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Exploring biochemical, extraction, and catalytic processes for sustainable sesame crop valorization in biorefinery applications

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The transition from fossil-based to bio-based chemicals and fuels is essential to mitigate environmental impacts and promote sustainability. Sesame (*Sesamun indicum L.*), a widely used oilseed crop, presents significant potential for biorefinery applications due to its high oil content, valuable bioactive compounds, and abundant lignocellulosic biomass. This review explores recent advances in bio-based, extraction, and catalytic processes for the integral valorization of sesame crops. Bio-based conversion routes, including anaerobic digestion and fermentation, enable the sustainable production of biofuels such as biogas, ethanol, and biodiesel. Advanced extraction techniques facilitate the recovery of high-value compounds, namely lignans and proteins, for use in pharmaceuticals and functional foods. Catalytic processes, such as transesterification and epoxidation, further expand the potential of sesame oil for bioplastics, polyurethane production, and biofuel synthesis. The novelty of this review lies in providing the first integrated assessment of sesame valorization pathways within a biorefinery framework, highlighting unexplored synergies across energy, materials, and nutraceutical applications. Key challenges such as process scalability, cost-efficiency, and environmental trade-offs were identified as critical barriers to large-scale implementation. Addressing these gaps can guide future research efforts and inform policymakers, ultimately creating economic opportunities for farmers, reducing reliance on fossil fuels, and promoting circular bio-economy models based on sesame and similar crops.

KEYWORDS

sesame, biorefinery, biochemicals, polyurethane, lignan, anaerobic digestion, epoxidation

1 Introduction

Reducing the environmental footprint of fuels and chemicals produced by oil refining through the transition to renewable raw materials is one of the main challenges in the chemistry industry for the upcoming years if we expect to reverse global warming and its noxious effects on the environment. Among these renewable sources, biomass from agricultural crops has emerged as a viable alternative to produce fuels and chemicals (Vogt and Weckhuysen, 2024; Kumar and Verma, 2021; Shahid et al., 2021).

Sesame (*Sesamum indicum L.*) is an ancient oilseed crop known for its seeds, which are highly valued for their oil content and nutritional properties. The plant is predominantly grown in tropical and subtropical regions, playing a significant role in the agricultural economies of many countries due to its adaptability to poor soils and relatively high temperatures (Yadav et al., 2022). Sesame seeds are notable for their high oil content, which ranges from 45% to 55%, while sesame oil is renowned for its stability and nutritional benefits due to its unique composition of fatty acids (>80%), lignans, tocopherols, phytosterols, natural oxidants, and bioactive compounds (Langyan et al., 2022).

By developing sesame-based biorefineries, there is a potential to create new economic opportunities for farmers and rural communities. Latin America offers promising prospects for the development of sesame-based biorefineries, given the historical importance of the crop and the widespread cultivation throughout the region. This can stimulate local economies, provide jobs, and reduce poverty by diversifying income sources and adding value to agricultural products.

This study explores potential bio-based, advanced extraction, and catalytic processes for the valorization of the sesame crop toward biorefinery applications. Figure 1 presents a proposed framework for the integrated valorization of sesame crop residues. Bio-based processes typically involve the use of biological materials and organisms to convert biomass into biofuels and biochemicals. These processes are environmentally friendly, as they minimize waste, and can be integrated into existing agricultural systems. Advanced extraction processes are critical for isolating high-value fine chemicals from vegetable oils. These methods address challenges such as low concentration, efficiency, selectivity, and environmental impact. Catalytic processes, on the other hand, rely on catalysts to facilitate the chemical conversion of biomass to high-value products such as biofuels, bioplastics, and specialty chemicals.

The primary hypothesis guiding this research is that the combination of bio-based, extraction, and catalytic processes within a sesame-based biorefinery framework can enable the sustainable production of fuels and high-value chemicals, thereby offering a viable pathway to reduce the environmental impacts associated with waste management in agribusiness and traditional petrochemical refining. To contextualize current advancements and identify opportunities for sesame crops, Table 1 summarizes the state of the art in bio-based, extraction, and catalytic processes relevant to sesame-based biorefineries.

