2017 Investing in the UN sustainable development goals: opportunities for companies and investors. *Journal of Applied Corporate Finance*. 29(2): 87-99.

Sharma SH, Varshney VK 2012 Chemical analysis of Agave sisalana juice for its possible utilization. *Acta Chim. Pharm. Indica*. 2(1): 60-66.

Šimonovičová A, Vojtková H, Nosalj S, Piecková E, Švehláková H, Kraková L, Drahovská H, Stalmachová B, Kučová K and Pangallo D 2021 Aspergillus niger environmental isolates and their specific diversity through metabolite profiling. *Front. Microb*. 12: 658010.

Siwal SS, Sheoran K, Saini AK, Vo DVN, Wang Q and Thakur VK 2022 Advanced thermochemical conversion technologies used for energy generation: Advancement and prospects. *Fuel*. 321: 124107.

Santos JD, Espeleta AF, Branco A and de Assis SA 2013 Aqueous extraction of pectin from sisal waste. *Carbohydr. Polym*. 92(2): 1997-2001.

Santos JD, Vieira IJ, Braz-Filho R and Branco A 2015 Chemicals from Agave sisalana biomass: isolation and identification. *Int. J. Mol. Sci*. 16(4): 8761-8771.

Saxena M, Pappu A, Haque R and Sharma A 2011 Sisal fibre-based polymer composites and their applications. *Cellulose Fibers: Bio Nano Polym. Compo: Green Chem. Technol*. 2011: 589-659.

Singh M, Rani H and Chopra HK 2025 Extraction, optimization, purification and characterization of inulin from chicory roots using conventional and greener extraction techniques. *Int. J. Biol. Macromol*. 306: 141385.

Srinivasakumar P, Nandan MJ, Kiran CU and Rao KP 2013 Sisal and its Potential for Creating Innovative Employment Opportunities and Economic Prospects. *IOSR J. Mech. Civil En*. 8(6): 1-8

Tawo OE and Mbamalu MI 2025 Advancing waste valorization techniques for sustainable industrial operations and improved environmental safety. *Int. J. Sci. Res. Arch*. 14(02): 127-149.

Terrapon-Pfaff JC, Fischedick M and Monheim H 2012 Energy potentials and sustainability—the case of sisal residues in Tanzania. *Energy Sustain. Dev*. 16(3): 312-319.

URT 2024 Ministry of agriculture budget speeches 2014 to 2024 fiscal year. United Republic of Tanzania. https://www.kilimo.go.tz/index.php/highlights/view/bajeti-ya-mwaka-2024-2025. Accessed 30 May 2024.

Virgin I, Diaz-Chavez R and Nzuve L 2022 State of the Bioeconomy in Eastern Africa: 2022 SEI: Stockholm Environment Institute. Sweden.

Vuorinne I, Heiskanen J, Maghenda M, Mwangala L, Muukkonen P and Pellikka PK 2021 Allometric models for estimating leaf biomass of sisal in a semi-arid environment in Kenya. *Biomass Bioenergy*. 155: 106294.

Wang X, Li C, Lam CH, Subramanian K, Qin ZH, Mou JH and Lin CSK 2022 Emerging waste valorisation techniques to moderate the hazardous impacts, and their path towards sustainability. *J. Hazard. Mater.* 423: 127023.

Warra AA and Prasad MN 2024 Industrial Crops: Bioresources to Biotechnology. 1st ed, CRC Press.

Xavier FD, Silva AJO, Lima MS, da Fonseca MG and da Conceição MM 2023 Potential Application of Membrane Obtained from Sisal Bagasse in the Removal of Inhibitors from the Fermentation Process. *J. Brazilian Chem. Soc*. 34(10): 1531-1540.

Yhdego M 2021 The circular economy in Tanzania: A self-referential system. In: *Circular economy: Recent trends in global perspective* (pp. 69-112), Springer Nature Singapore.

Zhang X, Liu L and Lin C 2014 Isolation, structural characterization and antioxidant activity of a neutral polysaccharide from Sisal waste. *Food Hydrocolloids*. 39: 10-18.

Zhang X, Zhu X, Shi X, Hou Y and Yi Y 2022 Extraction and purification of inulin from Jerusalem Artichoke with response surface method and ion exchange resins. *ACS Omega*. 7(14):12048-12055.

Zu H, Wu Y, Liao Z, Wang Y, Wang B, Qin P, Ren W, Zhao J and Cai D 2024 Research progress on the biosynthesis of d-lactic acid from low-value biomass materials. *Biomass and Bioenergy*. 182: 107067.