



Cannabis sativa L. biomass valorization as a strategic bioresource for South Africa's circular bioeconomy: integrating biorefinery pathways and green extraction

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Abstract

South Africa's legalized *Cannabis Sativa* L. industry generates substantial biomass waste, including post-harvest materials such as stalks, leaves, roots, and seeds, as well as post-extraction residues rich in lignocellulosic components (cellulose, lignin, hemicellulose) and functional compounds (fibers, phenolic compounds, and proteins) which remain largely unvalorized. This review critically and systematically examines valorization pathways for *Cannabis sativa* L. biomass within the context of a circular bioeconomy, focusing on its potential as a bioresource amid South Africa's evolving regulatory, agricultural, and industrial landscape. A systematic scoping review of 65 peer-reviewed studies (2018–2025) was conducted using international databases to evaluate biochemical and thermochemical conversion, integrated biorefinery strategies, and green extraction methods such as supercritical CO₂ extraction, microwave-assisted extraction (MAE), and ultrasound-assisted extraction (UAE). Compositional analysis indicates that lignocellulosic fractions from *Cannabis sativa* L., particularly bast fibers and hurds, are well-suited to cascaded biorefinery applications, enabling the recovery of cannabinoids, carbon-based materials, and bioenergy. However, several challenges persist, including biomass recalcitrance to enzymatic hydrolysis, inconsistent feedstock availability, and the lack of a standardized protocol within South Africa's regulated environment. Techno-economic assessments (TEA) highlight the need for financial incentives, decentralized infrastructure, and cohesive policies among government entities, including DALRRD, SAHPRA, and DTIC. The review proposes a South African collaboration framework linking policy with research-based process design. Key gaps include the need for life cycle assessment (LCA) and TEA validation at the pilot scale, characterization of landrace cultivars, and development of accessible pretreatment technologies for smallholders.

Keywords Biomass valorization · *Cannabis sativa* L. · Conversion Technologies · Circular bioeconomy · South Africa

1 Introduction

The recent easing of regulations in the industrial hemp and medical cannabis sectors, driven by national ambitions to position South Africa as a leading global producer, marks a significant step toward industrialization. Industrial hemp and medicinal cannabis both originate from *Cannabis sativa* L., but their Delta-9-tetrahydrocannabinol (THC) levels legally distinguish them. In South Africa's updated regulations, “hemp” refers to fiber-type varieties with THC content no more than 2% in the leaves and flower buds, used for fiber, seed, and Cannabidiol (CBD) production [1, 2]. Meanwhile, medicinal cannabis includes drug-type varieties with higher THC levels, cultivated and processed for medical and pharmaceutical uses [2, 3]. To further the broader agricultural

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objectives, the Department of Agriculture (DoA) has begun a significant expansion of the South African Plant Improvement Act (PIA), aiming to recognize cannabis as an agricultural crop [1]. This regulatory update will lift previous restrictions set by the South African Health Products Regulation Authority (SAHPRA) and help remove market barriers [4]. Notably, cannabis has been removed from the Drug and Drug Trafficking Act, now falling under the Medicines Act, and the longstanding restriction on South African farmers growing varieties with THC levels below 2% without a permit has been eradicated [5].

A recent study by the Localization Support Fund, published in March 2026 and conducted in collaboration with the Presidency, the Industrial Development Corporation (IDC), and the Department of Trade, Industry and Competition (DTIC), estimates that the South African hemp industry could expand from R7.3 billion in 2025 to R40 billion by 2040 [6]. Additionally, a DTIC presentation reported that South Africa's formal cannabis industry currently generates approximately R5.5 billion (US\$ 318 million) annually, with ongoing growth in both medical and recreational markets [7]. South Africa's varied agro-ecological zones and a counter-seasonal production cycle drive this growth, allowing the country to supply global markets year-round and fill gaps left by Northern hemisphere producers [6]. This presents significant opportunities for smallholder farmers in marginalized regions like the Eastern Cape and KwaZulu-Natal, who produce over 38,000 tonnes of cannabis annually. These farmers have relied on cannabis as a crucial cash crop and now have the opportunity to participate legally in the formal market [2, 8]. However, this swift shift from an informal to a formal, industrial-scale sector poses a significant challenge due to the substantial generation of biomass waste [9].

Post-harvest residues, including stalks, leaves, roots, seeds, and extraction leftovers, contain various compounds in their structural materials, such as proteins, lignin, phenolic compounds, functional lipids, and fibers [10–12]. These components have been demonstrated to have significant potential in food products, health supplements, bio-based materials, and renewable energy sources [13–15]. Currently, the main methods for disposing of cannabis waste include landfilling, composting, or incineration [16]. This reliance on destruction methods is primarily driven by concerns over security, legislation, and licensing related to cannabis production [16]. In South Africa in particular, waste management relies heavily on landfilling, with about 89% of municipal waste sent to landfill facilities, as illustrated in Fig. 1 [16]. This results in landfills reaching capacity and infrastructure that does not meet minimum regulatory standards, highlighting the over-reliance on this disposal method. Conversely, biomass or material reuse, recycling,

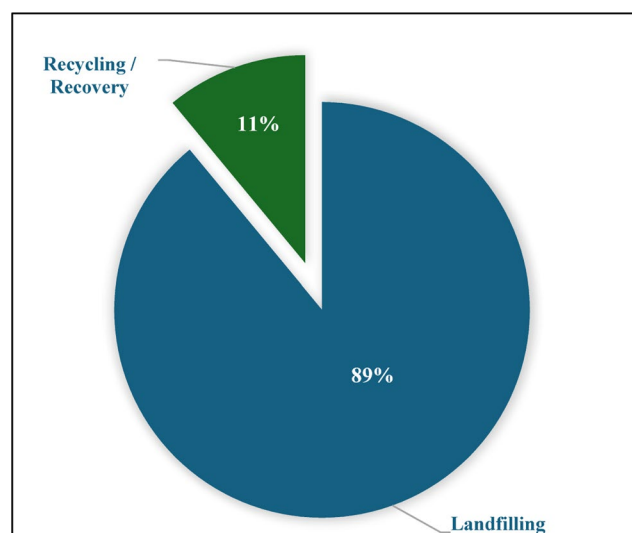


Fig. 1 Current Waste Disposal Method Fractions [16]

and recovery remain low, accounting for only 11%, as noted in the National Waste Management Strategy [16, 17]. This unregulated infrastructure gap, combined with national policy gaps, the high capital costs of waste-processing facilities, and limited knowledge of resource-recovery technologies, poses challenges for local cannabis-waste valorization, especially in rural municipalities [18]. The current regulatory frameworks under the SANS 10,248 mandate the destruction of the THC content or rendering of the substance impossible to use for consumption, although this is understandable from a safety perspective, this also represents a substantial economic loss and a missed resource recovery opportunity [8].

South Africa's theoretical renewable energy potential from biomass waste incineration and landfill gas is estimated at 104,463 TJ/year and 22,710 TJ/year [19]. Given cannabis waste's energy potential, prioritizing medicinal cannabis as an organic waste stream is important, but the lack of standard handling and valorization protocols hinders this progress. This conflicts with South Africa's draft National Waste Strategy 2026, which emphasizes organic waste to promote a circular bioeconomy and aligns with United Nations Sustainable Development Goals (SDGs), South Africa's renewable energy targets in the SAREM, and the National Biodiversity Economy strategy that aims to preserve ecological integrity and promote native crop use [19–22]. The conversion of lignocellulosic biomass, such as cannabis waste, into biofuels and bioenergy has significant potential to reduce greenhouse gas (GHG) emissions, provide a renewable energy source as an alternative to fossil fuels, and help the country achieve climate change mitigation objectives [22, 23].

Research in the bioeconomy sector indicates that lignocellulosic biomass, like cannabis biomass, has structural

properties comparable or even superior to other lignocellulosic feedstocks, and findings from pre-treatment studies in sectors such as forestry and fibrous agriculture can be applied and tested in cannabis applications, using biochemical, thermochemical, and integrated conversion methods [24, 25]. These methods combine advanced extraction with traditional conversion to maximize resource use. Incorporating lignocellulosic biomass into biorefineries can extend beyond traditional biofuels into advanced composites and bioactive products for various industries [13, 26]. For example, the biochemical conversion pathways of cannabis residues used as feedstock for anaerobic digestion (AD) to produce methane-rich biogas can be integrated into a broader system. This system combines biochemical AD with thermochemical pyrolysis to simultaneously capture both fuel gases and solid biochar co-products for soil amendment to cultivate future cannabis crops [27]. Implementing a hybrid cannabis valorization model in South Africa could boost export competitiveness and diversify products. While cannabis is often considered for biofuels and biochemicals, the idea of turning waste into proteins has also shown economic potential, especially when using hemp seed cake or defatted oil residues [28].

Hemp seeds are a rich source of protein, amino acids, and bioactive compounds, offering notable health benefits. Hemp cake provides histidine and albumin proteins and can be processed into protein isolates (> 90% protein) and concentrates (30–80% protein) using advanced ultrasonic-assisted extraction methods [29]. Such processes overlap with Single Cell Protein (SCP) production from agri-food wastes, showcasing the versatile potential of hemp biomass, which can be used in microbial cultivation with hydrolysates from cannabis fibers as substrates [30]. However, the successful implementation of these valorization strategies requires comprehensive life-cycle assessment (LCA), technical and economic assessment (TEA), and the development of regulatory frameworks that integrate cannabis waste management requirements and resource recovery strategies [31].

Against this backdrop, this review systematically examines waste generation and biomass valorization pathways across the industrial hemp and medicinal cannabis sectors in South Africa. In this review, the term “cannabis biomass” broadly refers to both industrial and medicinal cannabis residues, unless specified otherwise, and evaluates the technical and economic feasibility of their integration into a circular biorefinery framework. Waste valorization pathways, such as biochemical, thermochemical, and green extraction methods, are thoroughly evaluated for their benefits, limitations, process efficiency, technology readiness levels (TRLs), and scalability in the context of South African agriculture, infrastructure, and regulations. The review also

explores how integrated biorefinery processes can enhance the co-recovery of high-value cannabinoids, lignocellulosic fibers, carbon-based materials, and bioactive compounds from cannabis waste streams, thereby promoting resource efficiency and reducing environmental pollution caused by landfill disposal. Ultimately, the review evaluates the current regulatory fragmentation across government departments (DALRRD, SAHPRA, DTIC, etc.), which hinders localized commercialization and advocates incorporating research-based process design. This aims to support the commercial viability of valorization technologies, fostering job creation, economic growth, and sustainable development throughout both large-scale cannabis industries and small-scale local producers and processors in South Africa.

2 Review methodology

This study involved a systematic search of two major international databases, Scopus and ScienceDirect, to find peer-reviewed articles on cannabis biomass valorization and biorefinery applications. The selection and screening of these articles were conducted as part of a systematic scoping review in accordance with the PRISMA framework [32]. The search was restricted to publications from 2018 to 2025, aligning with South Africa’s landmark 2018 Constitutional Court ruling that expanded legal and research engagement with cannabis. The two main keyword search strings used in both databases were “Cannabis waste valorization” and “Cannabis sativa L. biomass research”. These were chosen through an iterative scoping approach. Initial broader searches produced overlapping and redundant results, showing that these two strings effectively covered relevant literature on valorization pathways, including biochemical, thermochemical, and extraction methods. Furthermore, database indexing in Scopus and ScienceDirect facilitated the incorporation of related terms such as ‘biorefinery’, ‘bioenergy’, and ‘lignocellulosic conversion’ through keyword mapping and citation chaining. This method follows best practices for scoping reviews, in which a targeted search strategy balances thoroughness and relevance. The initial search yielded 865 records from Scopus and 380 from ScienceDirect, for a total of 1,245 records; after removing 235 duplicates, 1,010 records remained. Screening excluded 780 records, with 230 for full-text review. Applying the same criteria, further exclusions included studies lacking methodologies ($n = 57$), falling outside the biomass scope ($n = 73$), and other exclusions, such as non-English publications and incomplete data ($n = 35$). In total, 165 articles were excluded, leaving 65 studies for final review. To assess research gaps in South Africa, these studies were classified by geographic relevance: 55 were globally relevant to

cannabis biomass valorization, while only 6 focused specifically on South Africa. The research gap was estimated at 89.1%, showing that most existing studies (89.1%) do not focus on the South African context. This methodology is illustrated in Fig. 2 in a PRISMA flow diagram. This underscores the limited research on cannabis biomass valorization within South Africa's regulatory, agricultural, and industrial settings.

This review methodology revealed that no peer-reviewed studies specifically examine cannabis biomass valorization in South Africa. Consequently, in this review paper, non-peer-reviewed sources were limited to regulatory frameworks, policy reports, and industry statistics, as peer-reviewed data on these topics is not readily accessible. The most closely related works identified during the research gap screening include a study by Viviers et al. [33] that examines solvent residue contaminants related to cannabis-based products in the South African market [33], a review

by Ndlangamandla et al. [2] review of South African cannabis genetic diversity, and chemical profile [2], a study by Duminy et al. [34] on valorizing wax by-products from commercial cannabis waste processing [34], research by Duminy et al. [35] on chromatographic techniques used to characterize wax by-products during cannabinoid extraction and broader biorefinery frameworks for lignocellulosic waste, which do not specifically address cannabis waste stream valorization [26, 35, 36].