2 Biochemical conversion of sesame biomass residue

2.1 Biogas production by anaerobic digestion

Sesame harvesting and processing generate two residues with potential for anaerobic digestion. One is the sesame seed coat (SSC), which accounts for approximately 12% of the total sesame seed. Due to its high solid content, SSC is a suitable candidate for dry anaerobic digestion (Dry-AD), a technology well-suited for substrates with solid contents exceeding 15%, such as energy crops and agricultural by-products. In recent years, numerous studies have compared traditional wet anaerobic digestion (Wet-AD) with Dry-AD for different sources of lignocellulosic wastes, including paper, corn stover, grass, and leaves, often reporting comparable overall methane yields (Momayez et al., 2019). Currently, there is a lack of studies investigating the anaerobic digestion of SSC either as a sole substrate or in co-digestion systems. Moreover, no specific data are available comparing methane yield rates from Dry-AD and Wet-AD for SSC. Given its high lignin content and solid fraction, SSC could potentially benefit more from Dry-AD. Future studies should explore both the general feasibility of biogas production from SSC and direct performance comparisons between Dry-AD and Wet-AD to guide optimal process selection for its valorization.

Another residue with the potential for biogas production is sesame oil cake. This solid waste is generated during sesame oil production through the grinding and squeezing process. Sesame residue contains proteins, carbon, nitrogen, phosphoric acid, and potassium, making it a promising candidate for biogas production via AD (Choi, 2022). However, its high nitrogen content can potentially disrupt the carbon-to-nitrogen ratio required for efficient AD. To date, limited studies have explored the co-digestion of sesame biomass with other substrates. However, insights can be drawn from the co-digestion of other residues. For instance, food waste and animal manure have been co-digested with lignocellulosic substrates, such as wheat straw or corn stover, to balance the C/N ratio and improve methane yields (Zhou et al., 2021). Additionally, the co-digestion of nitrogen-rich organic fractions of municipal solid waste with animal manure has been proven to improve methane yields (Franceschi et al., 2023). These findings suggest that combining sesame oil cake or SSC with high-carbon agricultural residues could be a promising strategy. Selecting appropriate co-substrates based on complementary nutrient content and biodegradability is essential to enhance process performance and stability.

With respect to sesame studies, only a few studies have investigated their co-digestion (ACoD). Choi et al. investigated the AcoD of sesame cake with sewage sludge, using two-stage AD process. A 50:50 ratio of substrates resulted in the highest cumulative biogas production (389.67 mL/g of volatile solids) and methane production (0.56m^3 of methane /kg of volatile solid), confirming the feasibility of biogas production (Choi, 2022). It is important to emphasize that the viability of bioenergy production relies heavily on the characteristics of the specific biomass used, the cultivation practices employed, and the efficiency of the energy generation technologies implemented (Alengebawy et al., 2024). Therefore, comprehensive studies that evaluate the properties, processing requirements, and environmental impact of specific biomass types, such as sesame residue, are essential for optimizing biogas production and ensuring the sustainability of bioenergy systems.

2.2 Biofuels and bioproducts

2.2.1 Bioethanol production

Bioethanol is the most widely used biofuel for transportation and is considered a sustainable alternative to gasoline. Additionally, it serves as an organic solvent for synthesizing valuable chemicals

