polymers

MDPI

Review

Strategies for the Transformation of Waste Cooking Oils into High-Value Products: A Critical Review

Valentina Beghetto [1,2,3]

[1] Department of Molecular Sciences and Nanosystems, University Ca' Foscari of Venice, Via Torino 155, 30172 Mestre, Italy; beghetto@unive.it; Tel.: +39-041-2348928
[2] Crossing S.r.l., Viale della Repubblica 193/b, 31100 Treviso, Italy
[3] Consorzio Interuniversitario per le Reattività Chimiche e La Catalisi (CIRCC), Via C. Ulpiani 27, 70126 Bari, Italy

Abstract: Waste cooking oils (WCOs) are generated globally from households, the hospitality industry, and other sectors. Presently, WCOs are mainly employed as feedstock for biodiesel and energy production, strongly depending on the availability of WCOs, which are often imported from other countries. The objective of this review is to give an overall comprehensive panorama of the impacts, regulations, and restrictions affecting WCOs, and their possible uses for producing high-value products, such as bio lubricants, bio surfactants, polymer additives, road and construction additives, and bio solvents. Interestingly, many reviews are reported in the literature that address the use of WCOs, but a comprehensive review of the topic is missing. Published studies, industry reports, and regulatory documents were examined to identify trends, challenges, production statistics, environmental impacts, current regulations, and uses for high-value polymer production. The data collected show that WCOs hold immense potential as renewable resources for sustainable industrial applications that are in line with global carbon neutrality goals and circular economy principles. However, achieving this shift requires addressing regulatory gaps, enhancing collection systems, and optimizing conversion technologies. This comprehensive review underlines the need for collaborative efforts among policymakers, industry stakeholders, and researchers to maximize the potential of WCOs and contribute to sustainable development.

Keywords: waste cooking oil; recycling; polymer synthesis; circular economy

check for updates

Academic Editor: Hu Li

Received: 9 January 2025
Revised: 25 January 2025
Accepted: 27 January 2025
Published: 29 January 2025

Citation: Beghetto, V. Strategies for the Transformation of Waste Cooking Oils into High-Value Products: A Critical Review. *Polymers* **2025**, *17*, 368. https://doi.org/10.3390/polym17030368

Copyright: © 2025 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Demand for and consumption of vegetable oils has significantly increased in the last 15 years, increasing from 83 Miot in 2000, to over 217 Miot in 2023, 167 Miot of which were employed for biodiesel production, while the remaining part was used primarily by the food, feed, and pharma industries [1,2].

Globally, palm and soybean oils dominate the market with shares of 40.0% and 29.0%, respectively, while other vegetable oils are produced in smaller quantities, and include sunflower (9.7%), rape (6.3%), peanut (4.1%), corn (2.1%), coconut (1.9%), olive (1.8%), and sesame oil (1.1%) [2] (Figure 1a). Asia satisfies over 54.0% of worldwide vegetable oil demand; in particular, Indonesia is the world's greatest producer, followed by China, Malaysia, the USA, and Brazil (Figure 1b) [3–9]. Although biodiesel may be considered an attractive alternative for the partial substitution of fossil-based fuels, edible oils are an essential source of nutrition, accounting for approximately 10.0% of the global average caloric food supply, second in importance only to cereals [10].

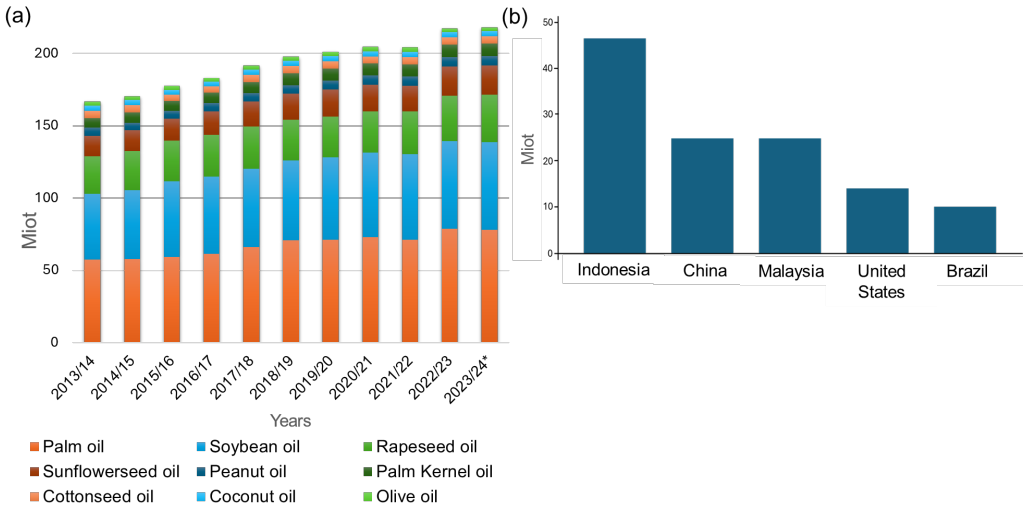

Figure 1. (**a**) Sources of Vegetable oils and (**b**) main geographical areas of production (Miot/year).

Additionally, it has been demonstrated that a correlation exists between the rise in biodiesel consumption in the USA and the increasing number of palm oil plantations in Southeast Asia, consequently increasing deforestation and global warming [11]. Thus, high production costs, and threats to the food and feed value chains, together with socio-environmental impacts, have made the use of edible oils as feedstock for biodiesel less appealing over time [12–14].

Alternative valuable feedstocks for biodiesel production are known, such as waste cooking oils (WCOs), fats, and grease, together with more recent technologies, starting from algae [1,15,16].

The term WCOs refers to exhausted cooking oils coming from the hospitality and industrial sectors, which are no longer suitable for human consumption [13]. If disposed of in drains or sewers, WCOs form products that linger in the environment for many years, generating odors and problems in wastewater treatment plants, and polluting soil and water courses, causing highly negative environmental impacts [17–19]. Additionally, WCOs may contain intermediate products, formed by oxidation or microbial degradation, which are toxic to microorganisms, algae, plankton, mussels, and amphipods [20,21], but also to humans, causing serious illnesses such as dyspepsia, stomach-ache, diarrhea, and gastric cancer [22]. The reuse and recycling of WCOs therefore open new frontiers, reducing the disposal costs and environmental impacts derived from them [23].

Presently, WCOs are mainly employed at the industrial level to produce biofuels and energy [24–35]; yet, in consideration of the EU requirements to reach carbon neutrality by 2050, the use of WCOs and, in general, of by-products and waste as fuels should be disfavored compared to their valorization for producing high-value chemicals [15,36,37]. In fact, the need to recover and recycle by-products or end-of-life products, reducing primary resource consumption and CO_2 emissions, is becoming increasingly urgent, leading to a change from a linear economy based on a "take-make-discard" model, to a circular economy based on green chemistry and eco-design [38–41].

It should be further considered that the use of WCOs as feedstock for biorefineries continues to face a very critical moment in the EU. The dramatic decline in biodiesel prices, largely attributed to competition from Chinese companies, led to notable shifts in 2024, so that Chevron decided to shut down its biodiesel facility in Germany, BP reduced its sustainable aviation fuel and renewable diesel plans in Europe, and Shell stopped the construction of a major biodiesel plant in Rotterdam [42]. The contraction of the biodiesel market is an opportunity to boost the use of WCOs to produce high-added-value polymeric

products at an industrial level, implementing innovative technologies and consequently supporting EU market competitiveness.

Alternative applications of WCOs include the production of bio lubricants [31,43–45], bio solvents [46], animal feed [47–50], asphalt additives [51,52], composite materials [53,54], polymers [55,56], fine chemicals [57–59], and non-aqueous gas sorbent devices [60,61], among others.

Within this panorama, the present review intends to give a general overview of the impacts, regulations, and restrictions affecting WCOs, and their possible uses, other than for fuel and energy, for producing high-value polymeric materials. The objective of this review is to give an overall comprehensive panorama. Data published in the last ten years in peer review papers have been subdivided according to the final application described. Interestingly, many reviews have been reported in the literature that address specific topics on the use of WCOs for the preparation of a specific class of polymer, but a general comprehensive review of this topic is missing.

2. Methods

Systematic research of the existing literature was carried out to analyze the current status of impacts, regulations, and restrictions affecting WCOs; the possible uses, other than fuel and energy, of WCO production, recycling, and upcycling technologies to produce high-value polymeric materials; and the impacts derived from these. A combination of different keywords were used in the search, such as "waste cooking oil", "used cooking oil", "bio lubricant", "bio surfactant", "bio solvent", "polyurethane", "bio polymer", "non isocyanate polymer", "acrylic polymer", "alkyd ester", "epoxy resin", "asphalt/construction additive, rejuvenating, anti-aging", "circular economy", "EU directives". Specifically, one or a combination of two keywords were chosen for the selection of the papers, and only English language papers published in peer review journals were included in the analysis.