3 Cannabis biomass characteristics

3.1 Cultivation and harvesting waste

The non-inflorescence biomass fractions of the *Cannabis sativa* L. plant represent components of the biomass harvested from the crop that have properties suitable for

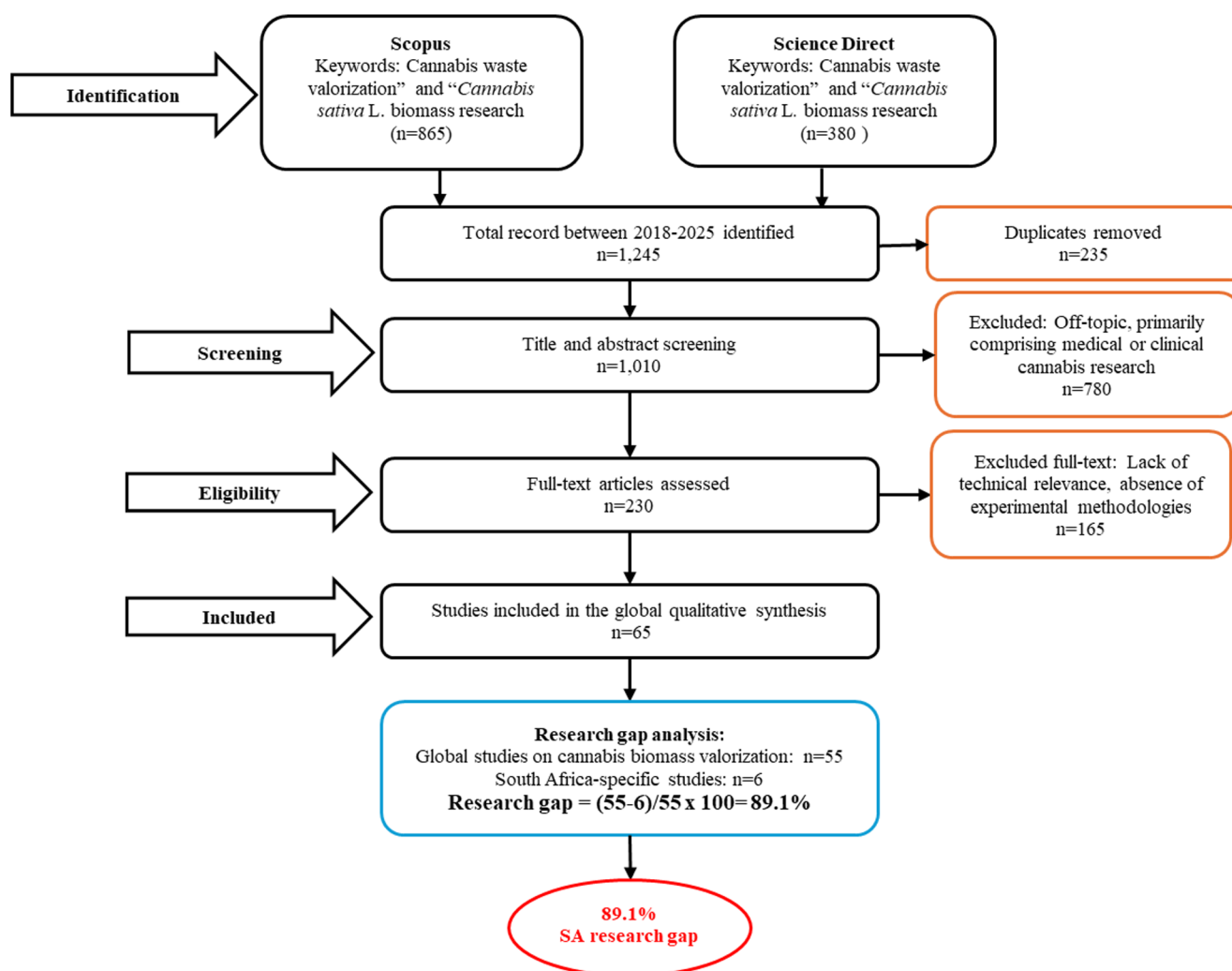


Fig. 2 PRISMA flow diagram illustrating cannabis biomass valorization research studies sourced from the Scopus and ScienceDirect databases between 2018 and 2025

various valorization pathways. These components include the lignocellulosic-rich stalks, roots, and stems, which make up about 70% of the plant's dry weight and are discarded after the valuable inflorescences are harvested [37]. Stems are characterized by their flexible bast fibers, which constitute approximately 35–40% of the stalk's total biomass [38]. Bast fibers have a multicellular and hierarchical structure containing roughly 61%–69% cellulose, compared to 40%–48% in hurds fibers, with the lower cellulose content in hurds resulting in a higher proportion of lignin and hemicelluloses [39]. As a result, hurds' fiber is better suited for lower-value applications, such as animal bedding and construction materials like hempcrete, while bast fibers are used in textiles or bio-composites [38].

Mechanical processing of cannabis plant stalks generates hurds as a waste fraction. Hurds are the woody inner core of the stem, produced after the outer bast fibers are separated by decortication, and have been reported to make up 50% of the whole plant's dry weight [40]. Downstream industrial processing of fiber generates waste in the form of dust, broken fiber segments, and short fibers that do not meet the quality requirements of textile or composite-industry end users, attributable to cultivar growth conditions and processing yields [41].

Leaves from the cannabis plant are also part of an additional waste stream, especially in the grain and cannabinoid industries, where plants are harvested at maturity. This waste contains bioactive compounds such as cannabinoids, terpenes, and phenols, though in lower concentrations than inflorescences [42]. Leaves have relatively high protein levels, with a reported concentration of 2%, making them a suitable feedstock for protein recovery or as a nutrient source in fermentation-based animal feed supplements [43]. A comparative study by Salami et al. [44] assessed pyrolysis liquids obtained through slow pyrolysis of industrial hemp leaves, hurds, and roots, revealing that the leaf fraction had the highest concentration of ketones, acids, and aromatics, making it suitable for various valorization pathways [44].

Root systems are another often-ignored waste fraction. Roots have shown a significant capacity to absorb and store heavy metals such as lead, nickel, and cadmium [45]. Gagné et al. [46] also demonstrated that the roots of *Cannabis sativa* L. exhibit potent antioxidant and anti-inflammatory properties, suggesting they could serve as a source for therapeutic applications rather than being discarded [46].

During commercial-scale cultivation, large amounts of water and energy are consumed, contributing indirectly to waste through resource depletion and potentially causing ecological harm through land clearance, excessive pesticide use, and fertilizer use [47]. Cultivation also produces significant non-organic waste, including used growing media

such as rockwool, fertilizer and pesticide containers, and plastic materials used for irrigation and coverings [47, 48].

3.2 Extraction residues

Extraction residues are considered a secondary biomass stream with residual value, depending on the targeted compounds and the extraction method used. These residues are usually generated from processes designed to extract cannabinoids, terpenes, proteins, or other bioactive molecules, leaving behind a matrix rich in fibers, lignin, cellulose, hemicellulose, and minor phytochemicals [49]. Techniques employed include traditional solvent extraction, pressurized liquid extraction (PLE), enzyme-assisted extraction, microwave-assisted extraction, ultrasonic extraction, and supercritical fluid extraction (SFE) [50–54]. Spent solvents from extraction processes create a significant waste stream. A study on solvent residue contaminants in cannabis-based products in the South African market revealed an alarming 37% noncompliance rate with USP 467 standards, highlighting a major regulatory and environmental issue that calls for the development of waste-stream valorization from cannabis processing [33]. An important yet often neglected byproduct is the waxy residue removed during winterization of crude cannabis extracts [49]. These waxes contain entrapped cannabinoids reaching 41–46% by weight, representing a major process inefficiency and valuable recovery opportunity [35]. Winterization involves treating biomass with solvents such as ethanol under counter-current flow at 20 °C to 24 °C, then cooling to approximately –40 °C to promote wax crystallization and separation [35]. Overall, cannabis extraction residues serve as a versatile feedstock, and maximizing their use requires careful consideration of how upstream extraction methods modify their physical structure and chemical composition, as well as downstream market demands aligned with South Africa's sustainable bioeconomy goals [55]. Figure 3 illustrates the waste produced across the cannabis value chain and its lifecycle.

4 Quantification of available cannabis biomass in South Africa

Quantifying South Africa's cannabis waste is vital for assessing its potential as a national bioresource. Although there are no published data on the amount of cannabis waste produced by South Africa's industry, this review provides an estimate using a bottom-up approach. This method uses assumptions and data from permits for industrial hemp, licensed medicinal cannabis, illicit cultivation in the Eastern Cape and KwaZulu-Natal, and South African Customs Union hemp



Fig. 3 Cannabis Sector Waste Generation Lifecycle

residues. Though it may include hemp-based animal feed, it cannot directly quantify cannabis waste. Table 1 summarizes the main South African data sources used to estimate available biomass since the industry was legalized.

According to data in Table 1 and assuming a 30% active cultivation rate as recorded in the parliamentary briefing, with 29,000 hectares cultivated, and considering that 70% of the harvested biomass comprises lignocellulosic stalks, roots, and stems (considered waste), the formal hemp sector generates an estimated 73,080 tonnes of waste biomass per year [37]. Full permit use indicates waste biomass could reach about 243,000 tonnes annually, despite a reported 30% active cultivation rate. The medicinal cannabis sector produces 601 tonnes of high-value residual biomass yearly from 93 licenses over 186 hectares. With an estimated yield

of 3 tonnes per hectare and a 20% harvest index, this results in roughly 558 tonnes of dried flower and 2,790 tonnes of total biomass. An 80.2% residue rate after extraction yields about 601 tonnes of waste biomass, primarily spent plant material with residual bioactive compounds. While smaller than the hemp stream, the medicinal fraction has a higher valorization value per kilogram due to cannabinoids, which can make up 41–46% by weight [34]. The illicit sector carries the highest uncertainty in estimates since cultivation areas after decriminalization are not reported in any published data. The estimated range is between 5,000 and 15,000 hectares, derived from data from the post-2018 and post-2024 decriminalization periods, using a 70% non-flower waste fraction. It is assumed to produce 2,226–6,678 tonnes of non-flower biomass annually. These estimates

Table 1 Input parameters and South African data sources for cannabis waste biomass estimation

Assumption	Value	Reference
DALRRD hemp data		
Total DALRRD permits issued (KZN: 664 cultivation permits for a 2 ha cultivation area; EC: 100 cultivation permits issued by ECRDA (1–50 ha each))	1,725	[56]
Total registered hectares	29,000 ha	[56]
Maximum cultivation area per permit	50 ha	[57]
Active cultivation rate (assumed)	30%	[58]
Estimated actively cultivated area	29,000 × 30% = 8,700 ha	
Hemp biomass yield (stalk + seed)	12 t/ha	[59]
Non-flower waste fraction	70%	[37]
Post-extraction residues (% total biomass)	80.2%	[60]
SAHPRA medicinal licenses		
SAHPRA active licenses	93 sites	[61]
SAHPRA licensed area	2 ha	[56]
SAHPRA licenses have been issued since 2022	83 cultivation + 4 manufacturing + 120 export + 30 research	[57]
Dried flower yield per hectare	3 t/ha	[56]
Informal Sector/Export		
Historical cultivation area range	2,000–82,000 ha	[62]
Illicit cultivation range (Assumed using Post-2018 and post-2024 CfPPA decriminalization context)	5,000–15,000 ha	
Illicit yield (Assumption based on the reported R36 billion) market + assumed cultivation size + price of flower biomass)	0.636 t/ha	[63]
SACU exported hemp agricultural residues (2024)	1.46 million kg	[64]

across the three sectors are conservative baseline figures, pending the publication of a primary national cannabis waste audit, which currently does not exist in South Africa.

5 Chemical composition of cannabis biomass

5.1 Lignocellulosic composition

Cannabis waste is primarily composed of lignocellulosic biomass, a complex structure mainly consisting of cellulose, hemicellulose, and lignin, along with minor quantities of other organic and inorganic compounds [31, 65]. The proportions of these main components determine the physical and chemical valorization potential; however, their reported resistance to biochemical conversion necessitates pretreatment before enzymatic hydrolysis or final application [66]. Hemp cultivar selection significantly affects the

lignocellulosic composition, as different cultivars influence bioenergy yield, pretreatment requirements, conversion efficiency, and the suitability of specific bioenergy pathways [67]. Table 2 summarizes the reported range of lignocellulosic composition, which varies by hemp cultivar.

Cellulose is a long chain of glucose units that provides plants with basic structural support [70]. Hemicellulose serves as a binding matrix, contributing to the flexibility of cell walls [13]. Lignin is a phenolic polymer crucial to vascular tissues, providing plants with strength while facilitating water movement and inhibiting microbial decay [71]. The lignocellulosic characteristics and composition of cannabis biomass have been extensively studied in recent years, and its advantages over conventional lignocellulosic residues have been reported due to its favorable composition and versatile applications [72]. Industrial hemp stalks have shown favorable compositional traits for use in biomass conversion, with the total polysaccharide fraction reaching 58–68% of dry matter, superior to corn stover and wheat straw [13]. The

Table 2 Chemical Composition of Hemp Cultivars and Plant Components

Biomass Source/Cultivar	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Industrial Hemp (General)	65–75	13–26	4.8–7.4	[13]
Hemp Stalks (Futura 75 cultivar)	43.6	15.1	21.5	[68]
Hemp (<i>Finola</i> cultivar)	62	17	19	[2]
Hemp bast fibers	57–77	9–14	5–9	[69]
Hemp Woody Core (Hurds/Shives)	40–48	18–24	21–24	[69]
Hemp (Henola Variety)	49	21	9	[14]
Hemp (Whole Plant)	77 (holocellulose)		4–5	[27]

Table 3 Compositional comparison of hemp stalks with corn stover and wheat straw

Biomass Source	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Hemp Stalks	38–45%	20–23%	16–22%	[13]
Corn stover	39–40%	30%	20%	[73]
Wheat straw	35–42%	20–26%	15–20%	[73]

compositional comparison between hemp stalks, corn stover, and wheat straw is summarized in Table 3.