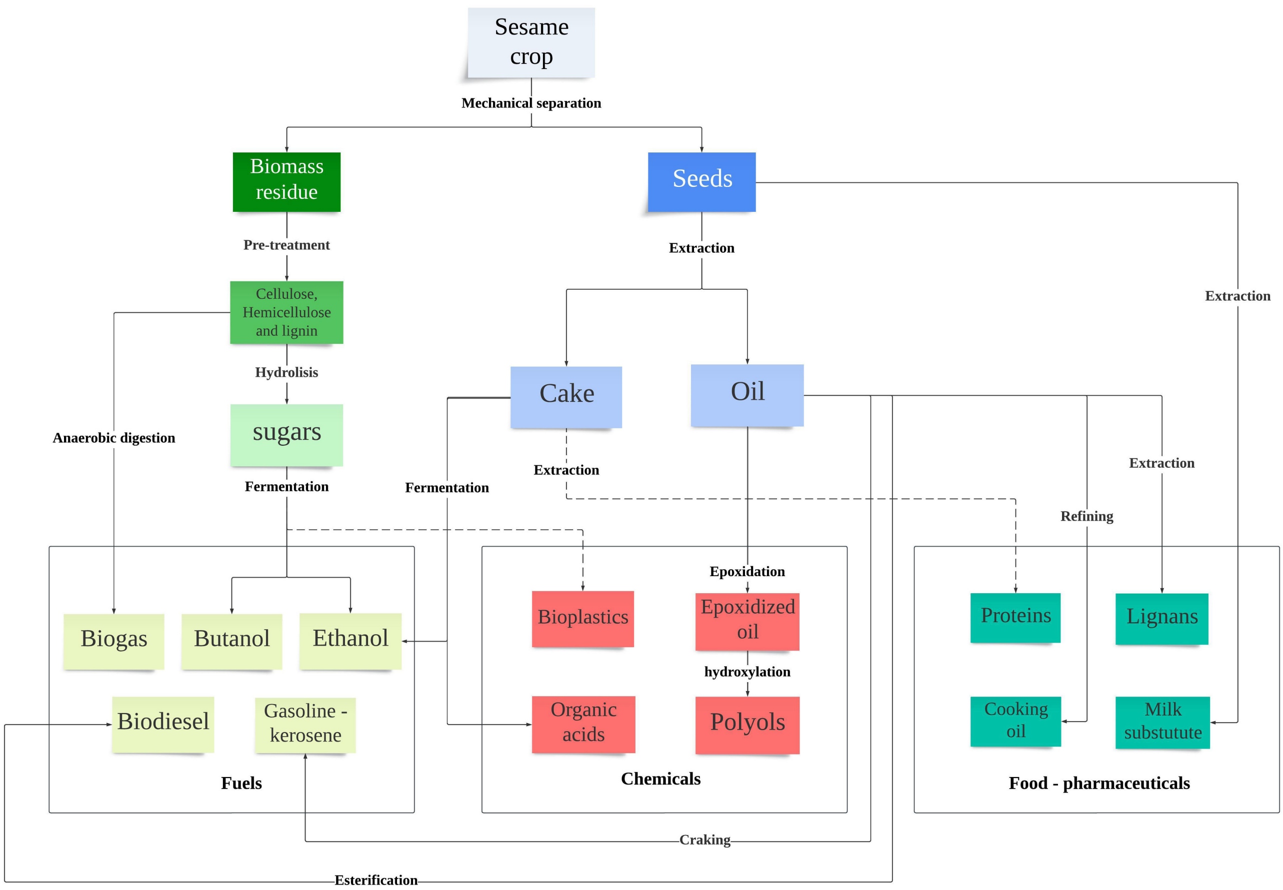

FIGURE 1
Proposed sesame processes for the valorization of sesame crop.

TABLE 1 State-of-the-art sesame valorization methods.

Valorization method	Process	Feedstock	Product	Findings	References
Extraction	Supercritical CO_2 extraction	Sesame cake	Lignans	Adding ethanol as a co-solvent significantly enhanced the extraction of lignans	Jan and Gavahian, 2025
	IR extraction–Water Bath extraction	Sesame husk	Polyphenols	IR extraction yielded 20% more polyphenols than water bath extraction	Khazaal et al., 2024
	Soxhlet extraction	Sesame cake	Polyphenols	Maximum recovery was obtained using aqueous ethanol over distilled water	Usman et al., 2023
	Enzyme-assisted treatment + subcritical fluid extraction	Sesame cake	Lignan-rich sesame oil	Dimethyl ether (DME) gave the best selectivity among three subcritical fluids	Qin et al., 2024
	Microwave, ultrasound, and accelerated solvent extraction	Sesame cake	Lignans	Yielded extracts 15% richer in lignans than Soxhlet method	Bouloumpasi et al., 2024
	Supercritical + Pressurized Liquid Extraction	Sesame cake	Bioactive compounds	Integrated process had higher yield and efficiency vs. Soxhlet	de Avila Souza et al., 2025
Bioethanol production	Microbial and chemical pretreatment + fermentation	Sesame plant residue (SPR)	Bioethanol	Maximum yield of 1.90 $g \cdot L^{-1}$ after 60 h with *S. cerevisiae*	Kumar et al., 2020
Biodiesel production	Microreactor-intensified enzymatic transesterification	Sesame cake	Biodiesel	Nano-biocatalyst (GO-Fe_3O_4@TiO_2 @CRL) gave 97.03% FAME yield	Parandi et al., 2023
Epoxidation	Homogeneous catalytic epoxidation with H_2SO_4	Sesame oil	Epoxidized sesame oil	No reports on heterogeneous ion-exchange resin catalysis for this oil	Musik and Milchert, 2017