The research papers included in the review were collected through Web of Science, Scopus, Google Scholar, ScienceDirect, and ResearchGate, and were published between 2014 and 2024. To find the most updated data and regulations, we also searched the websites of relevant organizations, such as the European commission portal [62], the European Law portal [63], the European Alliance of News Agency [64], the European Environment Agency (EEA) [65], the European Chemicals Agency (ECHA) [66], Statista [67], and Eurostat [68]. Once relevant sources were identified, references were reviewed for additional relevant information. This review focuses on the reuse of WCOs to produce polymeric materials, while papers concerning the use of WCOs for fuel and energy are not reported.

3. WCO Production and Market

Although much information is available in the literature on the production of vegetable oil worldwide (see Figure 1a,b), it is rather difficult to find accurate data quantifying the amounts of WCOs that are produced and available for valorization. Teixeira and coworkers reported that about 320 Kg of WCOs are produced for every ton of cooking oil used, with a variable valorization rate (between 75% and 23%), according to the geographical area [18]. A rather worrying fact that emerges from the analysis by Teixeira is that out of 23 states evaluated, over 85% had no specific legislation regarding WCO management. These data were also confirmed by a more recent paper by Zhao and coworkers, which indicated a general static trend over the recent years in the adoption of more sustainable management strategies for WCOs, and indicated that the main alternative remains inadequate disposal in the environment [69].

In the USA, according to the Environmental Protection Agency, nearly 11.4 Miot of WCOs are collected from restaurants yearly, only small percentages of which are ade-

quately managed [70], while production estimates are of about 15.0 Miot of WCOs [71]. Even the virtuous EU has a long way to go, considering that according to estimations, the pro-capita production of WCOs in the EU is 8L/year, which, considering a population of around 500 million people, corresponds to a yearly production of WCOs of 4.0 Miot. This value, which is four times higher than the currently collected amount, clearly evidences the gap between WCO production and collection [44]. Another way to estimate the annual production of WCOs in the EU is by considering the region's yearly consumption of vegetable oils, which amounts to 24.0 million tons (Miot). With 32% of this consumption being discarded, the annual production of WCOs in the EU could potentially reach around 7.7 million tons [18]. This also accounts for the great difference between vegetable oil consumption (220.0 Miot) and the amount of WCOs collected worldwide (about 15.0–18.0 Miot) [71], distributed geographically as reported in Figure 2.

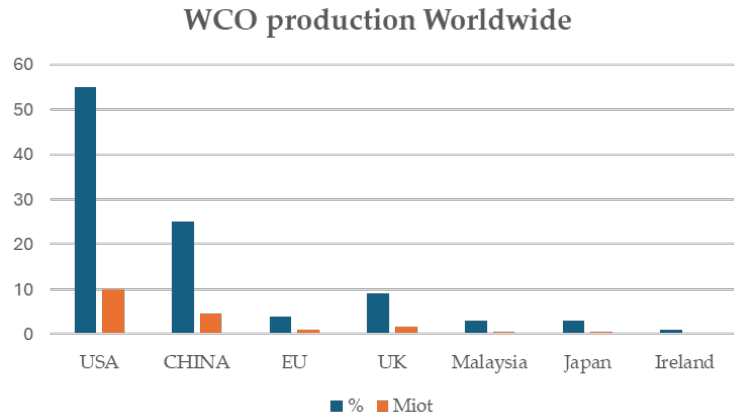

Figure 2. Geographical distribution of WCO production worldwide.

Presently, WCOs are mainly employed by the industry as feedstock for biodiesel and energy production [72–80]. In fact, it is well known that WCOs can be used to produce fatty acid methyl esters (FAMEs) through alkali-catalyzed transesterification, and used as biodiesel [34,54,81,82]. Other processes for the valorization of WCOs are known, such as cracking or hydrocracking, pyrolysis, and gasification processes to produce biofuels [76]. Additionally, energy production by WCO combustion has been reported in the literature, under different conditions, and with WCOs having different viscosity and acidity [83,84].

It should nevertheless be considered that although the use of WCOs can reverse the noncompetitive price of biodiesel produced from virgin biomass and reduce negative environmental impacts [85,86], the use of WCOs as a primary feedstock for second-generation biodiesel production depends on their large-scale availability, and since local food waste is often insufficient, the importation of biodiesel or WCOs from other countries is required [87–89]. As evidenced by various LCA studies, the importation of WCOs is neither a sustainable practice to guarantee energy supply, nor does it contribute to reducing gas emissions [72,90]. In this concern, the recently approved EU renewable energy directive (Directive (EU) 2023/2413) states that "the share of biofuels and bioliquids, as well as of biomass fuels consumed in transport, where produced from food and feed crops, shall be no more than one percentage point higher than the share of such fuels in the final consumption of energy in the transport sector in 2020 in that Member State, with a maximum of 7% of final consumption of energy in the transport sector in that Member State" [91]. Within this panorama, the alternative use of WCOs for high-value products should be privileged as an alternative to their use as biodiesel. Thus, in this review, no further discussion on the use of WCOs for biodiesel production is reported.

4. Regulations and Restrictions Affecting WCOs

As far as the EU is concerned, starting from the 1970s, with the waste oil directive 75/439/EEC, the European Commission committed to collecting used oils, limiting environmental hazards, and promoting recovery and recycling technologies [44,92].

During the last decade, many regulatory updates have been implemented at the EU level for the classification, storage, recovery, or disposal of waste oils from hospitality, household, and other industrial compartments. Amending Directive 2008/98/EC and European Commission (EC) Decision 2000/532/EC, EC Decision 2014/955/EU of 18 December 2014 [93] reports a harmonized list of wastes, which is continuously updated based on new knowledge and research studies. It should nevertheless be stressed that the inclusion of materials in this list does not necessarily imply that the material is waste under all circumstances. A material is waste only when the definition of waste in Article 1(a) of Directive 75/442/EEC is met [94].

Different wastes are defined by a six-digit code (Directive 2014/955/EU) [93], where the first two digits identify the manufacturing compartment generating the waste, the second two, processing operations, and the last ones a specific material. This implies that waste may be identified by different EWC codes according to the manufacturing process that generates it, and vice versa, specific production units may need to classify their waste according to several codes. As regards WCOs, they are classified as 200125, where 20 corresponds to "municipal wastes (household waste and similar commercial, industrial, and institutional wastes)", 01 to "separately collected fractions", and 25 to "edible oil and fat". Edible oils are also found as mixtures with grease coming from wastewater treatment plants, and are identified by EWC 190809, while if coming from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation, and processing wastes, the EWC is 0203.

Additionally, WCOs classified under EWC 200125 are not hazardous to human health, but their inadequate disposal makes them potentially harmful to the environment. For this reason, Art. 1 of Directive 2008/98/EC lays down the "measures to protect the environment and human health by preventing or reducing the adverse impacts of waste mismanagement and improving the efficiency for reuse", requiring Member States to adopt waste management plans [95]. As in similar cases, the need to promote the development of a unified EU policy program, while preserving Member State sovereignty, in order to adopt independent approaches to waste management, recycling, and disposal, inevitably creates logistical barriers across borders [36].

Considering that in 2018, many Member States still had not yet developed the necessary waste management infrastructure, EU Directive 2018/851 was issued, amending EU Directive 2008/98/EC to "prevent the creation of structural overcapacities for the treatment of residual waste" and "improve the efficiency of resource use and ensuring that waste is valued as a resource, can contribute to reducing the Union's dependence on the import of raw materials and facilitate the transition to more sustainable material management and to a circular economy model"(Directive (EU) 2018/851) [96]. This directive sets out the EU legislative framework pushing towards the achievement of the EU Action Plan and the Sustainable Development Goals of the Agenda 2030 to achieve carbon neutrality by 2050. It is of fundamental importance that a congruent and unified legislative framework is adopted within the EU to develop and promote near-zero waste processes [31,43,45,97].