5.2 Physicochemical characteristics

The physicochemical characterization of *Cannabis sativa* L. biomass includes ultimate and proximate analyses that confirm its biochemical composition, thereby verifying its suitability as a feedstock for bioenergy and material valorization, particularly from waste streams such as stalks, leaves, and residues. Composition varies by plant part and chemotype (e.g., seed, flower, roots; THC- or CBD-dominant) [43, 67]. During the literature review, it was observed that no South African primary data reported or published information on the physicochemical characteristics of locally cultivated medicinal or industrial hemp. This confirms the research gap identified and highlights the urgent need for local physicochemical characterization and mapping studies. Variability in the physicochemical composition of different cannabis plant parts influences the optimal valorization strategy and can result in inefficient process design if not properly considered [10]. Therefore, waste streams from industrial hemp and medicinal cannabis must be characterized separately, as their different cultivation, harvesting, and processing methods produce biomass with distinct properties [74]. Hussain et al. [10] reviewed the physicochemical, nutritional, and metal characteristics of Cannabis species [10]. While Audu et al. [43] performed a proximate analysis of *Cannabis sativa* from Nigeria, providing detailed nutritional information for various plant parts [43]. Both studies highlighted

that *Cannabis sativa* has diverse biomass, with non-flowing parts such as leaves and stems holding considerable value. These parts contain proteins, amino acids, minerals (K, Ca, Mg), carbohydrates, and bioactive compounds such as phenolics and flavonoids [10]. While cannabinoids are most concentrated in inflorescences, the residual biomass still offers nutritional and functional benefits for applications in biorefineries, nutraceuticals, and materials [75]. Table 4 and Table 5 summarize the nutritional and compositional characteristics of *Cannabis sativa* plant fractions as reported by two researchers.

Thermochemical characterization is a key step in analyzing cannabis biomass composition, as it determines the energy content, decomposition behavior, and suitability of the plant residues [76]. This information supports the selection, design, and optimization of conversion processes such as pyrolysis, gasification, and bioenergy production within a circular economy framework [13]. Marrot et al. [76] conducted a detailed thermochemical analysis of hemp stalk biomass, reporting the proximate analysis, which includes moisture, volatile matter, fixed carbon, and ash, and calorific values for raw hemp stalks and biochar produced at a range of pyrolysis temperatures [76]. In thermochemical analysis, fixed carbon is the solid, combustible residue after volatile compounds are removed. It indicates potential energy release during combustion and, along with volatile matter, influences the waste's calorific value [77]. The proximate thermochemical properties of the hemp stalk biomass and biochar produced are summarized in Table 6. In addition to this study, Salami et al. [44] performed slow pyrolysis on industrial hemp Futura

Table 4 Nutritional proximate composition of *Cannabis sativa* plant fractions by tissue type

Parameter	Range	Tissue/Notes	Reference
Moisture content	1.1–11.90%	Moisture varied from seeds (lowest) to Cannabis indica (highest), measured by loss on drying at 105 °C.	[10]
Oil content	Up to 51.06%	Highest in seeds; lower in flower and stem tissues	[10]
Ash content	3.7–25.7%	Varies by tissue type; elevated ash increases combustion challenges	[10]
Protein	4.21–43.04%	Varies by tissue type	[10]
Carbohydrates	4–43%	Varies by tissue type	[10]
Fibre content	4–43%	Varies by tissue type	[10]

Table 5 Nutritional proximate composition of *Cannabis sativa* plant fractions

Plant fraction	Moisture (%)	Crude protein (%)	Crude fibre (%)	Ether extract/lipid (%)	Ash (%)	NFE (%)	Reference
Leaves	6.87	23.00	18.95	19.97	11.18	19.25	[43]
Stem	5.16	17.20	23.13	8.02	6.78	39.70	[43]
Seeds	5.91	20.19	25.36	9.31	7.20	32.03	[43]

Table 6 Proximate analysis and thermochemical properties of industrial hemp biomass by plant fraction

Plant fraction	Moisture (%)	Volatile matter (%)	Fixed carbon (%)	Ash (%)	Temperature range (°C)	HHV (Raw biomass) (MJ/kg)	HHV (Post-treatment) (MJ/kg)	Reference
Hemp stalks (Whole stalk: fibers + shives)	6.76	72.1	25.2	2.7	400–600	18.77	-	[76]
Hemp stalk biochar	1.65–2.50	10.4–27.1	63.1–86.8	6.8–9.8	800–1000	-	28.45–30.95	[76]

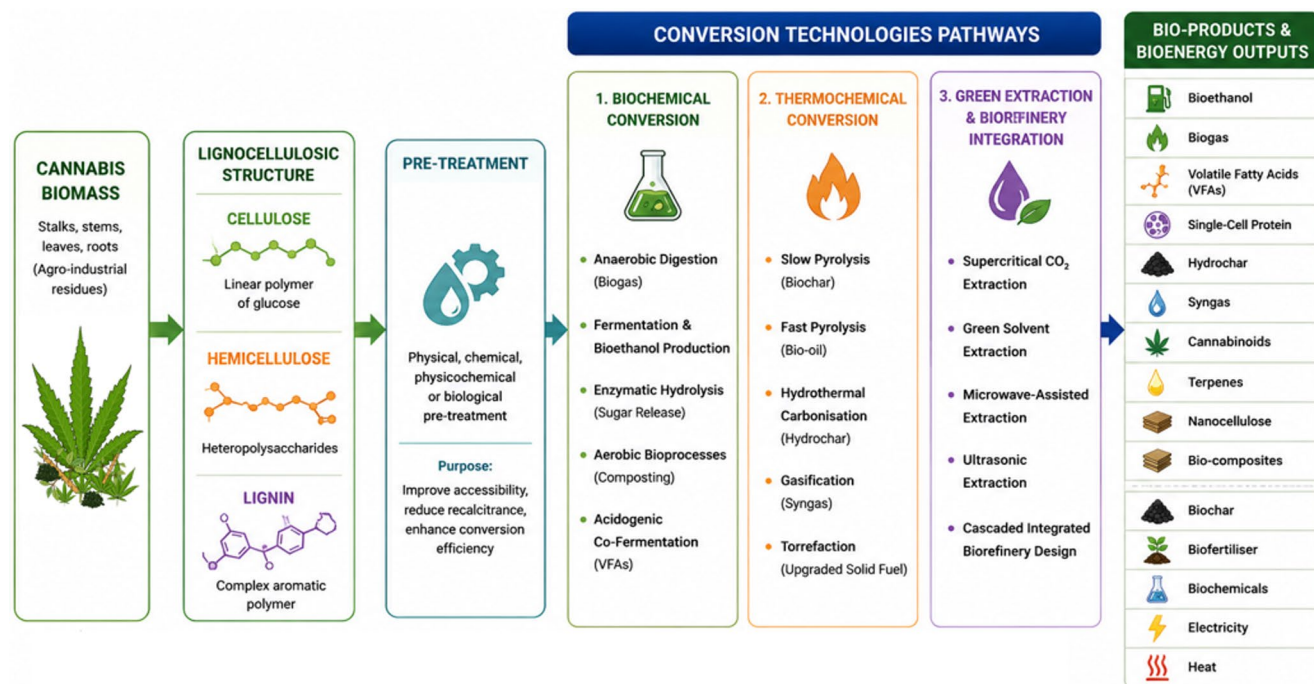
Table 7 Slow pyrolysis product yields and key pyrolysis liquid compounds by industrial hemp plant fraction

Plant fraction	Moisture (dry wt basis, %)	Biochar yield (% mass)	Pyrolysis liquid yield (% mass)	Gas loss (% mass)	Key bio-oil compounds	Reference
Leaves (LV)	106%	29%	47%	22%	Cannabidiol (CBD) most abundant; CBN 2.4%; Δ 8-THC 0.92%; 4-ethylphenol 3.0%	[44]
Hurds (HR)	135%	30%	43%	27%	2,6-dimethoxyphenol 9.7%; 2-methoxyphenol 4.5%; HMF and furfural detected	[44]
Roots (RT)	130%	29%	48%	21%	2,6-dimethoxyphenol 16.6% (highest); 2-methoxyphenol 5.1%; p-cresol 4.0%; 4-ethyl-2-methoxyphenol 4.0%	[44]

75 at 275–350 °C to analyze pyrolysis liquids. Biomolecule levels varied among leaves, hurds, and roots. Leaves produce liquids rich in cannabinoids and aromatics, mainly cannabidiol (CBD). Table 7 demonstrates product yields from slow pyrolysis and the main compounds identified in the pyrolysis liquids across various parts of the industrial hemp plant. Understanding the physical and chemical characteristics of cannabis waste helps researchers and industry experts develop innovative waste management strategies and emphasizes the need for advanced recovery methods that utilize the plant's complete chemical profile [78].

6 Cannabis biomass valorization pathways

To maximize the utility of medicinal cannabis waste, biomass pretreatment and four primary valorization pathways have been explored, including: Biochemical Conversion, Thermochemical Conversion, Green Extraction Technologies and Integrated Biorefinery Conversion. Figure 4 illustrates the intricate structure of lignocellulosic biomass and how it can be converted to produce biochemicals and bioenergy through integrated pretreatment methods designed to overcome the limitations imposed by lignin and conversion

**Fig. 4** Conversion pathways of lignocellulosic cannabis biomass through pre-treatment methods and conversion pathways to produce value-added products

technology pathways to produce value-added by-products and bioenergy outputs [75, 79, 80]. This section will review existing studies discussing these valorization pathways and examine how they can be adopted for South Africa.

6.1 Biomass pretreatment

Pretreatment is a crucial step in bioconversion processes, as it influences downstream process efficiency, final product yield, and the economic viability of the conversion technology [31, 77, 80]. Existing pretreatment methods can be broadly classified as physical, chemical, biological, and thermochemical, with each method offering distinct advantages and limitations in terms of energy requirements, solvent use, processing time, and scalability [81]; [79]. In South Africa, the selection and use of appropriate pretreatment methods for biomass, such as cannabis biomass, are further constrained by considerations of resource efficiency, infrastructure availability, and regulatory compliance [82]. Physical pretreatment methods aim to reduce particle size and increase surface area and porosity, thereby improving enzyme accessibility [79]. Yu et al. [83] used acid-assisted mechanocatalytic depolymerization on rice straw, a lignocellulosic biomass similar to cannabis. Pretreatment reduced particle size from 279 μm to 11.8 μm , lowered cellulose crystallinity from 43.05% to 22.71%, and increased surface area by 177%, compared to untreated straw [83]. Physical pretreatment is typically followed by chemical pretreatment, which uses chemical agents to achieve higher delignification efficiency than physical methods [79]. Alkaline pretreatment with sodium hydroxide (NaOH) at concentrations of 2–10% has been shown to be highly effective for lignin removal, achieving 62–79% lignin removal while retaining 85–95% of cellulose [72]. Kim et al. [84]. Alkaline pretreatment with non-catalytic proteins enhances cellulose conversion from hemp waste by preventing enzymes from binding non-productively to lignin. It involves saponifying the ester bonds between lignin and hemicellulose, thereby disrupting their structure and increasing porosity [84]. Another researcher, Arıç et al. [85] examined how different pretreatment methods affected the biochemical methane potential (BMP) of hurds from two industrial hemp varieties, Narlısaray (NS) and Futura 75 (F). They found that combining alkaline and thermal pretreatments yielded the highest BMP values of 272 mL CH_4/g VS for Futura 75 and 218 mL CH_4/g VS for Narlısaray, corresponding to hemicellulose degradation rates of 143% and 74%, respectively, which are significantly higher than those from untreated hurds [85]. Biological and thermal pretreatments enhance lignocellulosic biomass such as *Cannabis sativa* L. Biological methods use microorganisms or enzymes to break down lignin and hemicellulose under mild, eco-friendly conditions, but

are slower [79]. Thermal pretreatment employs heat, pressure, or steam to loosen the biopolymer structure quickly but consumes more energy and may produce inhibitors [31, 86]. Understanding biomass helps identify specific pretreatments to bypass lignin barriers. Machine learning (ML) and explainable AI streamline energy-intensive processes like enzymatic hydrolysis, reducing energy consumption by up to 15% while preserving cellulose accessibility. Support vector regression (SVR) models with R^2 values above 0.95 for glucose and 0.99 for xylose reduce the need for trials by analyzing compositional data [87]. These advances improve biomass conversion efficiency, saving time and resources. Still, a gap remains between AI performance and pilot-scale economic benefits, with no validation of ML approaches for cannabis or hemp pretreatment in South Africa. To enable comparison of these pretreatment techniques with other methods investigated for lignocellulosic biomass, Table 8 summarizes reported pretreatment approaches for cannabis biomass, highlighting their operating conditions, treatment effectiveness, benefits, and drawbacks.

6.2 Biochemical conversion pathways

Biochemical conversion encompasses anaerobic digestion (AD), fermentation, and enzymatic hydrolysis [93]. Quantitative performance data in this section are based on international studies of similar lignocellulosic feedstocks, as no cannabis-specific pilot data from South Africa was identified in the literature review.