and other compounds (Ashokkumar et al., 2022). There is an increasing interest in producing bioethanol from crops such as corn, wheat, sugar cane, and other agricultural wastes. Lignocellulosic biomass can be converted into bioethanol through saccharification and fermentation (Balat, 2011). Abada et al. (2018) evaluated bioethanol production from sesame seed residue through saccharification using cellulase enzymes from Bacillus cereus, producing bioethanol when Saccharomyces cerevisiae was used as a fermentation agent. Kumar et al. (2020) further investigated bioethanol production from sesame plant residue (SPR) and found that the highest yields were achieved with a particle size of 400 m following acid pretreatment and fermentation. This study reported an ethanol yield from 0.87 to 1.90 g/L. Additionally, it was the first to report on bioethanol production from SPR, highlighting its potential as an untapped resource.

Studies involving other agricultural residues have reported higher bioethanol yields, ranging from 2.77 to 25.63 g/L using rice husk and up to 22 g/L from banana peels (Hamdi et al., 2024). These studies also investigated different pretreatment methods and fermentation strategies to improve yields. The study by Kumar et al. (2020) demonstrates the potential of SPR for bioethanol production. However, to enhance process efficiency, it is essential to optimize key stages. First, the pretreatment step should be refined to maximize the release of fermentable sugars, employing different methods to improve substrate accessibility. Additionally, fermentation parameters such as pH, temperature, inoculum concentration, and fermentation time must be precisely controlled to increase the conversion rate of sugars to ethanol (Kumar et al., 2020).

Scaling up bioethanol production still faces key technical barriers. The variability and limited availability of waste feedstocks, which require proper classification and supply prediction, are among the most relevant. Additionally, high production costs are driven by biomass recalcitrance and energy-intensive pre-treatments, which can account for up to 40% of total costs. Additionally, the formation of inhibitors such as furans, carboxylic acids, phenolics, and glycolaldehyde during pretreatment disrupts fermentation. Chemical residues, heavy metals in feedstock, and ethanol itself further complicate the process, demanding optimized and selective pretreatment strategies (Al-Hammadi et al., 2025).

2.2.2 Biodiesel production

Biodiesel is a renewable fuel derived from sustainable materials such as animal fats and vegetable oils and produced by the reaction of triglycerides in the oil with an alcohol to produce fatty acid methyl esters (FAME) and glycerol, in a process called transesterification. It emits significantly fewer greenhouse gases than fossil fuels (Bajwa et al., 2024). According to Roy, the properties of sesame seed oil (SSO) are particularly promising for biodiesel production. The high degree of unsaturation in SSO provides excellent cold flow properties compared to other vegetable oils. Additionally, the unsaturated fatty acids in SSO enhance the oxidative stability of biodiesel, while the natural antioxidants content makes SSO less susceptible to oxidative rancidity, offering greater stability than other vegetable oil-based biodiesels (Roy, 2021). Bajwa et al. further explored the optimization of biodiesel yields by using a mixture of 70% waste cooking oil and 30% SSO. Using artificial neural networks and response surface methodology, they conducted a microwave-assisted transesterification process, achieving biodiesel yields ranging from 75% to 94%. These findings highlight the potential of SSO as a valuable feedstock for sustainable biodiesel production (Bajwa et al., 2024).