As far as the US is concerned, back in October 1997, the Environmental Protection Agency (EPA) rejected a petition from several agricultural trade organizations seeking permission for facilities storing vegetable oils or animal fats to use less-stringent response methods for spill planning under the Facility Response Plan (FRP) rule (40 CFR 112.20-21; 1 July 1994) [98]. Subsequently, in 2000, the EPA introduced a revised FRP rule that

clarified its applicability to facilities managing, storing, or transporting large quantities of animal fats and vegetable oils, particularly those transferring significant volumes of oil over water or storing at least one million gallons of oil. The updated rule aligned with the Edible Oil Regulatory Reform Act, by distinguishing animal fats and vegetable oils from other oil types based on their properties and environmental effects [99]. The revised rule introduced a specific methodology for calculating worst-case discharge planning volumes for animal fats and vegetable oils, using similar principles as those for petroleum oils, but incorporating tailored factors for estimating recovery needs on water and onshore. Separate regulatory sections were created for animal fats and vegetable oils, while maintaining the same response planning scenarios (small, medium, and worst-case discharge) from the original rule. New definitions for animal fats and vegetable oils were also added, along with a classification system dividing oils into Groups A, B, and C based on their specific gravity.

In 2002, the SPCC rule (40 CFR Part 112) was revised to address the Edible Oil Regulatory Reform Act's requirements, dividing the rule into subparts [100]. Subpart A outlined general requirements for all facilities, Subpart B addressed petroleum and non-petroleum oils (excluding animal fats and vegetable oils), and Subpart C covered requirements for animal fats, greases, fish and marine mammal oils, and vegetable oils derived from seeds, nuts, fruits, and kernels. The revised rule also emphasized the significant environmental impact of oils on soil components. To advance sustainable processes aligned with the Circular Economy Action Plan, the adoption of a unified legislative framework is crucial, enabling the upcycling of waste and fostering near-zero waste processes [31,44,45].

In this connection, the EU End of Waste directive 2008/98 is a fundamental milestone, determining the necessary criteria to transform waste into a valuable secondary primary material [95,98]. Directive 2008/98/EC defines "recovery" as "any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy" [98]. Additionally, "recycling" is defined as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes not including energy . . . fuels or for backfilling operations". Specifically, requirements for "End of waste status" are that a waste shall cease to be waste if the following conditions are met: (i) it has been demonstrated that "the substance is commonly used for specific purposes"; (ii) "a market or demand exists for such a substance or object"; (iii) "the substance fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products" and (iv) "the use of the substance will not lead to overall adverse environmental or human health impacts".

5. Environmental Impacts of WCOs

The environmental impacts derived from the inadequate disposal of WCOs are numerous, and derive from their accidental or deliberate release, causing environmental and biological alterations. WCOs' highest environmental impacts occur when they are discharged into water bodies or indirectly enter them after being spilled into sewer systems [101–103]. WCOs are immiscible with water and generate a thin film, reducing oxygenation, limiting light filtration, and affecting the life of aquatic plants and living beings. It is estimated that 1 kg of used vegetable oil can be evenly distributed to cover an area of 1000 m^2 [18]. Similarly, WCOs tend to form a hydrophobic film around earth particles and plant roots, creating a barrier to water and, consequently, precluding the intake of nutrients. Moreover, WCOs that penetrate the ground may reach drinking water wells, which become unsuitable for human consumption [102]. For this reason, it is essential to take appropriate precautions to protect groundwater and wells but also surface waters

that may be in contact with the deeper water reservoirs. Moreover, like synthetic oils and fossil-based products, WCOs can cover the surfaces of living organisms (for example birds and aquatic animals), forming an insulating film which decreases their ability to breathe, exchange heat, and, in some cases, move.

The great risks associated with improper disposal of these substances has led to the development of a different regulation, the establishment of Consortiums devoted to the collection of WCOs, even if they are currently mandatory only for industrial activities, while the management of WCOs produced by citizens, defined as "urban waste", is in the charge of municipalities.

6. WCO Composition and Pretreatments

In general, WCOs are mainly composed of 95% triglycerides with aliphatic chains ranging from 16 to 18 carbon atoms [104], derived from palm, soybean, canola, sunflower, peanut, cottonseed, coconut, olive, and corn oils [3] (Figure 1a).

WCOs are mostly produced from food frying at temperatures between 150 °C and 200 °C, and cannot be reused for food processing [55,105,106]. In fact, during use, vegetable oils undergo three main chemical reactions, i.e., hydrolysis, oxidation, and polymerization, which alter their physical chemical characteristics [3,48,104] (Figure 3). Hydrolysis occurs in the presence of moisture in food, resulting in the formation of glycerol and free fatty acids (FFAs), which cause color changes and the production of smoke. Oxidation reactions naturally occur when the double bonds in vegetable oil interact with atmospheric oxygen, leading to the formation of highly reactive hydroperoxides. Additionally, polymerization reactions take place between unsaturated fatty acyl groups, forming dimeric or oligomeric triacyl glycerides [48,55]. Additionally, thermal cracking of unsaturated fatty acids, followed by oxidation at high temperatures, may also promote polymerization reactions, forming a variety of toxic compounds such as heterocyclics [107].

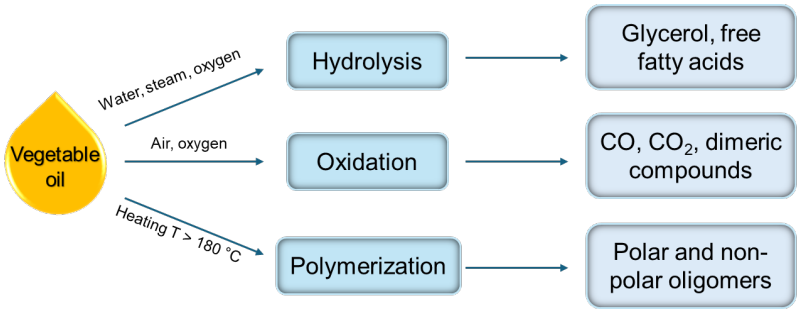

Figure 3. Chemical degradation reactions of vegetable oil.

WCOs differ [25,27] in color, viscosity, density, pH, flash point, number of unsaturated bonds, chemical composition, and toxic components, because of chemical degradation [13,59,108–110]. Data reported in the literature clearly highlight changes in the pH (from 5.34 to 7.38), kinematic viscosity (from 28.744 mm^2/s to 68.568 mm^2/s), and molecular weight of WCOs produced from different vegetable oils and under different cooking conditions (Table 1) [110,111]. For this reason, many different WCO pretreatment processes prior to recycling, such as filtration, extraction, and distillation to eliminate water and impurities, have been reported in the literature [26,112].

Table 1. Chemical physical characteristics of vegetable oils and WCOs derived.

Component	Sunflower Oil [a]	Sunflower Oil WCO [b]	Rapeseed Oil [a]	Rapeseed Oil WCO [a]	Palm Oil [a]	Palm oil WCO [a]	Sun Foil [a]	Sun Foil WCO [a]
Saturated fatty acids	71.5	32.0				80.0–93.0	74.4	73–15
Monounsaturated fatty acids	-	62.0				20.0–7.0		27–6
Polyunsaturated fatty acids	28.5	6.0					25.6	0–79
Acidic value (mg KOH/g oil)	0.30	2.29	0.06	1.06		0.66–1.13		0.72–1.44
pH	7.38	5.34			6.34	5.73–6.19	8.63	6.14–6.61
Density at 20 °C (kg/m^3)	919.21	920.40	918.00	929.00	919.48	923.2–913.4	919.6	919.8–923.2
Kinetic viscosity at 40 °C (mm^2/s)	28.744	31.381	63.286	68.568	27.962	44.254–38.407	28.224	43.521–35.236
Molecular weight (g/mol)	670.82	51.94	869.16	871.01	535.08	135.66–586.05	119.71	55.18–395.28

[a] Ref. [13]. [b] Ref. [111].

Additionally, the recycling of WCOs depends on their acidity, iodine value, and number of conjugated dienes or trienes, which influence their recyclability [55]. For example, it is evident that highly acidic WCOs need to be neutralized before base-catalyzed transesterification [27]. Further pretreatments may be necessary to meet specific standards, such as EN 14214 for biodiesel [113], while specific standards related to the volatile components present in WCOs must be met for polymer synthesis [27,55]. A very interesting work has been published by Mannu and coworkers which reports an extensive characterization of different WCOs subjected to several different frying cycles and purified with different methods (pH, Temperature) [46]. This complex study was carried out to increase the standardization of pretreatment procedures, improving WCOs' recyclability. In fact, according to the authors, the combination of data acquired allowed the determination of the best recycling protocols for a given WCO [45,46].

Leaving aside its main use for biodiesel production, WCOs can be chemically modified to produce bio lubricants [48,114], bio surfactants [110,115], bio-based plasticizers [116–118], polymers and polymer additives [55,57,119,120], binders and additives for roads and constructions [51,121–124], and bio solvents [31]. All of these applications will be further discussed in separate sections.