6.2.1 Anaerobic digestion (AD)

Anaerobic digestion (AD) is a biological process in which microorganisms break down organic matter in the absence of oxygen for the recovery of energy from organics and allows the recycling of nutrients when digestates are applied on agricultural lands [94]. AD involves several stages, starting with the hydrolysis of complex biopolymers such as cellulose, hemicellulose, proteins, and lipids into soluble organic monomers. This is followed by acidogenesis, which generates volatile fatty acids. Next, acetogenesis produces acetate and hydrogen, and finally, methanogenesis converts these into methane and carbon dioxide [77, 95]. This process depends on microorganisms, especially methanogenic bacteria like *Methanobacterium*, *Methanococcus*, *Methanosarcina*, *Methanosaeta*, and *Methanothermobacter*, which breakdown organic matter without oxygen. During anaerobic digestion, the resulting biogas mainly contains CH_4 (40%–70%), CO_2 (15%–60%), H_2 (2%–5%), and trace gases such as H_2S [96–98]. The technology is well-developed at TRL 8–9 for common lignocellulosic feedstocks, but the high lignin content of cannabis hurds, reported at 21–24%,

Table 8 Pretreatment methods for *Cannabis sativa* L. lignocellulosic biomass (operating conditions and treatment efficiencies)

Pretreatment Method	Operating Conditions	Lignin removal (%)	Hemicellulose removal (%)	Cellulose recovery (%)	Advantages	Disadvantages	Reference
Mechanical pretreatment	PS: 0.2–10 mm E: 10–50 kWh/t T: 60–105 °C t: 2–4 h MC: <15%	Not applicable	Not applicable	70–90% particle size reduction	Simple and safe Reduces moisture content Reduces microbial growth	High energy input Limited standalone cellulose accessibility Requires additional pretreatment	[88]
Acidic Pretreatment	H ₂ SO ₄ : 1–5% w/w T: 160–190 °C t: 15–60 min	20–40%	50–80% removal	39.5% recovery (low - acid degrades cellulose at high severity)	Selective hemicellulose removal Increases enzymatic accessibility Fast and established	Equipment corrosion costs Lower cellulose yields Acid neutralization required	[79]
Alkaline Pretreatment	NaOH: 2–4 w/w T: 160–180 °C t: 20–30 min	60–85%	40–60% removal	73.3% recovery	High cellulose yield Better sugar recovery Lower inhibitor	Slower reaction Alkali costs Neutralization required	[71]
Enzymatic Pretreatment	Enzyme: Cellulase/ Laccase T: 40–60 °C t: 24–72 h pH: 4.5–7	10–40% (up to 60% with mediator-assisted systems)	Minimal	> 80% (high selectivity preserves cellulose structure)	Non-toxic Specific degradation No inhibitor formation	Extremely slow reaction Expensive enzymes Low industrial viability Inhibitor sensitivity	[89]
Deep Eutectic Solvents (DES)	ChCl: Lactic Acid 1:2 T: 100–120 °C t: 30–120 min	50–75%	30–50% removal	65–75%	Recyclable Enzyme compatible Green solvent	High viscosity Higher temperature needed Limited scalability	[90]
Hydrothermal pretreatment	Water-only media T: 160–180 °C P: 5–20 bar t: 10–30 min	40–60% solubilization	50–75% removal	85–95%	No added chemicals Water-based treatment Minimal waste produced	Moderate efficiency Inhibitor formation Pressure requirement Reactor corrosion	[91]
Steam Explosion	Water/Steam: Saturated Temp (°C): 180–200 °C P: 15–20 bar T: 3–10 min	20–50%	80–95% hydrolysis	90–95%	Effective delignification Simple process High recovery Scalable No added chemicals Fiber separation	Inhibitor formation Lignin redeposition Equipment wear Pressure safety concern Incomplete delignification	[92]

1. PS=particle size; E=energy input; MC=moisture content; DES=deep eutectic solvents; ChCl=choline chloride. Cellulose recovery and lignin/hemicellulose removal values are reported on a dry weight basis

hampers microbial access to cellulose, while residual cannabinoids may inhibit methane-producing archaea at higher concentrations [75, 99]. A methane yield of 234 ± 35 m³/t volatile solids was reported for industrial hemp harvested in September [65]. This yield is competitive with corn stover but falls short of the theoretical maximum. Reviews by Ji et al. [100] and Zhao et al. [101] reported that industrial hemp's high cellulose yields could generate abundant fermentable sugars, surpassing those of corn stover or sorghum [100, 101]. Additionally, cannabis biomass has been reported to produce up to 3066 m³/ha more biogas than other feedstocks, such as Jerusalem artichoke [75]. However, the reviews highlighted the importance of pretreatment selection and conditions, recommending further research on C5

sugar fermentation from hemp and a life-cycle assessment of the bioethanol valorization process [100].

6.2.2 Fermentation

Fermentation process includes pretreatment methods like steam explosion and acid hydrolysis, then enzyme hydrolysis and employs *Saccharomyces cerevisiae* or other appropriate microorganisms to produce sugars from biomass [102]. These sugars are then converted into biofuels such as bioethanol and biochemicals such as organic acids [72, 75, 101]. Reported ethanol and methane derived from steam-pretreated hemp stems can produce twice the energy output of transportation fuel, at 11.1–11.7 MJ/kg processed stem

matter (DM), compared with ethanol from hexoses, which yields 4.4–5.1 MJ/kg processed stem DM [66]. Dantas et al. [103]’s findings on modifying the acid-to-residue ratio highlight improved glucose yields while minimizing inhibitor formation, crucial for cost-effective bioprocessing [103]. However, further research on pre-treatment optimization is needed. Incorporating calcium carbonate (CaCO_3) into the fermentation process to achieve a two-step fermentation underscores an innovative strategy to enhance ethanol concentration, reaching an impressive 30 g per 100 g of biomass [103]. This level of productivity could have significant implications for scaling up production, although it raises questions about the cost-effectiveness of integrating additional material into the fermentation process. Furthermore, the potential for methane production from distilling vinasse to generate biogas at 270 L CH_4/kg VS expands the utility of the biomass beyond ethanol production [103]. This multi-fuel approach enhances the efficiency of biomass utilization, including cannabis biomass, and promotes a closed-loop sustainability model, which is essential for modern bioenergy systems.

6.2.3 Enzymatic hydrolysis

Enzymatic hydrolysis is a crucial step in processing lignocellulosic biomass, converting cellulose and hemicellulose into fermentable sugars [72]. The process involves cellulase enzyme complexes, often supplemented with β -glucosidase, xylanase, and hemicellulose components, to break the β -1,4-glycosidic bonds in cellulose and the branched xylan backbone of hemicellulose. However, the structural recalcitrance of cannabis biomass caused by its lignin-carbohydrate complex, the crystallinity of its cellulose fraction, and the presence of residual phenolic compounds and terpenes, limits enzymatic access unless it undergoes pretreatment. Therefore, selecting the appropriate pretreatment method is crucial for optimizing the efficiency of enzymatic hydrolysis [84]. Lignocellulosic biomass, especially bast fibers and hurds, demonstrates potential for biochemical conversion. However, enzymatic hydrolysis of these biomasses faces challenges due to the complex structure of cellulose, hemicellulose, and lignin, which hinder enzyme access. The integration of computational analytics, artificial intelligence algorithms, and pattern recognition techniques offers valuable opportunities to systematically explore and predict how different biomass compositions and pretreatment conditions influence enzymatic hydrolysis [104]. Enzyme bioenhancers significantly improve the productivity and efficiency of biogas production from cannabis and hemp residues. A study by Sun et al. [80] demonstrated a highly efficient conversion of cellulose, with enzymatic hydrolysis productivity reaching 93.0% after targeted pretreatments [80]. Additionally, pilot experiments

revealed that using enzyme bioenhancers at organic loading rates of 3% and 5% led to a substantial increase in biogas output, with an enhancement of 129.8% with enzymes compared to 77.9% without [77]. This approach, which also involved optimizing the use of hemp straw, resulted in optimal biogas performance with a methane yield of 0.248 Nm^3/kg VS. Consequently, the energy output from the digestion of cannabis waste can be quantified at approximately 8.9 MJ/kg VS, highlighting the critical role of enzymes in enhancing the overall process [77].

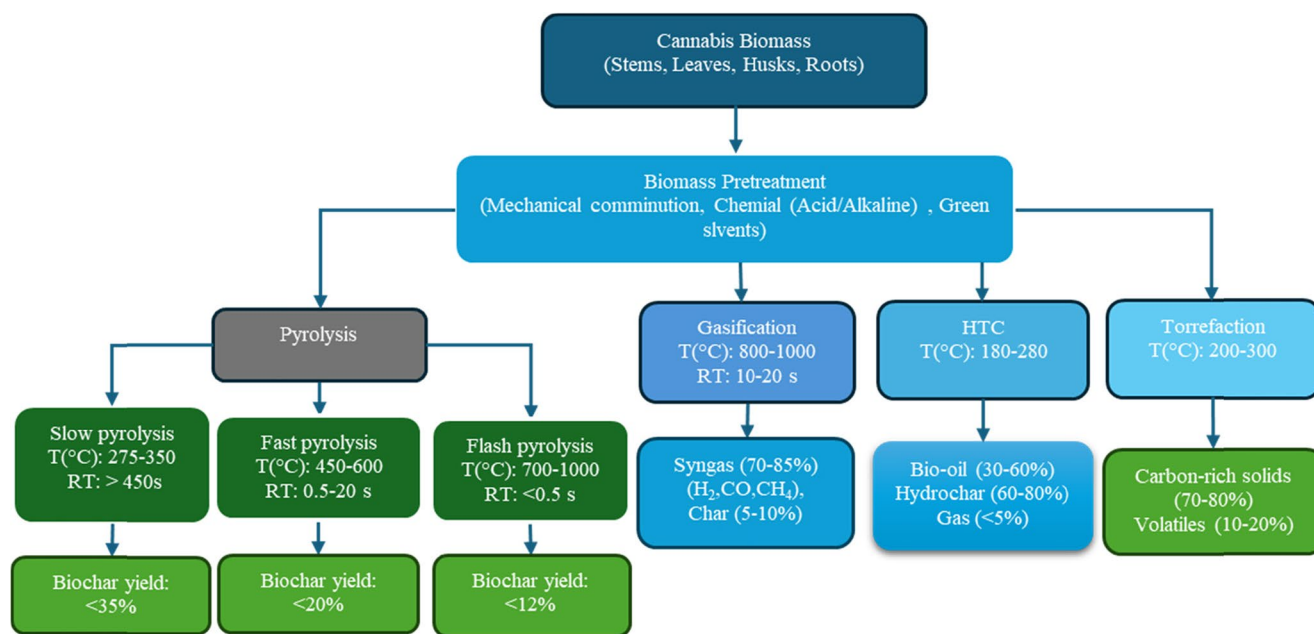
The selection of conversion technologies for lignocellulosic biomass depends on the main output, process conditions, yield, and energy efficiency. Alkaline and acid pretreatments of *Cannabis sativa* L. waste produce high-pH and corrosive effluents, requiring advanced wastewater infrastructure that is not widely available in South Africa [23]. Therefore, biochemical methods such as anaerobic digestion, enzymatic hydrolysis, and fermentation are more sustainable, allowing waste to be converted into bioenergy like biogas, and supporting national waste management and energy goals [105]. Table 9 presents case studies in which cannabis waste was converted via biochemical methods, highlighting the yields and energy produced.

6.3 Thermochemical conversion pathways

Thermochemical valorization is a pathway that typically follows the biochemical conversion of polysaccharides. It employs heat and chemical processes to transform biomass into energy carriers or chemical feedstocks [31, 113]. Applying this pathway is particularly significant because the high temperatures involved can degrade psychoactive cannabinoids (cannabidiol (CBD) and delta-9-tetrahydrocannabinol (THC)), directly addressing the regulatory challenge of disposing of cannabis waste that retains scheduled substances [114]. Beyond cannabinoid degradation, thermochemical conversion stabilizes potentially toxic heavy metals such as lead, cadmium, and zinc within the resulting solid matrix, thereby reducing their environmental mobility compared to the disposal of untreated biomass [115]. The principal thermochemical processes encompass hydrothermal carbonization (HTC), pyrolysis, torrefaction, and gasification. These processes are generally less sensitive to variations in feedstock moisture and composition than biochemical routes, making them particularly advantageous for managing the heterogeneous waste streams characteristic of South Africa’s emerging cannabis industry [116, 117]. Figure 5 presents a process flow diagram for cannabis biomass valorization through thermochemical conversion pathways and the pretreatments it can undergo before these processes. The figure also summarizes the operating conditions of the various

Table 9 Biochemical technology parameters, yield, and energy output from cannabis biomass

Technology	Typical yield	Energy efficiency/ Energy Output	Key process limitation	Reference
Anaerobic digestion	234 ± 35 m ³ CH ₄ /t VS (industrial hemp, no pretreatment) 286.7 mL CH ₄ /g VS (CBD hemp residues, LCA operational) 422 ± 20 mL CH ₄ /g VS (hemp fibers with pre-treatment) 738.7 mL CH ₄ /g VS with co-digestion and pretreatment 118 ± 8 mL CH ₄ /g VS (mix of leaves and inflorescence)	NER 1.5–2.5; deteriorates with thermal pretreatment	Lignin recalcitrance (hurds 21–24%) Terpene toxicity reduces methane yield by up to 57% Cannabinoid properties suppress	[40, 106–109]
Ethanol Fermentation	77 g/L ethanol (industrial hemp, optimized solids loading) 30 g EtOH/100 g (biomass with biological pretreatment) 9.2–20.2 g/L (raw cannabis material)	Energy yield: 11.1–11.7 MJ/kg processed stem DM (co-production bio-ethanol + methane)	Inhibitor formation (furfural, HMF, acetic acid) Xylose fermentation requires non-standard organisms Product inhibition by glucose/cellobiose at high solids	[66, 75, 103, 110]
Enzyme Hydrolysis	71% (glucose conversion (acid-pretreated of hemp stems)) 54% (glucose conversion from treated branches) 38–35% (untreated raw branches) 90% xylose + 40% glucose after alkaline pretreatment 70.3% (glucose yield increase with lignin-blocking agent (BSA))	NER < 1 without heat integration; enzyme cost 15–25% of total process cost	Non-productive enzyme adsorption onto residual lignin Hurd fraction greater than the recalcitrance of the bast fiber Inhibitor formation during pretreatment	[72, 111, 112]

**Fig. 5** A sequential diagram of cannabis biomass pretreatment and thermochemical conversion pathways of cannabis biomass and lignocellulosic biomass [44, 103, 118–121].

thermochemical processes, based on studies of cannabis and other lignocellulosic biomass reported in literature.