Although there are currently no available life cycle studies (LCA) comparing the environmental burdens of biodiesel production from sesame oil to those from more widely used feedstocks such as palm oil, it is plausible to anticipate lower impacts in the case of sesame. Sesame cultivation is well adapted to semi-arid and low-fertility soils, reducing pressure on ecologically sensitive areas (Tanwar and Goyal, 2020; Wei et al., 2022). In contrast, palm oil production has been closely associated with deforestation and biodiversity loss (Cisneros et al., 2021). Furthermore, the relatively low free fatty acid content in sesame oil reduces the risk of soap formation during transesterification, thereby enhancing conversion efficiency and reducing the need for pretreatment steps (Comini et al., 2023).

2.2.3 Bio-plastics

Synthetic plastics are widely used in packaging, toy manufacturing, supermarket bags, cutlery, and more. However, their environmental impact is alarming: only 9% of total plastics are recycled, 12% are incinerated, and a staggering 70% ends up in landfills or dumped in the environment (Mandal et al., 2024). In contrast, bioplastics offer a sustainable alternative. Bioplastics are a family of materials characterized by being bio-based, biodegradable under specific conditions, or both. One widely known bioplastic, polylactic acid (PLA), is derived from agricultural waste and is both biodegradable and biocompatible. Another promising bioplastic is polyhydroxyalkanoates (PHA), a renewable bio-polyester synthesized by bacteria and archaea. To date, research on producing bioplastics from sesame waste is scarce. One notable study investigated the use of sesame wastewater generated during the sesame seed hulling process to produce PHA. Results showed a maximum PHA concentration of 0.53 g/L when the wastewater was supplemented with NaCl and yeast extract, highlighting the need for an additional carbon source to enhance production (Alsafadi et al., 2023). Sesame seed residues, rich in lignocellulosic content, present a promising yet underexplored feedstock for bioplastics production. Research can focus on characterizing the feedstocks, optimizing cellulose and sugar extraction, and developing biodegradable materials such as nanocellulose films, fermented biopolymers, or fiber-reinforced composites. Additionally, evaluating the environmental impact, economic feasibility, and integration into biorefinery models can support sustainable valorization, contributing to circular economy strategies in sesame-producing regions.

3 Extraction

3.1 Lignans extraction from sesame oil

The lignans sesamin and sesamolin, as well as the alcohol sesamol, are high-value fine chemicals present in sesame seeds. Studies have shown the role of sesamin, sesamolin, and sesamol as bioactive compounds for reducing the risk of cardiovascular diseases, as anti-inflamatory agents, inhibitors of diabetes-related

TABLE 2 Nutritional benefits and market potential of sesame-based milk substitute.

Component	Content (per 100 mL)	Health benefit	Market potential
Energy	45–60 kcal	Low-calorie alternative to dairy	Appeals to weight-conscious consumers in North America and Europe
Protein	2.5–3.5 g	High-quality plant protein; rich in methionine	Suitable for vegetarians, vegans, and sports nutrition markets globally
Fat	3.5–5.0 g	Rich in MUFAs and PUFAs	Targets heart-health-conscious consumers, especially in urban Asian markets
Calcium	250–350 mg (can be fortified up to 600 mg)	Bone health; often higher than almond or oat milk	High demand among elderly populations and women in Europe and East Asia
Magnesium	30–50 mg	Muscle and nerve function	Relevant for athletes, pregnant women, and individuals with metabolic risk
Phytosterols & lignans	~10–20 mg	Antioxidant and cholesterol-lowering properties	Marketable as a functional beverage in North America, Japan, and India

Values correspond to unfortified sesame milk (Aydar et al., 2020; Silva and Smetana, 2022).

compounds, and neuroprotection against cerebral ischemia and anti-cancer (Dossou et al., 2023; Kuo et al., 2020; Sohel et al., 2022; Hadipour et al., 2023; Zhang et al., 2023; Dalibalta et al., 2020). Various techniques have been used for the extraction of sesamin, sesamolin, and sesamol from sesame seeds. Liquid–liquid extraction (LLE) using a range of solvents has been employed to isolate lignans from sesame oil. However, this approach is often associated with challenges such as the low solubility of lignans in typical solvents and concerns over the toxicity and environmental impact of these solvents (Andargie et al., 2021).