7. WCOs for Bio Lubricants and Bio Surfactants

7.1. Bio Lubricants

Bio lubricants (BLs) are anti-friction agents with improved viscosity, higher thermal tolerance, and lower volatility compared to petroleum-based lubricants. The BL world market had a value of 2 Mio$ in 2022 and is projected to reach a value of 2.8 Mio$ by 2031, registering a CAGR of 3.8% during the forecast period of 2023–2031 [125]. WCOs are an efficient and environmentally sustainable feedstock for BLs due to their high lubricity, high biodegradability, low volatility, and low cost. Different modification routes have been reported for the conversion of WCOs into BLs, such as hydrolysis, esterification, transesterification, hydrogenation, and epoxidation, using both chemical and enzymatic catalyzed reactions [114,126–130], as summarized in Figure 4.

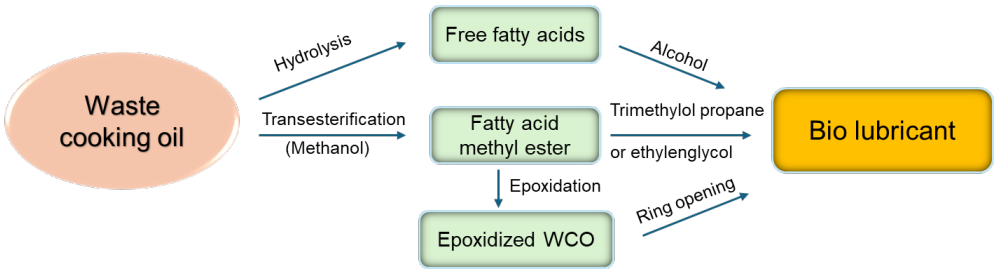

Figure 4. Main chemical reactions to produce bio lubricants from WCOs.

The different routes foresee the hydrolysis of WCOs to FFAs, followed by esterification with high-molecular-weight alcohols or polyols [131–133], or the transesterification of WCOs to FAMEs, followed by transesterification with high-molecular-weight alcohols such as trimethylol propane (TMP) [134–139], or other polyols [114,140]. Alternatively, FAMEs may be epoxidized with hydrogen peroxide and acetic acid [131,141,142], followed by epoxy ring-opening by alcoholysis or hydrolysis in the presence of a catalyst [136,138,143,144].

From an industrial point of view, transesterification is one of the most feasible routes for the conversion of WCOs into BLs, and, consequently, the most investigated [114,138,145–147]. Although, in most cases, high conversions are reported, nevertheless, BLs produced by transesterification reactions have low viscosity indexes and modest performances at low temperatures.

Zhang et al. improved the efficiency of the process [130] by employing lipase and [HMIm][PF_6], a recyclable ionic liquid used as catalyst, producing a product with excellent lubricant properties, such as a low pour point (−61 °C), high viscosity index (149), and high thermal-oxidation stability (312 °C). Sarno and coworkers adopted a similar transesterification process, starting with WCOs and neopentyl glycol, to produce bio lubricants [148]. A lipase immobilized on nanoparticles of modified magnetite was employed as a catalyst, showing high activity and recyclability up to ten times.

Alternatively, Jahromi and coworkers also explored the improved thermophysical and rheological properties of BLs generated by epoxidation in the presence of cyclic oxygenated compounds (cyclopentanone, cyclopentanol, anisole, and 2-methylfuran) via a four-step pathway: hydrolysis, dehydration/ketonization, Friedel−Crafts acylation/alkylation, and hydrotreatment [143]. The process allowed the achievement of BLs with a low pour point (−12 °C), a kinematic viscosity of 47.5 cP (at 40 °C), a viscosity index of 186, and a Noack volatility of 17 wt %, comparable to commercially available lubricants.

7.2. Bio Surfactants

Another interesting application of WCOs is to produce bio surfactants (BSs), which are employed by the food, cosmetic, textile, health, pharmaceutical, mining, and paper industries [103,115,149–155]. The market of BSs has grown constantly during the last two decades, and is expected to reach 4.8 Mio€ by 2025 [156].

BSs are secondary metabolites, generated by a variety of microorganisms such as fungi (yeasts) or bacteria (actinomycetes), that can either remain attached to the cell surface or be secreted outside the cell [157,158]. Like BLs, BSs also have several advantages over their synthetic equivalents, since they can be produced by fermentation from renewable feedstocks, are environmentally compatible, and show better foaming properties under a wide range of conditions (pH, salinity, and temperature) [34,159].

BSs have been classified either by their molecular weight (high and low molecular weight), ionic charges (anionic, cationic, non-ionic, and neutral), or secretion type (intracellular, extracellular, and adhered to microbial cells). However, their identification based on chemical structure remains the most widely adopted method, dividing them into glycolipids, lipopeptides, fatty acids, phospholipids, neutral lipids, and polymeric surfactants [152]. Glycolipids are low-molecular-weight amphiphiles that consist of a hydrophilic polysaccharide headgroup and one or more hydrophobic fatty acid tails [156,160], which may be produced from WCOs [161–163]. In fact, WCOs are an interesting feedstock for BSs, which may be converted by various yeast species into sophorolipids, rhamnolipids, mannosylerythritol lipids, and other glycolipids [110,161,162]. The use of several microbials, such as Bacillus, Pseudomonas, Acinetobacter, and Candida, has been extensively reported in the context of bio surfactant production with different methodologies (metagenomics, metatranscriptomics, and metaproteomics) [161]. Nevertheless, to date, BSs are not widely employed, due to unsustainable production costs [103].

The chemical modification of WCOs for BS production could be a more economically sustainable alternative, and, therefore, has been extensively studied. For example, Yusuff and coworkers recently reported the use of WCOs as a low-cost carbon source for producing anionic surfactant fatty acid methyl ester sulfonate via a transesterification–sulfonation process [164]. Furthermore, Permadani developed a bio-detergent from methyl ester-sulfonate (MES) produced from WCOs, using titanium dioxide nanoparticles as catalyst [165]. In fact, several studies have been reported in the literature on the production of MES from WCOs [103,166], and these are among the leading renewable surfactants and detergents at the industrial scale, exhibiting superior detergency efficiency compared to fossil-based products, lower toxicity, and better skin compatibility [108,165]. The production of MES

from WCOs foresees preliminary purification, followed by transesterification to form the corresponding methyl esters, which are then reacted with sodium bisulfite as a sulfonating agent [108]. Various papers dealing with the environmental performance of BSs using WCOs as feedstock clearly demonstrate that their use significantly reduces environmental impacts compared to the use of other feedstocks [161,162,167].

In the field of branched non-ionic surfactants, Dong and coworker synthesized a new series of bio-based, branched non-ionic surfactants (ethoxylated dihydroxy stearic acid methyl ester, DMOE) from renewable oleic acid derived from WCOs [168]. The results showed that DMOE has low foaming ability, strong defoaming ability, good wetting performance, and outstanding emulsifying capabilities, enabling the application of these surfactants for industrial cleaning activities.

Another interesting study has been published by Khalaf and coworkers [169] on the preparation and use of cationic gemini surfactants prepared from WCOs as green inhibitors against acidic corrosion of N80-steel. Gemini surfactants are also highly demanded worldwide for their promising applications in the paper, medical hygiene, and textile industries [170]. Additionally, cost-effective and efficient adsorbent macro-porous organic polymers based on WCOs were synthesized on a Kgs scale by Wu and coworkers, which were able to remove oil and heavy metals from wastewater ($\geq$94%), exhibiting excellent hydrophobic and super-oleophilic properties [122].

8. WCOs for Polymer Additives

With the introduction of new regulations that are increasingly restrictive, on the use of components classified as toxic, research is opening up new horizons for the use of new bio-based components as additives in the plastics industry [31,116]. The addition of plasticizers in the formulation of polymers plays a very important role in modifying the chemical and physical properties of plastic manufacts [31,171,172]. Plasticizers have been extensively used to produce flexible polyvinyl chloride (PVC) plastics, which otherwise are hard and brittle [173–175]. Phthalate esters, conventionally employed at the industrial level for PVC production, are known to exhibit a migration phenomenon from the polymer matrix to the surrounding media and to accumulate in the environment [116,171,175–177], and they are subject to REACH restriction. Due to their negative impact on human health and the environment, they have been banned in several countries in the production of toys and packaging materials [118,178,179]. In this context, the syntheses of epoxidized soybean oil (ESO), methyl epoxy soyate, amyl epoxy soyate, acetylated derivatives of castor oil, tall-oil fatty esters, and dicapryl sebacate have been described as alternative ecofriendly substitutes for phthalate esters, yet with limited applications, due to the high costs of the starting materials used [173,177,178]. More sustainable alternatives have recently been reported which employ WCOs as feedstock [117,118,179–182]. As reported by Liu et al. [183], acetylated-fatty acid methyl ester-malic acid ester (AC-FAME-MAE), obtained by modification of WCOs (Figure 5, route I), may be used as additive in PVC formulations, giving a product with chemical and physical performances that are in line with those of the common industrial additive (phthalate), making it an excellent environmentally safe substitute for phthalate esters. Cai and coworkers also reported the synthesis of bio-plasticizers from WCOs according to the strategy reported in Figure 5, routes II and III [182]. Two different highly epoxidized compounds (EGE-WCO and EP-WCO) were obtained, and their characteristics as plasticizers for PVC were tested.