6.3.1 Pyrolysis

Pyrolysis involves heating biomass in the absence of oxygen, producing three main products, including solid biochar, liquid bio-oil, and gaseous syngas [44, 122, 123]. The distribution of these products mainly depends on temperature, heating rate, and vapor residence time, as summarized in

Fig. 5. It is crucial to measure heating rates in consistent units (°C/s) to prevent confusion between modes [120]. Slow pyrolysis and hydrothermal carbonization are particularly effective for converting feedstocks into biochar. Biochar plays a crucial role in environmental management by mitigating greenhouse gas emissions, including sequestering CO₂ and CH₄, and reducing emissions of the ozone-depleting N₂O. Biochar produced through thermochemical processes such as pyrolysis, gasification, hydrothermal carbonization, and torrefaction serves as a soil enhancer and

solid fuel, exhibiting properties such as electrical conductivity, porosity, thermal stability, and high surface area. These characteristics enable innovative uses in coatings, nanomaterials, and bio-composites [115, 124]. Salami et al. [44] assessed pyrolysis liquids from the slow pyrolysis of industrial hemp leaves, hurds, and stems were examined using proton nuclear magnetic resonance (NMR) [44]. The aqueous fractions contained notable compounds, including acetic acid (50–241 g/L), methanol (2–30 g/L), propanoic acid (5–20 g/L), and 1-hydroxybutan-2-one (2 g/L). Both aqueous and oily fractions included various volatile and non-volatile compounds, like acetic acid, 2,6-dimethoxyphenol, 2-methoxyphenol, and cannabidiol, which hold significant economic potential if properly valorized [44]. On the contrary, converting product distribution toward liquid bio-oil with heating values of 18–25 MJ/kg. Fast pyrolysis occurs at high temperatures with very short vapor residence times of 0.5 to 10 s, maximizing bio-oil production while producing less biochar and gases during rapid heating at 450–600 °C. In comparison, flash pyrolysis involves higher heating rates of about 300–1000 °C/s and similar temperatures, resulting in increased bio-oil yields [125]. The goal of the process is to raise the temperature above the point at which char formation is less desirable than decomposition. Prior to converting biomass into biochar, the very rapid heating causes it to produce condensable vapours [124]. Large-scale applications of fast pyrolysis remain limited, indicating a need for further advances to achieve optimal flash pyrolysis conditions. Nevertheless, studies on advanced modeling of hemp pyrolysis kinetics indicate that elements such as Cd, Pb, and Zn, along with the material's heterogeneous composition, can significantly affect devolatilization and biochar quality [126]. This insight is essential for scaling up reactors and enhancing the economic efficiency of industrial pyrolysis processes.

6.3.2 Hydrothermal carbonization (HTC)

Hydrothermal Carbonization (HTC), also called wet pyrolysis, is a thermochemical process carried out in the presence of sub-critical water at temperatures typically ranging from 180 to 280 °C and under autogenous saturated vapor conditions (10–80 bars) [121]. This method has been reported to be suitable for wet biomass, as it eliminates the need for energy-intensive drying equipment [127]. During the HTC process, some inorganic components transfer to the liquid phase, reducing the solid residue of hydrochar, minerals, and ash, and increasing the higher heating value (HHV). This lowers the risk of slugging and fouling during hydrochar combustion compared to pyrochars. Unlike fast pyrolysis, this process is more feasible to scale industrially due to its milder conditions, making it an effective method for

converting lignocellulosic cannabis biomass into a valuable resource [121]. A study by Kanchanatip et al. [56] showed that HTC treatment of cannabis waste at 170–230 °C with a biomass-water ratio of 1:10 to 1:20 produces hydro-char with a higher heating value up to 24.65 MJ/kg, compared to 17.50 MJ/kg for untreated waste, with energy yields ranging from 70.41% to 82.23% [118]. This indicates that the process can convert cannabis waste into a solid fuel comparable to low-rank coal. Recirculating liquid effluent improves the HHV and reduces wastewater emissions [118].

6.3.3 Gasification

Gasification is a thermochemical conversion process that occurs at very high temperatures, where biomass undergoes partial oxidation with limited oxygen and gasifying agents to produce syngas composed of H₂, CO, CO₂, and CH₄ [113]. The efficiency of gasification and the composition of syngas are heavily affected by various operational factors, including feedstock type, moisture content, reactor type, temperature, gasifying agent, and equivalence ratio [128]. Pedrazzi et al. [129] conducted a techno-economic analysis (TEA) of gasifying a small hemp farm, which revealed a payback period of about 3.5 years and a net present value of \$270,000 over its lifespan. The biochar produced boosted hemp yield by roughly 7.7% and reduced fertilizer costs during cultivation. Employing less energy-intensive thermochemical methods such as HTL, HTC, and pyrolysis could further shorten the payback period and enhance profitability. To fully realize the hemp plant's potential, adopting an integrated farming system is highly advisable, enabling investors to maximize their profits [129]. For South Africa's cannabis industry, with a cultivation area registered under 5 hectares by SAHPRA, straightforward technologies such as combustion, slow pyrolysis, and anaerobic digestion under mesophilic conditions are well-aligned with the country's available resources, infrastructure, and operational capacity. When combined with biochar storage and periodic application, this approach offers an optimal compromise between capital costs, product recovery, and greenhouse gas emissions [130].

6.3.4 Torrefaction

Torrefaction is an important thermochemical pretreatment method, often referred to as a mild form of pyrolysis. It occurs at relatively low temperatures, typically between 200 and 300 °C, in an oxygen-deficient or inert atmosphere [131]. This distinguishes it significantly from conventional pyrolysis. The optimal torrefaction temperature usually falls between 250 and 300 °C, with the exact temperature chosen based on the feedstock type, targeted product qualities,

and intended downstream uses [131]. During torrefaction, biomass is initially heated to eliminate unbound water. As heating continues, bound water is removed via chemical reactions. It is generally believed that most bound water is driven out through a thermo-condensation process, which takes place above 160 °C, when CO₂ production starts [132]. Torrefied biomass has higher energy density, is hydrophobic, easier to grind, and has lower moisture and oxygen levels. These improve its stability and suitability for thermochemical conversions like pyrolysis, gasification, and combustion [123]. South Africa has ample biomass resources suitable for torrefaction, including agricultural residues from sugarcane processing, maize cultivation, and grain production, which serve as significant potential feedstocks [26]. The most notable research focuses on two types of pine sawdust (PSD) waste produced in large quantities by timber industries in Nigeria and South Africa. The study investigated how torrefaction could improve the fuel properties of the biomass. Results showed that torrefaction at 300 °C for 45 min increased the higher heating value (HHV) by 37.9% in South African samples, making their energy levels comparable to coal [133]. These results show the potential of torrefaction to enhance the use of South African biomass, boosting energy security and export markets for biofuels. Research on cannabis biomass torrefaction is limited, mainly from early studies on hemp residues like hurds and stems [134]. This indicates a notable gap in the current research on this topic.

Thermochemical processes such as pyrolysis, hydrothermal carbonization, gasification, and torrefaction show promise for cascaded cannabis valorization by processing lignin-rich residues that biochemical methods can't efficiently utilize. However, in South Africa, these technologies are still in early development stages [26]. For example, lignocellulosic biomass gasification has been demonstrated using small-scale systems aimed at rural energy, but these have seen limited deployment and demonstration (TRL 5–6) [135]. Additionally, university research has extensively tested the use of lignocellulosic biomass, mainly from invasive species, for biofuel production in controlled lab environments (TRL 3–4) [136]. Reviews on converting waste via thermochemical pathways in a circular economy context highlight that these processes are still mainly at laboratory and pilot scales [26, 36].

6.4 Green extraction technologies

Innovations in agricultural waste valorization are rapidly growing worldwide. These advancements improve traditional methods, enhancing efficiency and sustainability in line with bioeconomy and circular economy principles. They've been adopted in the cannabis residue industry,

using clean, green techniques to extract bioactive secondary metabolites often missed by conventional processes [137]. Though mainly tested at pilot scale, these innovations effectively recover valuable bioactive compounds from cannabis waste. They selectively target and extract specific compounds, improving purity, yield, and efficiency [138]. This section reviews three modern extraction methods: Supercritical Fluid Extraction (SFE), Microwave Assisted Extraction (MAE), and Ultrasonic Assisted Extraction (UAE), which have been identified in peer-reviewed studies applied to cannabis biomass, and explores how these technologies can be integrated into cannabis waste management.

6.4.1 Supercritical carbon dioxide extraction (SC-CO₂)

Supercritical Carbon dioxide (SC-CO₂) extraction employs CO₂ at its critical temperature of 31.1 °C and critical pressure of 73.8 bar as a solvent [53]. It is chosen for its abundance, non-toxicity, and ease of removal from the extract, enabling the recovery of phytochemicals such as THC and CBD from plants [53]. This technology is popular for its flexibility in precise fractionation through pressure and temperature adjustments, and for CO₂ in its supercritical state, behaving as both a liquid and a dense gas, thereby enabling efficient extraction of compounds while minimizing harmful by-products [53, 139]. It also has the advantage of recycling CO₂, thereby reducing consumable costs. Additionally, this technology can be applied to extract terpenes. It has supported the health and pharmaceutical sectors, particularly driven by demand for health-promoting, bioactive-rich extracts. Additionally, the technology is based on green chemistry and sustainability principles [54]. For example, using SC-CO₂, lower pressures (90–110 bar) and moderate temperatures (40–50 °C) are ideal for extracting terpene-rich fractions, whereas much higher pressures (200–300 bar) are required to maximize cannabidiol (CBD) recovery [53]. This technology has been extensively validated in academic literature, especially in review articles by de Aguiar et al. [54] and Luca et al. [53]. These studies examine how changes in pressure and temperature settings during step-gradient SC-CO₂ extraction enable the simultaneous collection of two high-purity fractions from a single biomass feedstock [53, 54]. Decarboxylation is a thermally driven reaction that removes a carboxyl group (-COOH) as carbon dioxide (CO₂) from acidic cannabinoid precursors, converting them into their pharmacologically active neutral forms. Specifically, cannabidiolic acid (CBDA) is converted to cannabidiol (CBD), cannabigerolic acid (CBGA) to cannabigerol (CBG), and tetrahydrocannabinolic acid (THCA) to the psychoactive compound delta-9-tetrahydrocannabinol (THC) [54]. It is important to clarify that decarboxylation does not generate phenols. Instead, it involves the loss of

CO₂ from the carboxylic acid group of the cannabinoid, resulting in the neutral form. The efficiency of decarboxylation mainly depends on temperature, duration, and the physicochemical conditions of the process. Higher temperatures and longer times promote complete conversion, but excessive heat can cause thermal degradation of cannabinoids and terpenes, ultimately diminishing the quality of the extract. Fernández et al. [140] highlights the practical importance of controlled decarboxylation in extraction design. It compares the chemical profiles and in vitro biological activity of extracts obtained by ethanol maceration or supercritical CO₂ extraction (SC-CO₂), from two different cannabis inflorescence chemotypes. Decarboxylation was conducted directly in the extraction vessel at 120 °C for 45 min immediately prior to SC-CO₂ extraction. The extract concentrations of CBD and THC from pre-heated samples were significantly higher than from non-decarboxylated controls, confirming that converting acidic precursors into neutral forms greatly enhances cannabinoid recovery. This finding is directly relevant for optimizing extraction procedures in an integrated cannabis biorefinery [140]. Therefore, a cost analysis of this new approach is essential to assess the feasibility of integrating biorefinery protocols to extract higher-value compounds from post-extraction residues. However, despite its advantages, scaling up SFE for cannabis biomass valorization has proven cost-prohibitive, primarily due to high equipment costs, with large-scale units ranging from USD 300,000 to USD 10 million [11].