Zhou et al. (2010) reported the use of macroporous resins for the extraction of lignans from sesame oil, achieving crystals with 76% sesamin. Most recently, Michailidis et al. (2019) introduced advanced centrifugal force-aided liquid–liquid extraction techniques, involving centrifugal partition extraction (CPE) and annular centrifugal extraction (ACE), which offer promising solutions for overcoming the low solubility of lignans in conventional solvents. In both cases, sesamin and sesamolin were obtained with 95% purity. Notably, CPE required three times less solvent than ACE. CPE and ACE can be tuned with green solvent combinations (e.g., ethanol, ethyl acetate, and water), reducing the reliance on petrochemical solvents. Additionally, both CPE and ACE operate in a closed-loop configuration, facilitating solvent recovery and minimizing waste generation (Michailidis et al., 2019).

3.2 Proteins extraction from sesame cake

Protein extraction from sesame cake is gaining interest due to the demand for sustainable, cost-effective protein sources. Conventional methods such as alkaline and enzymatic hydrolysis are well-studied. During alkaline extraction, the proteins are solubilized in an alkaline medium and then precipitated by lowering the pH. While this method yields high protein recovery (typically 60%–70%), the harsh pH conditions can result in protein denaturation, loss of essential aminoacids (e.g., lysine), and reduced digestibility (Hernández-Álvarez et al., 2023). To address these limitations, alternative methods have been explored. Aqueous extraction processes (AEP) and enzyme-assisted aqueous extraction processes (EAEP) use water, with or without proteolytic enzymes, under milder conditions to preserve protein functionality and nutritional quality. These methods can achieve protein yields of 40%–60% while maintaining higher digestible indispensable amino acid scores (DIAAS), making them suitable for food and nutraceutical applications (Souza et al., 2019).

Another innovative approach involves the use of deep eutectic solvents (DES), such as glycerol-choline chlorine mixtures, which have demonstrated efficacy in extracting proteins from oilseed cake such as flax, camelina, and sunflower. DES offers advantages, including low toxicity, biodegradability, and customizable polarity, enabling selective extraction while preserving bioactivity. Yields in DES-based systems can reach up to 50%, with improved retention of essential amino acids and minimal environmental impacts (Parodi et al., 2021). Additionally, subcritical water extraction, which uses water at temperatures between 100 and 374°C and pressure sufficient to maintain a liquid phase, represents another "green" D alternative. This method enables simultaneous extraction and hydrolysis of proteins without the need for organic solvents and can result in hydrolyzates rich in bioactive peptides with enhanced digestibility and functional properties (Švarc Gajic et al., 2020).

4 Food products from sesame seeds

4.1 Plant-based milk substitute

The increasing preference for plant-based milk substitutes over traditional cow milk is driven by concerns about lactose intolerance, environmental sustainability, and ethical considerations. Sesame seeds are rich in essential nutrients, including calcium, protein, and healthy fats, making them a promising base for non-dairy milk production (Silva and Smetana, 2022). Nutritional benefits and market potential of sesame-based milk substitute are presented in Table 2.

To produce a sesame vegetable milk substitute, the seeds are first cleaned and soaked in water to soften. After soaking, the seeds are ground into a paste in water, and the mixture is homogenized to ensure a uniform consistency. The resulting liquid is filtered to remove solids and pasteurized. Enrichment with vitamins, minerals, and natural stabilizers is added to enhance nutritional value and shelf life (Aydar et al., 2020). Finally, innovations such as probiotic integration and artificial intelligence-powered optimization further enhance the sensory appeal and functional benefits (Ayana et al., 2024).

4.2 Cooking sesame oil

Solvent extraction has been a prevalent method for extracting sesame oil, primarily due to its efficiency in yielding higher oil quantities than mechanical pressing. This technique typically employs organic solvents, such as n-hexane, to dissolve the oil from the sesame seeds. The process involves immersing the ground seeds in the solvent, followed by the solvent–oil separation from the solid residue. Subsequent evaporation of the solvent yields the crude sesame oil. While effective, the use of n-hexane raises environmental and health concerns due to its toxicity and volatility (Trad et al., 2023).