EGE-WCO with an epoxy value of 6.57% showed high compatibility with PVC and high plasticizing efficiency, decreasing the Tg of PVC films from 62.8 °C to 15.8 °C and improving their elongation at break. Migration phenomena of EGE-WCO were found to be negligible. Additionally, Jia and coworkers proposed the synthesis of a covalently

bonded plasticizer to the PVC backbone (WCOs methyl esters), avoiding possible migration phenomena, which have also been reported with some WCO-based plasticizers [116].

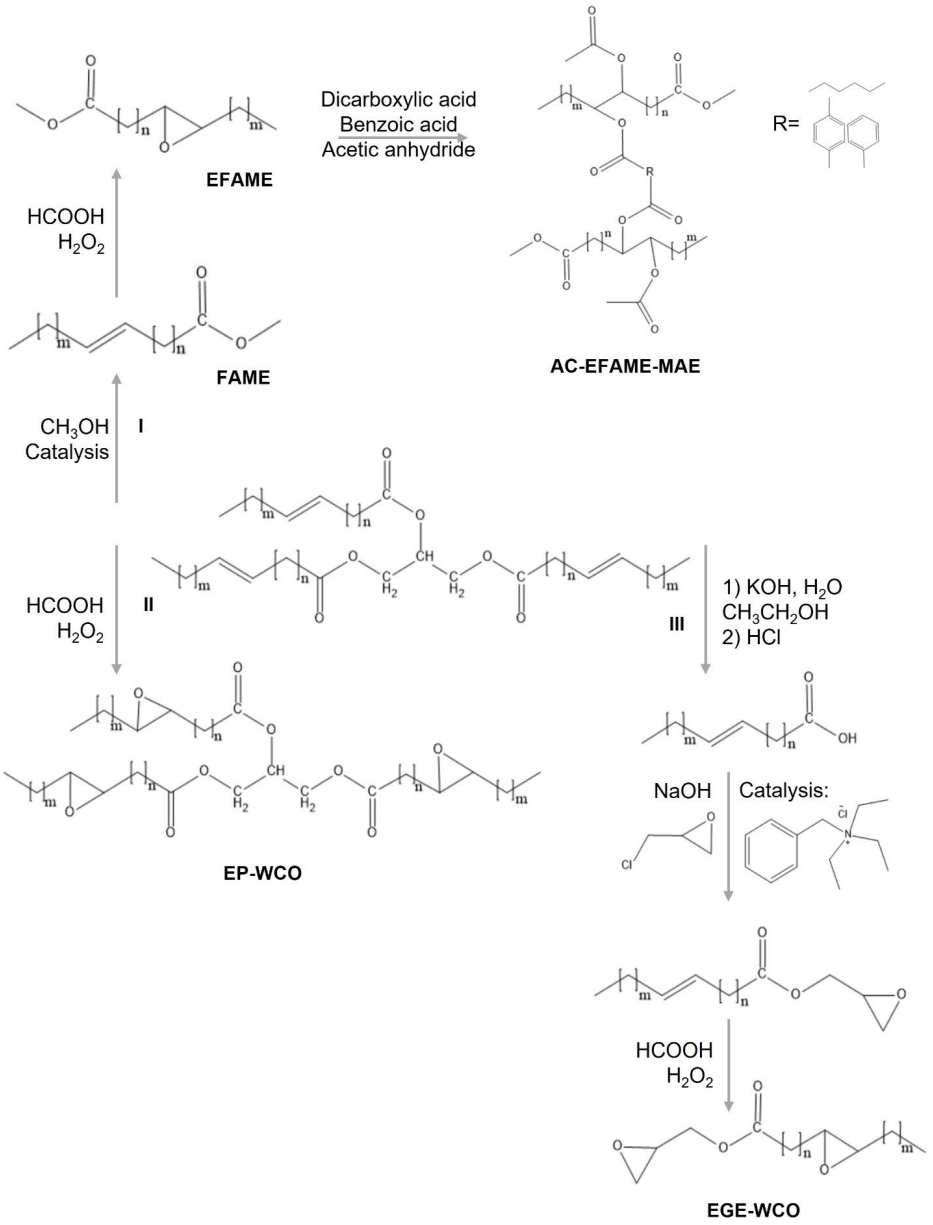

Figure 5. Examples of PVC additives prepared from WCOs.

9. WCOs for Polymer Synthesis

9.1. Polyurethane

Polyurethanes (PUs) are an important class of polymers that had a global market of about 26 Miot in 2022, which is estimated to reach 31 Miot by 2030, positioning PUs as a major player in the polymer market [45,184–186]. In fact, due to the broad chemical and physical characteristics of these polymers, it is possible to produce flexible and rigid foams, or nonporous materials for different applications, ranging from the automotive sector to the construction industry [187,188]. Currently, PUs are prepared from virgin naphtha; however, scientific research is pushing towards replacement with renewable raw materials. In this context, many efforts have been made to prepare bio-based polyols from WCOs and achieve more renewable and sustainable PUs [57,189–192].

Although many strategies have been used to produce polyols from vegetable oils, such as transesterification, epoxidation, ozonolysis, thiolene coupling reactions, hydroformylation, and photochemical oxidation (Figure 6) [187,193–196], polyols from WCOs are mainly obtained by transesterification or epoxidation (Figure 6a, route I and Figure 6b) [186,191,197,198].

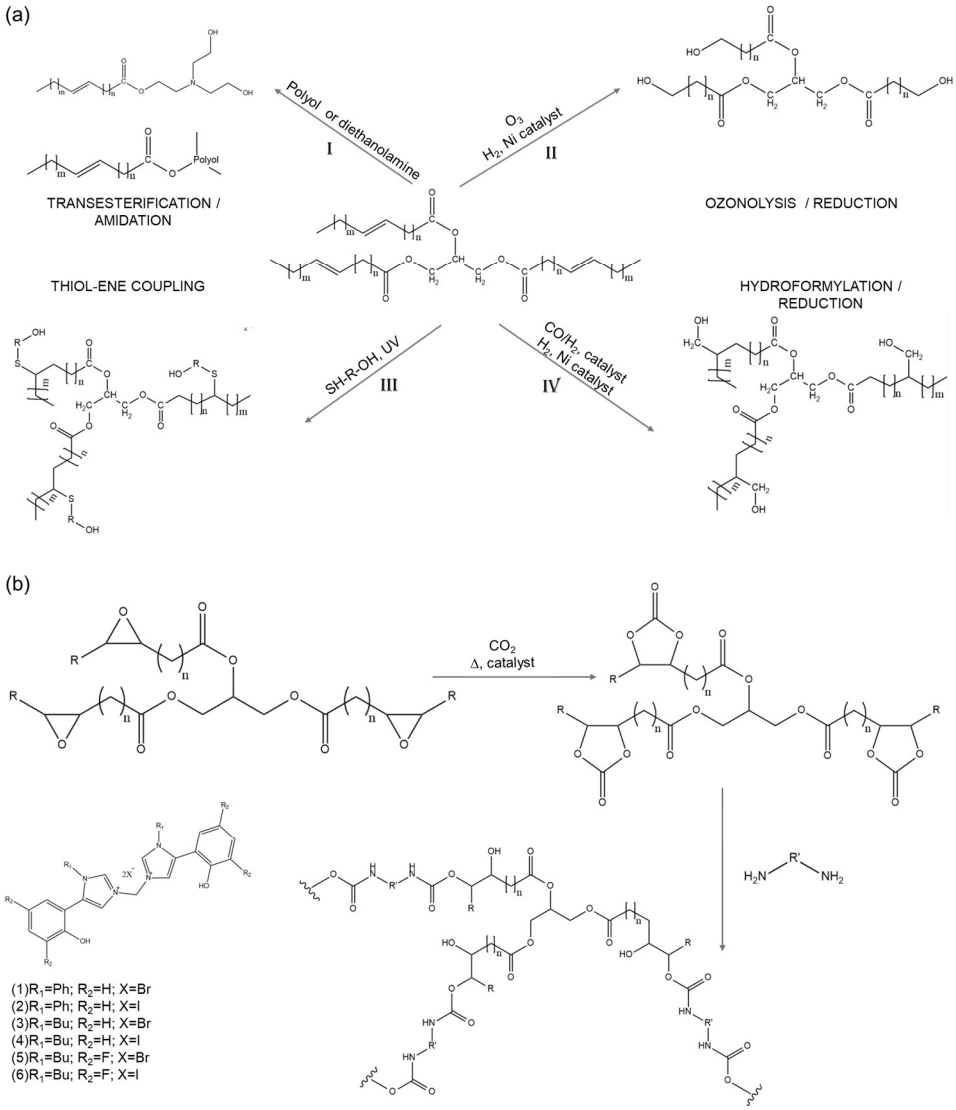

Figure 6. Different strategies for the synthesis of polyols from vegetable oils and WCOs.