6.4.2 Microwave-assisted (MAE) and ultrasound-assisted extraction (UAE)

Microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE) are eco-friendly methods that use electromagnetic radiation and high-frequency mechanical waves. MAE uses electromagnetic radiation (300 MHz to 300 GHz) to directly heat polar molecules within plant cells through dipole rotation and ionic conduction, achieving rapid internal heating that disrupts cell membranes and releases intracellular compounds without requiring prolonged external heating [139]. In contrast, the UAE uses high-frequency sound waves (20 kHz to 2 MHz) to generate alternating cycles of compression and rarefaction in a liquid medium. This process causes acoustic cavitation and the violent collapse of tiny bubbles, which produce shockwaves. These shockwaves are strong enough to break plant cell walls, enhance solvent penetration, and accelerate mass transfer between the solid cannabis biomass and the extraction solvent [29]. This characteristic allows the UAE to decrease solvent volume and extraction time, making the technology more cost-effective and environmentally friendly than solvent-based methods. Most experiments

involving UAE are conducted in an ultrasonic bath using methanol or an aqueous methanol mixture as the solvent. These solvents are commonly used to extract antioxidants from plant biomass. The effect of solvent type on the ultrasound-assisted extraction of phenolic compounds from defatted plant seeds and meal has been studied. The solvents used for phenolic extraction include water, MeOH, EtOH, and acetone at various concentrations [139]. There is still limited research on optimization processes for recovering valuable bioactive compounds from *Cannabis sativa* L. biomass. Agarwal et al. [141] used UAE to extract bioactive compounds from *Cannabis sativa* L., including polyphenols, flavonoids, and cannabinoids, under optimal extraction conditions of 15 min, 130 W, and 80% methanol [141]. The results of this study showed that extraction time and solvent concentration significantly influence the yield of phenolic compounds [141]. Additionally, when comparing the ultrasonic process with other extraction techniques for improved selectivity, higher responses were observed for each cannabinoid in *Cannabis sativa* L. [142]. However, separating terpenes from cannabinoids using UAE is less efficient than using SC-CO₂ with ethanol as a co-solvent [11]. MAE is an eco-friendly method for extracting polar molecules, such as phenolics, from plant materials. Few studies have focused on extracting phenolic compounds from cannabis biomass. Izzo et al. [143] applied MAE to four industrial hemp cultivars, revealing cannabis-specific flavonoids, particularly cannflavins A and B at concentrations 10 to 100 times greater than in other plant tissues, alongside significant quercetin-3-glucoside, catechin, and epicatechin levels [143]. Furthermore, the combination of MAE and UAE resulted in an oil yield of 48.93%, surpassing the yields of each technique alone: MAE, 40.2 ± 0.53%; UAE, 41.17 ± 0.41%. This was achieved using a biomass-to-ethanol ratio of 1:5, with ultrasound at 35 kHz and 800 W for 10 min at 20 °C [144]. These findings highlight the advantages of selectively retaining volatile compounds during the extraction of terpene-rich fractions, such as essential oils or flavor enhancers, in biorefineries. However, UAE probe systems require thorough cleaning between batches due to surface fouling from high-resin cannabis biomass. Both methods also demand tight temperature control to prevent degradation of cannabinoids and terpenes, which could lead to regulatory non-compliance under SAHPRA pharmaceutical-grade manufacturing standards [33]. In South Africa, the expanding cannabis processing sector is largely driven by SMEs, but there is a lack of strict regulation in managing temperature and solvents. Adopting MAE and UAE technologies requires both operator training and the development of quality control systems. A practical short-term solution in South Africa is to establish a centralized, shared-use facility for MAE and UAE equipment,

which can lower individual producer costs and streamline quality control and solvent management [6]. This approach aligns with the regional processing hub concept outlined in the National Cannabis Master Plan [7]. Research into green extraction technologies for South African cultivars and environments that have not yet been validated through experiments remains a top priority for the national cannabis biorefinery sector. Table 10 summarizes the experimental findings and the technology readiness levels (TRL) of current green extraction methods, highlighting their advantages and disadvantages as reported in various sources.

6.5 Integrated biorefinery conversion pathways

Integrated biorefinery pathways, also known as multi-platform biorefinery systems, use one or more types of agricultural lignocellulosic biomass (cellulose, hemicellulose,

lignin) through sequential or parallel mechanical, biochemical, and thermochemical processes. The goal is to maximize the production of biofuels, biochemicals, bio-based materials, and energy carriers while minimizing waste, enhancing resource recovery, enabling cost-effective processing, and reducing energy consumption, all without compromising the potential recovery of each product [26, 103, 147, 148]. Unlike single conversion pathways described in Sect. 6.2–6.3, integrated biorefineries direct each waste fraction into value-added applications, making sure they do not harm, degrade, or contaminate the intermediate process or other conversion pathways of any other stream [26, 148]. The primary objective of biorefineries is to direct every waste fraction into value-added applications, reducing landfill disposal and preventing unnecessary energy losses [149]. This cascaded process design, where residues from one process are used as feedstock for the next, exemplifies the application of

Table 10 Other green extraction methods are used for obtaining cannabis phytochemicals and their respective characteristics

Technology Pathways	Advantages	Limitations	TRL	Findings	Reference
Supercritical CO ₂ extraction (SC-CO ₂)	High selectivity, no toxic residues, high purity, tunable, recyclable CO ₂	High initial investment, high temperatures/pressures required	8 (Industrial)	Supercritical CO ₂ technologies have been shown to enable the sustainable valorization of cannabis for pharmaceutical and food applications.	[145]
Pressurized Liquid Extraction (PLE)	Quick, automated, efficient with lower solvent usage	Expensive equipment, potential thermal degradation	7–8 (Demo-pilot)	Pressurized ethanol extraction achieved 99.3% recovery of cannabidiol from hemp threshing residues.	[50]
Pressurized hot water extraction (PHWE)	Reduced degradation, no extra cleanup, less solvent use, simpler concentration, better selectivity, improved kinetics, enhanced extraction efficiency, and easier automation.	Thermal degradation, loss of terpenes & cannabinoid acids, Poor extraction of non-polar compounds, and scalability issues	7 (Demo-pilot)	Optimized PHWE enables selective CBD/CBC/CBG extraction from seeds while minimizing THC levels efficiently.	[55]
Cryogenic Ethanol Extraction	Higher selectivity and cleaner extracts preserve terpenes and delicate compounds, reduce fats and waxes, enable faster extraction, increase throughput, and often eliminate the need for winterization.	This process has high capital costs due to specialized cryogenic equipment operating below – 40 °C, posing safety and operational challenges. There's also a risk of terpene formation under cold conditions.	6–7 (Pilot)	Cryogenic ethanol extraction at –20 °C optimizes cannabinoid selectivity while minimizing chlorophyll impurities	[146]
Solvent-assisted recrystallization (SAR)	The method employs solvent screening by evaluating biomass polarity, boiling points, and other solubility parameters to identify the most suitable solvents for effective cannabinoid crystallization, thereby achieving over 99% CBD purity.	There is limited research on the characterization of cannabinoid wax in SAR, which makes process optimization difficult. The method uses solvents that pose safety and regulatory risks and require additional downstream steps, increasing labor and equipment costs.	7–8 (Industrial)	Method demonstrated high recovery (96.3%) of cannabinoids from waste wax sourced from the cannabinoid extraction industry.	[49]
Deep Eutectic Solvent Extraction (DES)	Eco-friendly, biodegradable, low toxicity, and simple synthesis	High DES viscosity poses challenges for the complex recovery of extracted compounds and for scalability.	3–4 (Lab-scale)	This high-temperature pretreatment, together with in situ acid-NADES catalysis during phenolic compound extraction, offers a sustainable method for cascade valorization, thereby optimizing the utilization of biomass waste.	[90, 142]

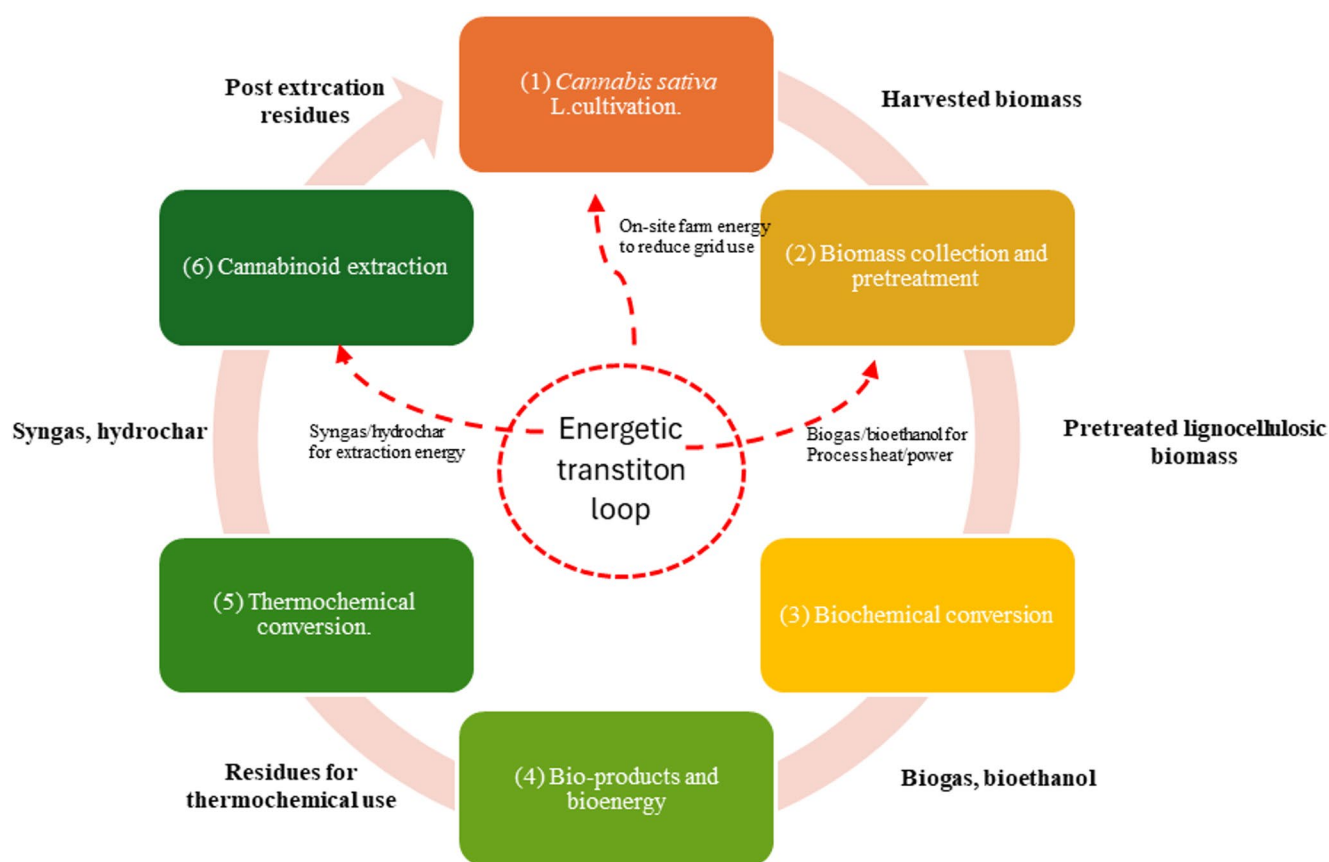


Fig. 6 Circular principle applied to cannabis biorefinery

circular economy principles to cannabis biomass [150, 151] Fig. 6 illustrates simplified circular economy principles that can be used to transform a *Cannabis sativa* L. biomass stream into multi-product biorefinery pathways, optimizing the value of each cannabis component and stream [147].

The success of these integrated systems relies heavily on accurately characterizing the physicochemical makeup of the input feedstock (Sect. 5) and applying appropriate pretreatment prior to downstream processing. Hemp hurds offer promising potential for integrated biorefineries focused on producing bio-composites for the construction and automotive sectors, thereby improving material durability and reducing the carbon footprint [13]. However, the heterogeneous and complex chemical composition of biomass poses a challenge to extraction efficiency and yield [27]. For example, producing biopolymers from lignocellulosic materials, such as hemp, requires effective pretreatment to facilitate degradation. Yet, traditional pretreatment methods often entail high costs and energy consumption, thereby reducing overall sustainability [152]. In addition to biopolymers, cannabis fibers have become a promising material for bio-composites due to their high tensile strength, low density, and natural biodegradability, making them ideal for reinforcing composite materials. An integrated hemp hurds biorefinery

demonstrated the valorization of hemp hurds through catalytic fractionation and metal-catalyzed reduction. This process yielded 38.3 wt% monophenolic compounds, representing 95% of the theoretical maximum. Furthermore, organosolv pulping was employed to produce pulp, followed by chlorine bleaching, yielding a 50 wt% yield suitable for textile fibers and nanocellulose [153]. Although conversion pathways for cellulose and hemicellulose are well established, the effective and affordable conversion of hemp lignin into high-value aromatics remains underdeveloped. Current depolymerization yields of 40–60% are below their technical potential, emphasizing the ongoing need for research into selective cleavage mechanisms, catalyst optimization, and solvent systems [154].

Biochemical routes are among the most commercially mature biorefinery pathways, having been shown to increase overall carbon efficiency and resource recovery dramatically, and to explore combining fermenting sugars to ethanol, anaerobically digesting residues to biogas, and finally valorizing lignin to produce phenolics or carbon-based materials [28]. Greenhouse gas mitigation through AD results from avoiding fossil fuel use and capturing methane directly to prevent its release into the atmosphere. This environmental mitigation strategy is effective, with biogas production

growing 11.2% annually, reaching about 58.7 billion m³ in 2017. Its adoption could limit global warming to 2 °C by reducing emissions by 3.3–4.4 billion tCO₂e annually, about 13% of global emissions [128]. A techno-economic analysis of large-scale hemp-based processes for transportation fuels demonstrates that a well-designed hemp biorefinery that co-produces biogas and ethanol from chopped, steam-pretreated hemp can achieve 84–88% recovery efficiency, reducing greenhouse gas emissions by 84% compared to fossil fuels. Additionally, this demonstrated that a single-producer configuration for ethanol production achieves only a minimum ethanol selling price of €0.90–1.10/L, compared to maintaining economically competitive minimum selling prices of €0.50–0.75/L bioethanol equivalent through a €0.30–0.40/L biogas revenue offset [155]. This study revealed that despite decades of research, pretreatment and CAPEX remain the most expensive aspects of biorefinery processes due to reliance on fixed feedstock ratios and conversion methods. In South Africa, where about 85% of the electricity grid is coal-based, biorefineries that draw power from the grid have a significantly higher carbon footprint

compared to those in Canada or the EU [156]. Addressing this issue requires dedicated off-grid or cogeneration energy strategies. Future systems should adopt flexible, modular designs that enable real-time optimization of conversion pathways and adapt to changes in feedstock, market prices, and energy needs through AI-driven control systems [157]. Figure 7 illustrates an integrated biorefinery pathway for the valorization of cannabis biomass.