Advanced extraction methodologies have been developed to improve the efficiency and sustainability of sesame oil extraction. Supercritical CO_2 extraction (SC-CO_2) is a particularly promising alternative. This method uses CO_2 above its critical temperature (31.1°C) and pressure (73.8 bar), where it exhibits both gas-liquid diffusivity and liquid-like solvating power. Under these conditions, SC-CO_2 can selectively extract lipophilic compounds, including oils, without the need for toxic solvents and preserve heat-sensitive bioactive compounds such as tocopherols, phytosterols, and lignans. Importantly, CO_2 is non-toxic, non-flammable, and leaves no solvent residue in the final product, making it suitable for applications in the food and nutraceutical industries. While solvent extraction is economically favorable at small scales due to its low capital investment, at large scale, it is inefficient and less sustainable given its high solvent consumption (de Avila Souza et al., 2025).

Following extraction, the crude sesame oil undergoes refining processes to remove impurities and improve its quality. The refining steps typically involve degumming, neutralization, bleaching, and deodorization. Degumming removes phospholipids and mucilaginous substances, while neutralization removes free fatty acids that can affect the oil's stability and flavor. Bleaching is performed to reduce color pigments and remove oxidation products, and deodorization eliminates volatile compounds responsible for undesired odors (Kaya and Hung, 2021).

5 Catalytic modification of sesame oil

5.1 Polyurethane by epoxidation-ring opening

Polyurethane is a versatile polymeric material with a wide variety of industrial applications. It is typically obtained by a tin-catalyzed one-step reaction of polyols (polyethylene glycol or polypropylene glycol) and isocyanates, both derived from petroleum. Oil-based polyols can be replaced by natural polyol-containing vegetable oils, such as castor and lesquerella oils, or by modified vegetable oils in which instaurations presented in fatty acids are converted in hydroxyl groups (Malani et al., 2022). For the case of sesame oil, authors have reported the production of polyurethanes by epoxidation-ring opening (Musik and Milchert, 2017; Nwosu-Obieogu and Kalu, 2020).

Epoxidation is the preferred method for hydroxyl modification of vegetable oils due to its ability to introduce reactive oxirane rings (three-membered cyclic ethers) onto unsaturated fatty acid chains (Singh et al., 2020). In this process, oxirane groups are formed by modifying carbon–carbon double bounds through ester rearrangement reactions or hydrogen peroxide-mediated oxidation. The most common epoxidation route involves the in situ generation of peracetic acid via the reversible reaction of a carboxylic acid (e.g., acetic acid) with hydrogen peroxide under the catalytic influence of a strong acid. This peracid then reacts with the unsaturated sites in the oil to form the peroxide (Wai et al., 2019; Armylisasa et al., 2017).

The conventional liquid-phase homogeneous epoxidation, typically catalyzed by formic or sulfuric acid, is performed at temperatures ranging from 50 to 70°C under atmospheric pressure. Despite achieving epoxide yields of 65%–85%, this method suffers from several drawbacks, including low selectivity, non-reusability of the catalyst, peracid instability, and equipment corrosion due to the use of strong acids (Tenorio-Alfonso et al., 2020). To overcome these limitations, heterogeneous catalytic systems, particularly those using ion exchange resins (AIERs) and metal-supported catalysts, are gaining attention (Freites-Aguilera et al., 2022; Dehonor-Márquez et al., 2018).

When using AIERs, such as Amberlite IR-120 or Dowex 50WX2, the reaction is generally conducted at 50–60°C, with hydrogen peroxide concentrations of 30–35 wt%, and a catalyst loading of 5–10 wt% relative to oil. Under these conditions, epoxidation yields exceeding 90% have been reported, along with improved oxirane oxygen content (OCC) and selectivity toward desired products (Freites-Aguilera et al., 2022). Moreover, the use of acetic acid instead of formic acid as the oxygen donor reduces the environmental impact and improves safety by generating fewer exothermic intermediates (Dehonor-Márquez et al., 2018). At the moment of publication of this article, there are no reports of the epoxidation of sesame oil using ion exchange resins.

The oxirane ring in an epoxidized vegetable oil can undergo ring-opening, resulting in the formation of diols, through various methods. Singh et al. reviewed several approaches for the ring-opening of epoxidized vegetable oils, including exposure to diethylamine in the presence of $ZnCl_2$ at 60°C, diethylene glycol at 105°C, hydrolysis in water, and methanol in the presence of water and a fluoroboric acid catalyst. Among these, the methanol-based reaction using fluoroboric acid was highlighted as the most preferred method, for having yields over 80% (Singh et al., 2020).