Polyols generated from the transesterification of WCOs are mixtures of triglycerides, monoglycerides184- and diglycerides, together with glycerol (Figure 6a, route I). Since transesterification is an equilibrium reaction, to achieve high ester yields, an excess of alcohol, in most cases methanol, must be used to shift the equilibrium towards the products. A catalyst (alkali, acid, or enzyme) is also added to improve the reaction rate and ester yields [199–201].

Kuranska and coworkers reported the synthesis of polyols from WCOs in the presence of ethylene glycol, propylene glycol, diethylene glycol, and triethanolamine (Figure 6a, route I), and their characterization by Gel Permeation Chromatography [198,202]. Taking into consideration the principles of Green Chemistry, the work by Kuranska and coworkers tried to maximize the incorporation of all reagents used in the final product, avoiding solvents and employing renewable reagents, so that bio polyols produced under optimized reaction conditions could be used, without purification, for PU synthesis [202].

A different approach has been reported by various researchers, who have reported the modification of WCOs by epoxidation and ring-opening reactions, allowing them to obtain rigid polyurethane foam with chemical and physical properties like those of common polyurethane materials used in building and construction [197,203,204]. Particular attention has been given to the optimization of the catalysts employed for epoxidation and ring-opening reactions, and the data reported demonstrate that Amberlite IR-120, an ion-exchange resin, and tetrafluoro boric acid give the highest yields and selectivities [203,204]. Interestingly, it has been demonstrated that modifying the additives used to produce PUs containing WCO-based polyols enables the adjustment of their physical–mechanical properties and biodegradability [204]. For example, the combination of polyethylene glycol (PEG), 4,4′-diphenylmethane diisocyanate (MDI), and WCOs allows the achievement of biodegradable PU sheets.

Salleh and colleagues [191] reported the preparation with waste cooking oils (WCOs) of polyurethanes (PUs) that exhibited suitable properties for solid polymer electrolyte production. This was achieved through pre-polymerization (epoxidation and hydrolysis) in the presence of lithium iodide, as a charge carrier, and ethylene carbonate. Finally, MDI was added, and films prepared by casting technology [191,205,206]. Few other works have been published on the production of composite materials containing PUs prepared from WCO-derived polyols. For instance, Lubis and coworkers [207] tested the preparation of reinforced sugar palm fibers for the preparation of PU foams from WCOs, polyols, and toluene diisocyanate. According to the authors, WCOs promote cross-linking and improve the interfacial adhesion between the fiber and the matrix. Additionally, WCOs have been employed as precursors for super-hydrophobic coating applications through a process of amidation of WCOs, followed by functionalization with diisocyanates and fatty acids [208], or with diisocyanates and amino-terminated polydimethylsiloxane [182]. Silva and coworkers recently reported a comparative life cycle analysis of fossil and bio-based polyurethane foams, evidencing the different benefits and criticalities offered by different methods of PU production [209].

A major concern remains regarding the use of toxic diisocyanates, which are also employed to produce PUs with bio-based polyols. Alternatively, non-isocyanate polyurethanes (NIPUs) have been widely studied, yet their industrial application is still hampered by the low physical–chemical characteristics of NIPUs, together with their unsustainable production costs. Nevertheless, NIPUs constitute the most promising frontier for producing environmentally sustainable PUs, and should therefore be implemented.

Within this panorama, the efficient synthesis of polyurethanes from WCOs and CO_2, in the presence of different organocatalysts, is a promising alternative (Figure 6b) [210,211]. This interesting alternative not only promotes the recovery and reuse of a waste (WCOs), but also of CO_2, consequently reducing greenhouse gas emissions, and avoiding the use of fossil-based chemicals and toxic diisocyanates. Werlinger and coworkers reported the synthesis of bis-imidazole salt catalysts (Figure 6b), bearing two -OH groups, for the synthesis of cyclic carbonates derived from WCOs, employed as starting materials for the synthesis of different NIPUs by polyaddition reactions of carbonated vegetable oils with a variety of diamines. The catalysts and cyclic carbonates prepared were characterized by NMR, whereas NIPUs were characterized by NMR, IR, and GPC, and their thermal properties were studied using TGA and DSC analysis.

9.2. Acrylic Polymers

A wide range of applications exist for the use of vegetable oil triglycerides to prepare acrylic polymers, and similar protocols have also been adopted using WCOs as a starting point [55,212]. For example, Wu and coworkers [213,214] reported that they successfully

converted WCOs from McDonald's restaurants into acrylic polymers for use in additive 3D printing manufacturing. Filtered WCOs were reacted with acrylic acid, in the presence of boron trifluoride etherate (BF_3xEt_2O), at 80 °C for 4 h. The product was characterized, showing that the double bonds of the triglyceride molecule break because of the grafting of the acrylic groups. After purification to eliminate residual unreacted acrylic acid, the product could be 3D printed, either with or without the addition of a photo inhibitor. Interestingly, the polymers were found to be biodegradable, showing 18% weight loss after 14 days of incubation in soil [215]. Further papers, such as those by Yan Liu, have also studied 4D printing of multifunctional photocurable resin based on waste cooking oil [138].

Onn and coworkers recently reported the modification of WCOs through enzymatic acidolysis, carried out to increase the unsaturation sites and chemical reactivity of WCOs, in order to produce an acrylic pre-polymer which was photo-cross-linked in the presence of a photo initiator [212].

9.3. Alkyd Esters

Alkyd ester resins are prepared by a condensation reaction between a polyol, a poly-basic acid, and a fatty acid. Alkyd esters are used in paints, varnishes, and casting molds, with a yearly world production of around 200,000 tons [216]. Fatty acids employed for the formulation of alkyd resins may derive from vegetable oils, animal fats, or WCOs, improving their sustainability. A common strategy employed to produce alkyd resins from vegetable oils, known as the monoglyceride process, is reported in Figure 7 [55], and foresees a two-step strategy: (a) base or acid catalyst alcoholysis of WCOs, to generate monoglycerides and diglycerides; (b) a polycondensation reaction of the monoglycerides with an anhydride (aromatic or aliphatic). According to the type and concentration of anhydride used, as well as the length of the oil, the properties of alkyd ester resins can be changed.

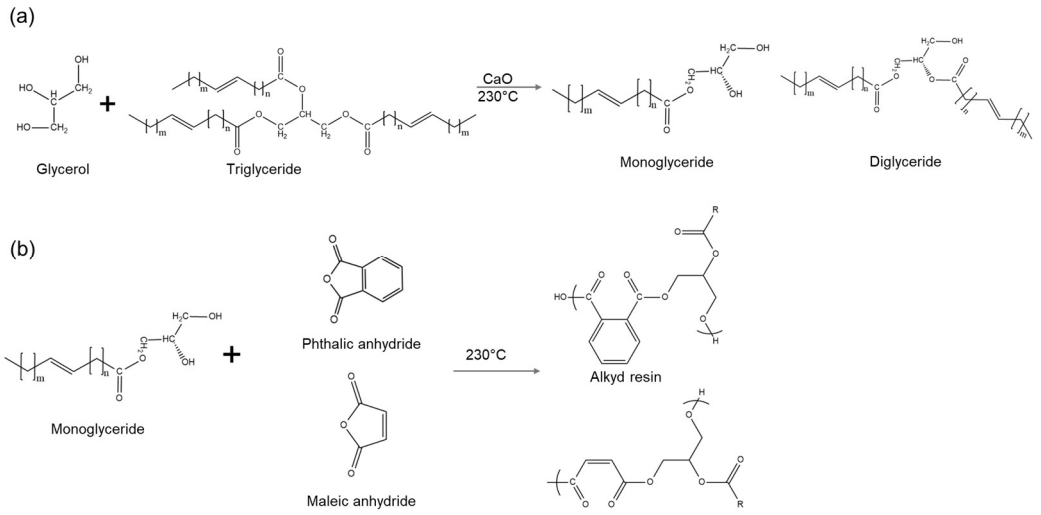

Figure 7. Monoglyceride process for synthesis of alkyd resins by (**a**) base or acid catalyst alcoholysis or (**b**) polycondensation reaction.