This section's integrated biorefinery framework combines the technology assessments from Sect. 6.1 to 6.4 into a unified cascaded valorization model. It demonstrates that the economic and environmental outcomes of cannabis biomass valorization are fundamentally system-level results, not just the sum of individual technologies. Table 11 provides a consolidated summary of the yield, energy efficiency, TRL, and cost data for the biomass valorization pathways discussed in Sect. 6.2–6.4. This serves as a practical reference to enable direct comparisons among technology options and assist South African cannabis biorefinery developers in decision-making, considering the specific regulatory, infrastructure, and funding constraints outlined earlier. The key takeaway

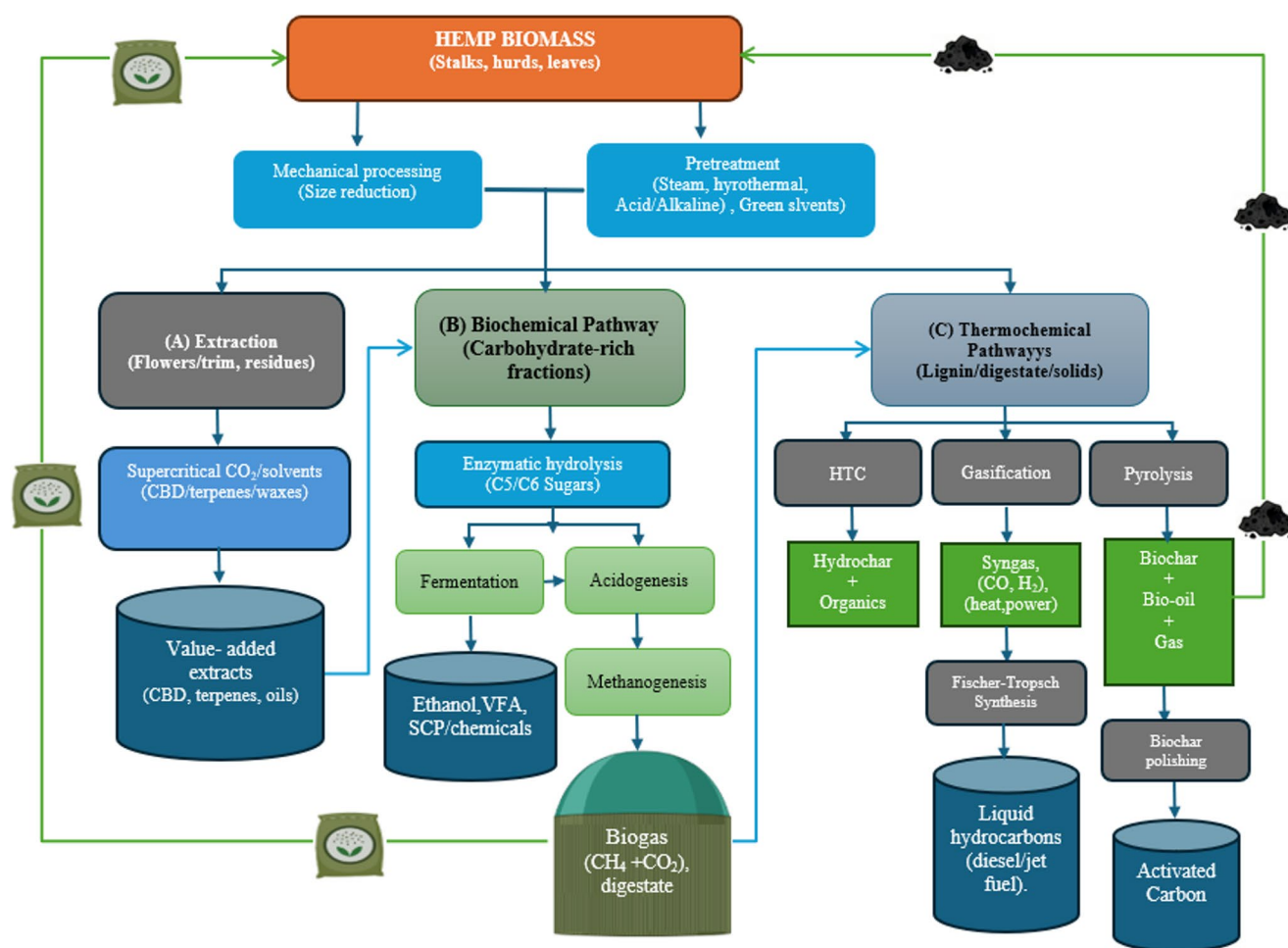


Fig. 7 Cannabis waste valorization through biorefinery

Table 11 Valorization technology readiness levels and required infrastructure for implementation

Technological Pathway	Technology Readiness Level (TRL)	Infrastructure Requirements	Reference
Anaerobic Digestion	Matured technology at TRL 8–9 for biogas production for biomass and agrowaste. Medicinal cannabis pathways still require R&D.	Large capital investments; successful implementations used Continuously Stirred Tank Reactors (CSTR) or Upflow Anaerobic Sludge Blanket (UASB) reactors.	[158]
Fermentation	Implementation at TRL 9 for bioethanol production.	Dedicated pretreatment consumables and equipment, microorganisms, hydrolysis, fermentation (SSF), and distillation units. Capital can be high when integrated with other resource recovery streams.	[73, 109]
Volatile Fatty Acids (VFA)/Single – Cell Protein (SCP)	TRL 3–6 (Lab/Pilot scale), dependent on specific conversion route.	Fermentation infrastructure (Acidogenic reactors and aerobic SCP production reactors).	[102]
Hydrothermal Carbonization (HTC)	TRL 4–5 (Pilot/demonstration scale)	Pressurized batch or continuous reactor systems. Lower energy compared to pyrolysis, as pre-drying of the biomass is not required.	[159]
Fast Pyrolysis	TRL 4–5 (poor commercial viability)	High infrastructure cost requires specialized reactors and rapid cooling systems.	[159]
Gasification	TRL 9 (Mature process for general biomass)	High infrastructure cost as the process requires gasifiers, gas cleanup systems, and compression.	[99]
Green extraction (SC-CO ₂)	TRL 9	High initial investment for the specialized, high-pressure processing infrastructure designed to safely operate above the critical point of CO ₂ (31.1 °C, 73.8 bar).	[145]

is that no single technology currently delivers both high resource recovery and commercial viability at the scale of South Africa's emerging cannabis sector. This supports the conclusion that a phased, modular, and cascaded approach is the most feasible path for near-term deployment.

7 South African collaborative framework for cannabis valorization

7.1 Government, regulatory agencies, and public collaboration

Implementing cannabis valorization strategies in South Africa requires a collaborative framework involving government, research institutions, public entities, financial institutions, and private industry, guided by the National Cannabis Master Plan. In technological or innovative progress, governments should lead by supporting new inventions to ensure their success and maturation. In South Africa, however, barriers such as a lack of government backing, limited incentives, regulatory hurdles, and constrained innovation capacity have been identified as key obstacles to the growth of waste-to-energy technologies [160]. The successful implementation of cannabis biomass valorization requires a supportive policy environment. Key policy measures include providing subsidies or tax incentives for renewable energy technologies, introducing progressive landfill taxes to promote environmentally sustainable waste management practices, implementing carbon pricing mechanisms to improve the competitiveness of bioenergy relative

to fossil fuels, and developing agricultural incentives, such as fertilizer blending schemes and nutrient credit systems for agro-processors [160]. Collectively, these measures can facilitate the transition toward more sustainable and resource-efficient cannabis waste management practices. However, the regulatory framework must also strike a balance between maintaining stringent quality standards and ensuring accessibility for emerging stakeholders. While the South African Health Products Regulatory Authority (SAHPRA) plays a critical role in enforcing Good Manufacturing Practice (GMP) standards to ensure product safety and international compliance, the associated costs of certification, testing, and regulatory compliance remain a significant barrier, particularly for small-scale producers and research institutions [4, 161]. To address this, a tiered licensing system involving partnerships among government agencies such as SAHPRA and the Department of Agriculture, research institutions, and GMP-certified facilities should be developed, enabling small enterprises to participate while maintaining quality standards. Certified GMP facilities must collaborate with small businesses, offering lower costs and small-batch options [162]. Non-financial barriers to implementing waste valorization technologies include innovative capacity and technical know-how. For cannabis-derived technologies, institutions such as the Cheeba Cannabis Academy and Agri Colleges International offer education on the industry supply chain, ecosystem, entrepreneurship, project management, and personal training [69, 163]. This education can equip industries and small, medium, and micro enterprises (SMMEs) in the cannabis processing sector. These institutions can also be advised to include

waste-to-resource courses in their current course modules, which will help processors understand potential pathways to add value to their waste streams, incorporate waste management into their processing schedules, and reduce time-to-market. Expanding and increasing the visibility of local laboratory capacity is crucial when implementing technology, as performing physicochemical characterization from feedstock to final product is vital, and the currently limited testing proficiency will further constrain large-scale production [164]. In South Africa, only five laboratories are accredited for cannabis analytics, namely, Vinab Pharma, Ecogreen Analytics, Afriplex Laboratory, Qure, and the National Analytical Forensic Services (NAFS) [69, 165]. Collaborations between academic institutions and analytical laboratories can boost investment in additional demonstration analytical pilot processing facilities, thereby reducing risks associated with technological deployment.

8 Economic and technological feasibility in South Africa

Assessing the readiness of South Africa's technology for implementing cannabis valorization pathways requires understanding the current state of technology readiness levels (TRL) for other lignocellulosic biomass, differentiating the maturity of these technologies, and evaluating the feasibility of their integration into a commercial-scale biorefinery. This assessment will then build on current findings on multi-product optimization strategies and waste minimization to design practical biorefinery pathways for cannabis-based valorization at laboratory, pilot-scale, and industrial scales, suitable for South Africa [166]. The TRL is a system for assessing a technology's maturity, ranging from its initial development stage (TRL 1) to full commercial deployment (TRL 9) [26, 73]. In South Africa, biorefinery technologies for many types of lignocellulosic biomass, such as sugar, starch, and wood, have already matured to TRL 9. However, implementing these for cannabis biomass, such as leaves, stalks, and processing residues, presents challenges due to its compositional characteristics [101]. Aside from lignocellulosic biomass, edible crop biomass, which is typically used for ethanol or biodiesel production, has also reached TRL 9. Surprisingly, this is not the case for second-generation cellulosic ethanol conversion pathways produced from lignocellulosic biomass such as cereal straw or woody residues, and, more recently, hemp hurds, which have only been demonstrated at a lower TRL of 6–8 [27, 73]. This discovery indicates that the technology is currently in the pilot scale validation phase and is not yet ready for widespread implementation. Specifically for cannabis biomass, its high lignin content and variability in cellulose

crystallinity pose challenges for enzymatic hydrolysis, necessitating a pretreatment step that has hindered the technology's development. Additionally, lignin-derived ethanol from this biomass is rare at an industrial scale [167].

From a South African regulatory standpoint, cannabis has been reclassified from the Drug and Drug Trafficking Act to the Medicines Act. The long-standing restriction that allowed South African farmers to cultivate varieties with THC levels below 2% without a permit has been lifted [5]. However, the residual cannabinoids present in biomass remain a challenge, potentially hindering advances in valorization technologies, even though these technologies are technically feasible in other countries. This challenge can be addressed in South Africa by adopting advanced green extraction methods and thermochemical conversion techniques, such as pyrolysis and gasification, to valorize cannabinoid-extraction residues, with necessary technical adjustments to these processes [167]. In contrast, the European Union regulates industrial hemp under a THC threshold of 0.2–0.3%, revised to 0.3% under Regulation (EU) 2021/2115, and treats biomass and processing residues under the EU Waste Framework Directive (Directive 2008/98/EC). Additionally, the European Green Deal and the Farm to Fork Strategy emphasize transitioning to a circular bioeconomy, explicitly supporting bio-based industries, including hemp value chains and biorefineries through dedicated research and innovation funding like Horizon Europe [168].

Technologically, various valorization pathways for medicinal cannabis biomass, as discussed in Sect. 6, have been demonstrated internationally. In South Africa, there remains a significant gap between lignocellulosic biomass valorization technologies demonstrated at the industrial scale and those at TRL 6. A study by Mandree et al. [110] found that South Africa continues to rely heavily on landfilling for waste management rather than valorization. Second-generation (2G) agricultural feedstocks available in South Africa, including fruit waste, sugarcane by-products and waste, forestry waste, and invasive alien plants, most remain unvalorized at a commercial scale, even though conversion of 70% of this lignocellulosic biomass available in South Africa would meet 24% of the country's liquid fuel requirement as a bioethanol equivalent [169]. Gasification has been shown to reach mature TRL when applied to fossil fuels like coal; however, its TRL drops below full maturity when applied to biomass such as hemp hurds due to compositional factors, including higher ash content and the presence of silica, which tend to promote slag formation [167]. This explains why renewable energy sources account for only about 3% of South Africa's electricity generation [170]. Such technological-maturity barriers require active research and development efforts integrated throughout the

development process to ensure commercial viability [170]. The CSIR's Biorefinery Industry Development Facility (BIDF) has played an active role in revitalizing local biomass industries by developing novel technologies through biorefinery processes, including AD, pyrolysis, and fermentation, to generate high-value products from their biowastes, as demonstrated at TRL 6 [26].