The resulting polyols serve as key precursors for the synthesis of bio-based polyurethanes, which are increasingly in demand for use in coatings, adhesives, foams, sealants, and elastomers. Polyurethanes derived from epoxidized vegetable oils offer several advantages, such as enhanced biodegradability, lower toxicity, and reduced carbon footprint, compared to petroleum-based analogs. These catalytic processes might be further refined in future to align with broader objectives of biorefinery development, particularly under the principles of circular economy. Processes can be designed to include the extraction of lignans and proteins alongside *in-situ* catalytic reactions, thereby enabling the comprehensive valorization of sesame biomass in a single integrated platform.

5.2 Gasoline and kerosene

Gasoline and kerosene are reported to be produced from vegetable oils by zeolite-catalyzed cracking in temperatures ranging from 360°C and 525°C. Solid, liquid, and gas fractions are formed, depending on the temperature, residence time, and the catalyst selected (Sembiring and Saka, 2019). Camelina, jatropha, sunflower, soybean, and palm oils have been cracked with conversion rates near 90% and liquid organic products over 80%. Although drawbacks associated with traditional fluid catalytic cracking (FCC) have been observed, mainly coke formation (Naji et al., 2021; Haryani et al., 2020), there are no reports about the catalytic cracking of sesame oil.

6 Perspectives and challenges

The integration of sesame crops into biorefineries presents significant opportunities for achieving sustainable development in agriculture and industry. By leveraging advanced catalytic processes, environmentally friendly extraction methods, and biochemical conversion techniques, sesame biomass and oil can be utilized to produce high-value products, including biofuels, bioplastics, nutraceuticals, and fine chemicals. Innovations such as enzymatic transesterification, supercritical fluid extraction, and advanced separation technologies open pathways for improving efficiency and reducing environmental impacts. Additionally, the ability to valorize by-products, such as sesame cake and lignans, not only adds economic value but also contributes to a circular bioeconomy model.

Despite promising advances, the deployment of such processes in developing regions faces economic and operational constraints. Enzymatic transesterification, while highly selective and operable under mild conditions, is limited by the high cost of commercial enzymes, restricted catalytic lifetimes, and challenges associated with large-scale immobilization and reuse. These constraints hinder its industrial adoption, particularly in contexts where capital and technical infrastructure are limited. Similarly, although supercritical CO_2 is an effective and environmentally alternative to conventional solvent extraction, it requires high-pressure equipment and substantial initial capital investment, making it less accessible, particularly to small and medium enterprises.

Latin America presents opportunities for sesame biorefinery development since sesame is a historically significant and widely cultivated crop in the region. However, in these developing economies, where sesame crop is predominantly carried out by smallholder farmers, the feasibility of biorefineries is closely linked to the development of decentralized, affordable, and context-adapted processing systems. Moreover, the lack of standardization in sesame biomass composition further complicates process optimization and reproducibility.

To improve the scalability of biorefinery processes, future efforts should focus on enhancing process integration through modular and mobile extraction units and supporting the establishment of local pilot plants. In addition, policies aimed at supporting green technologies through financial incentives, cooperative investment schemes, and public–private partnerships will be critical to enable widespread adoption.

7 Conclusion

The valorization of sesame crops within a biorefinery framework presents a sustainable alternative to fossil-based industries, enabling the production of biofuels, bioplastics, and high-value chemicals. This study has highlighted the potential of biochemical conversion, advanced extraction, and catalytic processes to maximize the utilization of sesame biomass and oil. Biochemical routes, such as anaerobic digestion and fermentation, support bioenergy production, while innovative extraction techniques enhance the recovery of bioactive compounds for pharmaceutical and food applications. Additionally, catalytic transformations expand the scope of sesame oil into bioplastics and polyurethane synthesis. Future research should focus on optimizing cost-effective and energy-efficient technologies, developing green catalysts, and integrating sesame-based processes into circular bioeconomy models.

Author contributions

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Conflict of interest

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