Research carried out by Silvianti and coworkers [126] reports the synthesis of alkyd ester resins from waste palm cooking oil, using zeolites as water absorbents, in alternative to distillation. At the same time, this reduces the concentration of FFA content, contaminants, toxic products, bad odors, and color. WCOs have also been employed by Phunphoem and coworkers to produce alkyd-based printing inks for vehicles (Phunphoem et al., 2020).

9.4. Epoxy Resins

Epoxy resins are thermosetting polymers made of monomers that have a three-membered epoxide ring. Epoxy resins are widely used in many applications thanks to their outstanding thermal and mechanical properties, and worldwide consumption of epoxy thermoset resins is expected to reach 17.0 Mio$ by 2028 [217]. The epoxy resin industry is presently based on diglycidyl ether of bisphenol A (DGEBA), produced by a reaction between bisphenol A and epichlorohydrin. All of these chemicals are listed as highly toxic to human health; DGEBA is identified as an endocrine disruptor and a teratogen, and has long-term effects on aquatic life, and has therefore been banned from materials used in baby milk bottles [218]. Bio epoxy resins thus appear to be a very important bio-based, renewable, biodegradable, and biocompatible alternative to petroleum-based epoxy resins and triglycerides coming from WCOs, and have been demonstrated to have a wide scope of applicability [219,220]. Epoxide resins are produced either by chain-growth ring-opening polymerization or step-growth polymerization [220]. Fernandes and coworkers are claimed to be the first to have used epoxy resins from WCOs, in combination with recycled carbon fibers, followed by casting, to produce composites with interesting tensile strength (53 MPa) and Young's Modulus (3.2 GPa), and to reduce the characteristic brittleness of DGEBA [221].

10. Waste Cooking Oils for Roads and Constructions

The increasing need for renewable resources as alternatives to fossil-based ones has also pushed many researchers to study the use of WCOs in the construction industry. Due to their similar elemental composition to petroleum, WCOs have been widely employed for the production of construction materials, mainly for asphalt and concrete production, as described below [137,214,222–233].

10.1. WCOs for Asphalt Production

Many different works have been published in the last decade on the use of WCOs as additives for asphalt concrete and asphalt cement to improve various characteristics, such as softening point, viscosity, complex modulus, creep stiffness, resistance to deformation, voids in mineral aggregate and elastic recovery [73,187,234–236]. On the other hand, in most cases, WCO additives adversely affect penetration, ductility, phase angle, stress relaxation, and thermal cracking resistance, and reduce the overall stability of asphalt concrete [224,234,235].

Wang and coworkers investigated the use of WCOs as modifiers for fossil-based asphalt binders. Based on infrared spectroscopy, frequency sweep rheological analysis, a multiple stress creep recovery test, and linear amplitude sweep tests, the authors verified that WCO-modified binders displayed a higher carbonyl index, lower binder stiffness and softening effects, and reduced rutting resistance at high temperatures [52]. Also, the fatigue life of bio binders under cyclic fatigue loading was significantly improved by increasing the wt% of WCOs by wt of bitumen, further confirming their potential applicability as sustainable asphalt binders [52].

Additionally, WCOs have been extensively studied for the recycling of reclaimed asphalt pavement (RAP) and grinded tire rubber (GTR) that would otherwise be discarded [98,230,236]. The recycling of RAP generates economic savings, reducing the exploitation of non-renewable resources, energy consumption, and polluting emissions in mining and transportation operations [237,238]. However, as bitumen ages, it loses its original properties, causing distresses in pavements that may endanger traffic safety and reduce travel comfort. In fact, when quantities above 20 wt.% of RAP by wt. of bitumen are used, a gradual decrease in fatigue cracking and low-temperature cracking of pavements is observed [239]. WCOs are an economically and environmentally sustainable alternative

to fossil-based rejuvenating agents, allowing these shortcomings to be solved [236]. Independently from the geographical origin of RAP and WCOs, data reported in the literature generally agree that WCOs between 1 and 8% wt.% by weight of bitumen positively affect penetration value [234,239–244]. This can be attributed to the alteration in the consistency of asphalt, contributing to improved fluidity and workability of the modified asphalt.

Pretreatment of WCOs is normally required to reduce acidity, due to variable quantities of FFAs present, which negatively influence performance [51]. Common pretreatment practices are esterification, transesterification in the presence of methanol, or refining processes which promote the overall performance of WCO-modified bitumen [245–247]. An interesting study has recently been published by Bardella and coworkers on the possibility of achieving highly performing rejuvenating agents by chemical modification of WCOs, or hydrolysis of WCOs by transesterification (other than methanol) or amidation reactions, to achieve various WCO esters and amides. All samples were characterized according to their nuclear magnetic resonance, melting point, and boiling point. The efficiency of WCO esters was assessed by means of the Asphaltenes Dispersant Test and the Heithaus Parameter, showing that bitumen blends containing 25 wt.% of WCOs by weight of bitumen, modified with 2-phenylethyl alcohol, performed better than bitumen alone [51].

Alternatively, in a recent work, Enfrin and coworkers studied the pretreatment of WCOs by the epoxidation reaction, which were used as rejuvenating agents for RAP [248]. This low-cost procedure allowed rejuvenating agents to be produced with immediate cracking resistance comparable to that of commercially available fossil-based rejuvenating agents, and higher long-term cracking resistance. The authors suppose that epoxide groups promote dispersion of the asphaltene clusters of bitumen, creating bridges between the molecules and preventing their agglomeration, slowing aging phenomena.

Another interesting work has been reported on the rejuvenating and self-healing efficiency of WCO capsule preparation by mixing WCOs with sodium alginate or chitosan powder, which were then poured in a $CaCl_2$ solution, and capsules produced with a micro-peristaltic pump. In general, the WCO performances were superior to those of commercially available products, and, in particular, the fatigue healing performances of asphalt mixtures were improved by 10∼30% [223].

From an environmental point of view, WCO rejuvenating agents reduce greenhouse gas emissions and energy consumption. For instance, emissions of CO_2 are reduced from 20.06 to 18.44 $KgCO_2e/t$ by switching from conventional bitumen to bio-bitumen, respectively, and energy consumption is reduced from 48.33 × 109 to 42.81 × 109 J per ton of material produced [130,249].

Elahi and coworkers very recently reported a study on the modification of WCOs with styrene-butadiene-styrene (SBS) from GTR to give a rubbery-solid used as a bitumen additive. WCOs promote the swelling and cross-linking process of SBS, improving the adhesion between the modified WCOs and the bitumen [238]. The following three-step process was used for the modification of WCOs: (i) filtration; (ii) pre-swelling of SBS with various wt./wt.% of WCOs/SBS (45:55 and 50:50 wt./wt.%) at 160 °C; (iii) reduction in size of the modified WCO mixtures and mixing of them with bitumen (between 5 wt.% and 25 wt.% by weight of bitumen). The data reported showed that increasing the content of SBS-modified WCOs improved the bitumen's stiffening, temperature susceptibility, viscoelastic response, and elasticity. Also, ethylene-vinyl acetate (EVA) has been used in combination with WCOs, producing highly performing rejuvenating agents [54,249].

10.2. WCOs for Concrete

WCOs have also been studied for the production of sustainable cements. Li and coworkers developed a cement clinker and gypsum mixture containing different WCOs,

and verified their physical mechanical characteristics, together with their economic and environmental impacts [142]. Results show that, overall, WCOs favorably improved cement grinding, and when highly unsaturated WCOs were employed, cement strength was also improved. Additionally, WCOs improved microstructure density, hardening the cement paste. The authors concluded that the use of WCOs as grinding promoters in cement processing is economically and environmentally beneficial. Recently, Liu and coworkers studied the use of WCO emulsions as shrinkage-reducing admixtures to improve concrete durability. The prepared oil and water emulsions were able to reduce cement shrinkage, enhancing its dispersion and stability [250]. The addition of different contents of WCOs and water emulsions reduced the total porosity and refined the pore size by significantly reducing $Ca(OH)_2$ crystals, probably because of the saponification reaction between WCOs and $Ca(OH)_2$.

11. WCOs as Bio Solvents

Another interesting characteristic of WCOs is their ability to capture volatile organic compounds (VOCs) [31,60] originating from different manufacturing procedures, such as emissions from rice husk pyrolysis and rubber vulcanization [60,251].