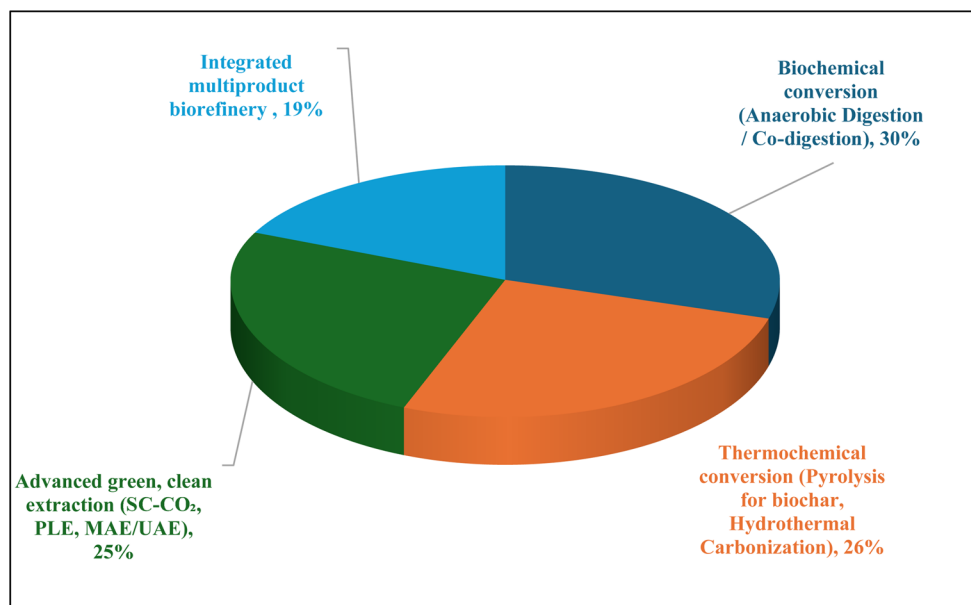
Economic indicators are closely linked to technology's TRL, biomass costs, and the required capital investment per annual production capacity. For example, the production of 2G ethanol was reported to cost USD 45 per liter compared to USD 0.5–0.6 per liter for conventional ethanol [171]. This demonstrates that technical feasibility alone does not determine a technology's scalability. In South Africa, logistical challenges like sourcing and transporting feedstock within legal bounds are significant. Systemic issues, such as regular power outages, threaten biorefinery operations. Furthermore, outdated and nonfunctional water treatment infrastructure exacerbates this situation, undermining the sustainability of the entire system [4, 19]. Economic assessments of the adoption of valorization technologies for cannabis biomass will also require evaluating capital expenditure (CAPEX), operating expenditure (OPEX), revenue streams from the outputs, and policy conditions. For South Africa's implementation of integrated biochemical and thermochemical biorefinery operations, CAPEX would include pre-treatment reactors and cannabinoid removal and monitoring equipment for cannabis-based biomass; enzyme hydrolysis reactors; extraction and distillation systems for bioethanol recovery; fermenters and dryers for protein isolates; and pyrolysis and gasification reactors for lignin-rich residues. A study by Duque et al. [73] indicates that the pilot-scale operational costs for lignocellulosic biomass biorefineries range from USD 44 to USD 45 per liter of annual capacity for advanced cellulosic ethanol and bio-based product processing units [73]. These costs are significantly higher than first-generation (1G) ethanol production, where the minimum ethanol selling price from sugarcane molasses at South African sugar mills has been reported at USD 0.52/L, and the integrated 1G–2G option using sugarcane lignocelluloses at USD 0.62/L, with enzyme costs identified as the primary inhibitive factor for the lignocellulosic pathway [26]. OPEX for valorization technologies encompasses feedstock procurement or collection, energy input for thermal pretreatment, the purchase of saccharification enzymes, maintenance of high-temperature and high-pressure equipment, and labor costs for skilled technicians and engineers [167].

Sensitivity analysis indicates that inconsistent product yields can lead to an unbalanced impact on IRR relative to changes in raw material costs, especially in complex integrated systems. In such systems, underperformance in

a single stream can drastically reduce the throughput or marketability of products from secondary streams. Processing cannabis stems using steam extraction and enzymatic hydrolysis can reduce glucose conversion rates by 5%, affecting overall ethanol yields and co-products. Sensitivity analyses reveal that feedstock composition and glucose conversion efficiency are crucial for determining the minimum ethanol selling price (MESP) [172]. For example, variations in glucose yield can cause an MESP uncertainty of about USD 0.15 per gallon in corn stover systems [172]. In integrated cannabis biomass biorefineries, shortfalls in enzymatic hydrolysis can lower both ethanol production and the availability of lignin-rich residues for thermochemical processing. This highlights the need for precise control over these processes to maintain economic stability, especially in South Africa, where feedstock variability across cultivars and harvests is not fully understood.

From a funding perspective, lower-Technology Readiness Level (TRL) pathways often rely on grants or blended finance until they demonstrate commercial viability. This is why South African government programs, such as the Department of Trade, Industry, and Competition (DTIC)'s Agro-Processing Support Scheme (APSS), which allocates over R20 million to small-scale agro-processors and communities for infrastructure, are valuable [117]. They support testing and validating biomass valorization technologies, helping to secure proof of concept to attract investors. Ultimately, while the technological feasibility of medicinal cannabis biomass valorization is promising, large-scale economic viability will depend on policy support, access to financing, and sustained investment in local technology capacity. Figure 8 ranks biomass valorization technologies suitable for South Africa's cannabis biomass, evaluated on TEA, TRL, skills, feedstock, policy, and market demand. Biochemical valorization with AD is a leading research focus in South Africa, delivering notable GHG reductions and landfill diversion, with favorable TEA outcomes [19, 173, 174]. Thermochemical conversion pathways ranked second due to the abundance of local lignocellulosic residues and the rising demand for biochar and hydrochar in South Africa, both of which promote circular soil and carbon benefits. Additionally, integrated refineries converting digestate into biochar are emerging as part of closed-loop systems [19, 93, 130, 134]. Advanced green extraction technologies, such as supercritical CO₂ extraction and microwave-assisted extraction (MAE), have also demonstrated the potential to valorize cannabis residues, thereby meeting the high-value stream safety requirements set by SAHPRA and the National Cannabis Master Plan's manufacturing pillar [4, 175]. However, despite the potential profitability at commercial scale shown in the TEA study of SC-CO₂ extraction of compounds and solvent recovery, with an

Fig. 8 Suitability of Cannabis Waste Valorization Pathways



internal rate of return of 40% and a payback period of 2.5 years, capital and utility costs remain barriers in the South African context [176]. Integrated biorefinery technologies ranked lowest due to their complex, capital-intensive nature [177]. Recent review studies suggest that phased and modular implementation of such lignocellulosic valorization technologies is more feasible in the near term in South Africa [16, 36, 160, 178].

8.1 Collaborations between Academic institutions, public institutions, and the private sector

The Department of Science and Innovation (DSI) funds research and development focused on innovation, product commercialization, and biorefinery projects related to biomass waste. This is exemplified by initiatives from Stellenbosch University and research organizations like the CSIR's Biorefinery Industry Development Facility (BIDF) and the CSIR's Agro Manufacturing groups [26, 69, 179]. Finding synergy among these programs can significantly boost the commercialization of cannabis valorization and product technologies. For instance, the CSIR's cannabis incubation program has supported 23 SMMEs in developing 40 CBD-infused and cannabis-based products, with funding from organizations such as the DTIC, DSI, GDARD, and DSBD [179]. Additionally, the African Legacy Cannabis Program, in collaboration with the Agricultural Research Council (ARC) and with DSI support, aims to assist communities and indigenous knowledge holders through germplasm maintenance and cultivation research [7]. These initiatives encourage collaboration among government, research institutions, and local communities. Furthermore, Stellenbosch University (SU) has conducted innovative studies that have

identified compounds such as flavoalkaloids in cannabis strains with high therapeutic potential [180].

Collaboration is also evident in the Eastern Cape, where the Eastern Cape Rural Development Agency (ECRDA) partners with the Mpondoland Cannabis Belt Association to transform local landrace strains into commercial products through traditional knowledge [181]. ECRDA mobilizes resources, develops infrastructure, and creates market opportunities, enabling the Mpondo community to drive regional economic growth via cannabis cultivation [181]. To promote collaboration and advance biomass valorization technologies, it is crucial to acknowledge the importance of integrating these technologies into existing companies and institutions that already utilize biomass for value addition, product recovery, and strategic purposes. A comprehensive mapping of South African companies and research institutions involved in cannabis, hemp, agricultural biomass, and organic agricultural biomass value chains was conducted to identify the most appropriate valorization pathways that can complement their existing infrastructure and feedstock access. Table 12 presents South African entities that could benefit from implementing biomass valorization strategies into their current processes.

Legally licensed cannabis growers and processors, like Afripex, adhere to strict regulations and manage waste per SAHPRA guidelines [161]. A collaborative effort involving Afripex, CSIR, and Stellenbosch University aims to fill gaps in cannabinoid extraction, wax fraction recovery, and residue characterization in South Africa. This partnership could establish a sequence of processes for a pharmaceutical-grade cascaded biorefinery. While the local and international market for hemp stalk is limited, converting biomass into high-value hurds and fiber addresses the

Table 12 South African industries that can benefit from biomass valorization strategies

Company or Institution Name	Sector	Products	Feedstock	Primary valorization pathway applicable	Reference
KKOG Global SA	Energy	Biofuels from biomass	General agricultural biomass	Pyrolysis/gasification and fermentation for bioethanol	[182]
Bio2Watt	Energy	Anaerobic digestion for electricity	Organic agricultural waste, food waste	Anaerobic digestion	[158]
Masterpack/Poly-oak Packaging	Manufacturing	Biomass to sustainable packaging	Conventional and bio-based polymers	Lignocellulosic bio-composites	[183, 184]
LABAT AFRICA Limited	Healthcare	CBD oil, hemp fiber, and hemp hurds are used in textiles and construction.	Whole hemp plant (<i>Cannabis sativa</i> L.)	Cascaded biorefinery; green extraction; valorization of fiber and hurds.	[59]
Hemp Solutions	Manufacturing	Hemp stalks and bast fibers to make textiles and paper	Hemp stalks and bast fibers	Fiber processing and bio-composites: enzymatic hydrolysis of the hurd fraction.	[185]
Afrimathemp	Construction	Hurds to hempcrete	Hemp Hurds	Hempcrete and construction materials; biochar soil amendment (by-product)	[186]
Afriplex	Pharmaceutical	Active pharmaceutical ingredients (APIs), CBD isolates, and cannabinoid-derived products.	Medicinal cannabis biomass	Supercritical CO ₂ extraction, winterization, wax recovery, and post-extraction residue valorization.	[187]
Council for Scientific and Industrial Research (CSIR)	Science council	The cannabis plant is used to produce extracts through SFE (CO ₂).	Cannabis plant material	Supercritical CO ₂ extraction (main method): Residue characterization after extraction and biorefinery planning.	[187]
Stellenbosch University (SU)	Academia	Active cannabis compounds from wax	Cannabis wax	Wax fraction cannabinoid recovery: research and pilot design for integrated biorefinery.	[35, 49]

growing global demand for plastics and textiles [70]. For instance, Labat extracts CBD oil for internal use, with the residual fiber and hurds being sold to farmers or companies like Labat Hemp Plastics, resulting in higher revenue and profit per hectare than traditional crops. Moreover, the industrial use of cannabis supports South Africa's green energy transition through large-scale biofuel projects, positioning the country as a leader in decarbonization. A notable example is KKOG Global SA's plan to use 10,000 hectares of hemp in the Eastern Cape to produce carbon-negative fuel, thereby significantly reducing carbon emissions and enabling sustainable industrialization [182]. Supported by government policies such as the SAREM and commitments under the Paris Agreement, this approach aligns policy, investment, and climate goals, thereby unlocking climate financing [21]. This comprehensive framework guarantees the inclusive, research-based, and commercially feasible deployment of cannabis technologies, fostering job creation, economic development, and sustainable growth in South Africa. Numerous public and private organizations are starting to integrate cannabis biomass and compounds into their product and process pipelines. As South Africa advances in the cannabis industry, several sectors stand to benefit significantly from adopting cannabis biomass valorization technologies.

9 Conclusions and future outlooks

South Africa's *Cannabis sativa* L. biomass remains an underutilized resource with high potential for applications in integrated biorefinery systems, including biochemical, thermochemical, multi-product, and green extraction pathways. While enabling factors such as favorable agro-climatic conditions, developing regulatory framework, and industrial capacity are present, the advancement of cannabis biomass valorization will likely depend on collaboration efforts across research, industry, and policy domains. Key challenges include limited investment, technical capacity constraints, fragmented governance, logistical issues, and feedstock variability. Although extraction residue fractions offer additional value streams, further optimization of recovery processes and current methods is necessary. Low-energy pretreatment methods, such as green techniques, may offer local benefits, but their overall effectiveness and scalability have not been thoroughly studied. Thermochemical processes also hold potential for low-grade biomass, supporting cascaded biorefinery strategies to maximize resource use. However, critical gaps remain, including the need for advanced analytical tools for strain-specific valorization and the development of LCA and TEA frameworks to assess commercial viability before large-scale deployment.

Future progress could benefit from improvements that depend on several key steps: (i) unifying the Cannabis Commercialization Policy with the Overarching Cannabis Bill, expected to be introduced in Parliament in 2027, and the 2025 amended Plant Improvement Act, which increases the THC limit to 2%. These efforts will foster a more cohesive legal framework, boosting economic prospects for both small and large-scale farmers; (ii) analytics for local cannabis strains have revealed that South Africa's landrace cannabis varieties, cultivated in provinces such as KwaZulu-Natal, Eastern Cape, and Mpumalanga, represent a strategically important and underexplored phytochemical resource. Protecting and characterizing this genetic heritage through a national landrace genetic database and intellectual property rights is essential to safeguard South Africa's indigenous cannabis varieties; (iii) establishing dedicated training programs to develop human capital for biorefinery technologies, using advanced extraction and conversion methods. This enables South Africa to become not just a raw cannabis biomass exporter, but also a developer and exporter of proprietary biorefinery technologies suited to African conditions.

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Author contributions All authors contributed to the study's conception and design. VL Motsa was responsible for conceptualization, drafting the initial manuscript, curating data, creating artwork, managing the project, and coordinating the review of both the manuscript and the first draft. N Seedat, L Mekuto, and P Sekoai supervised, reviewed, and edited the writing. Collectively, all authors reviewed and approved of the final manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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