Lhuissier and coworkers [60] developed a non-aqueous phase absorption and degradation bioreactor for Volatile Organic Compounds (VOCs). The VOCs targeted were n-heptane, ethyl acetate, isopropanol, methyl isobutyl ketone, toluene, m-xylene, and 1,3,5-trimethylbenzene. The data reported showed that WCOs have an absorption efficiency which is comparable to that of fossil-based oils. Tarnpradab and coworkers employed WCOs to reduce the emissions produced during rice husk pyrolysis [251], and in this case, WCOs were able to reduce the content of the organic hydrocarbons formed. Other different examples exist for the use of WCOs for the adsorption of VOCs produced by the leather industry [252], or of other industrial contaminants such as mercury [61].

In addition, WCOs have been employed as solvents for the pretreatment of GTR, to compensate for the insufficient storage stability of GTR-modified asphalt [224,253]. GTR is one of the most common bitumen modifiers used to improve bitumen's rheological properties. However, bitumen containing GTR generally has poor storage stability and workability, affecting the performance of the pavement [224,253]. Pretreatment of GTR with WCOs reduces polymer segregation phenomena, improving aging resistance and reducing environmental impacts [254,255]. In addition, recent research also indicates that a rejuvenator with excellent storage stability and regeneration effects can be obtained when GTR is pyrolyzed in a WCO-rich phase [256].

12. Other Applications

Although data are available from the literature on the use of edible [257,258] and non-edible waste oils [259,260] as organic phase change materials for food preservation, asphalt, or building thermoregulation, the use of WCOs for this scope is very limited [261–266].

Different works have reported on the use of filtered WCOs for thermal energy storage, showing they significantly reduce energy consumption compared to analogous products prepared from other virgin or waste oils [260,262].

Alternatively, phase change capsules (PCCs) have been prepared by mixing WCOs in the presence of sodium alginate and Tween80, an emulsifying agent, and microcapsules have been prepared by microfluidic technology [261]. PCCs have been employed for the preparation of foamed concrete with mechanical properties that are within standard requirements (strength > 4.80 MPa) and interesting thermal insulation properties.

13. Conclusions

Based on literature data reported in this work, it evidently emerges that WCOs are a valuable type of food waste that can be used as feedstock to produce a variety of different bio-based polymeric materials. Although WCOs are renewable starting materials for sustainable biorefinery, nonetheless, they struggle to find industrial applications. The complexity and variability in the composition of WCOs, together with an inadequate collecting system, are among the main barriers for the introduction of WCOs as feedstock at the industrial level. Competition for the use of WCOs in the biofuel market is also a drawback, reducing their availability. The large-scale adoption of WCO-derived polymers faces significant economic challenges, despite their environmental advantages and coherence with circular economy principles. These challenges include the following:

1. Feedstock availability and cost variability: WCO supply is inconsistent due to regional and seasonal variations, high transportation costs, limited collection infrastructure, and competition from industries like biodiesel production, making it an expensive feedstock.
2. High initial capital investment: scaling production requires costly infrastructure and advanced technologies.
3. Processing costs and technological barriers: converting WCOs into polymers is more expensive than traditional methods, due to the need for impurity removal, quality control, and, often, complex processing technologies.
4. Market competition and price sensitivity: competing with low-cost petrochemical polymers is difficult without incentives, especially in price-sensitive sectors.
5. Regulatory and certification challenges: complying with varying regional regulations and obtaining the necessary certifications adds significant financial and administrative burdens.
6. Consumer perception and demand uncertainty: limited awareness and misconceptions about waste-derived materials hinder market demand, requiring costly consumer education campaigns.
7. Competition for alternative uses of WCOs: consolidated applications like biodiesel production, supported by mature markets and incentives, reduce the availability of WCOs for polymer production.
8. Limited policy support and economic incentives make it difficult for WCO-based polymers to compete with conventional materials.

To overcome these problems, future efforts should address the adoption of legislative strategies aiming to harmonize the collecting system throughout the EU and promote campaigns to raise awareness among consumers of the importance of WCOs' separate collection. Furthermore, strengthening WCO collection networks will help to enhance their availability and reduce costs. Additionally, investments in research to develop cost-effective and scalable technologies are necessary, as well as supportive policies, including subsidies and tax incentives, to promote the upcycling of WCOs on an industrial scale.

From a technological point of view, many different strategies and applications exist to produce high-value polymeric products from WCOs, although only a few of them have been implemented at the industrial level today. This evidently testifies that further efforts need to be made both by the scientific community and the industry to reduce the complexity of the processes necessary to transform WCOs into polymeric materials, which are strictly connected to collecting systems and management capacities. Once WCOs are collected, managed, and used properly, they will surely become a valuable feedstock for the polymer industry, satisfying most of the sustainable development goals of the 2030 agenda and of the principles of green chemistry. Further industrial prospects, the market availability of

WCO-based polymers, and patent analysis are under investigation, and will be the object of the next publication.

Funding: This research was carried out within the "Interconnected Nord-Est Innovation Ecosystem (iNEST)" project and received funding from the European Union Next-Generation EU—National Recovery and Resilience Plan (NRRP)—MISSION 4 COMPONENT 2, INVESTIMENT N. ECS00000043—CUP N. H43C22000540006. This manuscript reflects only the authors' views and opinions; neither the European Union nor the European Commission can be considered responsible for them.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further material is available on request.

Acknowledgments: The author would like to thank Gloria Saorin for her support for the graphical editing and reviewing activities.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Ferrusca, M.C.; Romero, R.; Martínez, S.L.; Ramírez-Serrano, A.; Natividad, R. Biodiesel Production from Waste Cooking Oil: A Perspective on Catalytic Processes. *Processes* **2023**, *11*, 1952. [CrossRef]
2. Statista. Global Production of Vegetable Oils from 2000/01 to 2023/24. 2024. Available online: https://www.statista.com/statistics/263978/global-vegetable-oil-production-since-2000-200 (accessed on 10 January 2025).
3. Azahar, W.N.A.W.; Bujang, M.; Jaya, R.P.; Hainin, M.R.; Mohamed, A.; Ngad, N.; Jayanti, D.S. The potential of waste cooking oil as bio-asphalt for alternative binder—An overview. *J. Teknol.* **2016**, *78*, 3722. [CrossRef]
4. Iowa Farm Bureau. What's Cooking with Vegetable Oils. 2022. Available online: https://www.iowafarmbureau.com/Article/Whats-Cooking-with-Vegetable-Oils (accessed on 12 January 2025).
5. Markets and Markets. Biofuel Market. 2023. Available online: https://www.marketsandmarkets.com/Market-Reports/biofuels-market-297.html?gad_source=1&gclid=Cj0KCQjwwMqvBhCtARIsAIXsZpYveQ0-50boErhnWFXCgq_Z0oq8tQpxCUuu7vgZ44hackufMVylwJEaAmf-EALw_wcB (accessed on 12 January 2025).
6. NationMaster. Vegetable Oils Production. 2023. Available online: https://www.nationmaster.com/nmx/ranking/vegetable-oils-production (accessed on 28 January 2025).
7. Oils and Fats International. Global Vegetable Oil Production in 2021/22 Crop Year Set to Reach Record High. 2021. Available online: https://www.ofimagazine.com/news/global-vegetable-oil-production-in-2021-22-crop-year-set-to-reach-record-high (accessed on 12 January 2025).
8. Statista. Forecast Volume of Vegetable Oil Consumed in the European Union (EU 27) from 2018 to 2032. 2024. Available online: https://www.statista.com/statistics/614522/vegetable-oil-consumption-volume-european-union-28/ (accessed on 12 January 2025).
9. Statista. Consumption of Vegetable Oils Worldwide from 2013/14 to 2023/2024, by Oil Type. 2024. Available online: https://www.statista.com/statistics/263937/vegetable-oils-global-consumption/ (accessed on 12 January 2025).
10. Isaksson, B. Demand for Edible Oils Increases as Biofuel Industry Grows. *Biofuels Int.* **2023**. Available online: https://biofuels-news.com/news/demand-for-edible-oils-increases-as-biofuel-industry-grows/ (accessed on 7 October 2024).
11. Waters, K.; Altiparmak, S.O.; Shutters, S.T.; Thies, C. The Green Mirage: The EU's Complex Relationship with Palm Oil Biodiesel in the Context of Environmental Narratives and Global Trade Dynamics. *Energies* **2024**, *17*, 343. [CrossRef]
12. Awogbemi, O.; Inambao, F.; Onuh, E.I. A review of the performance and emissions of compression ignition engine fuelled with waste cooking oil methyl ester. In Proceedings of the 2018 International Conference on the Domestic Use of Energy (DUE), Cape Town, South Africa, 3–5 April 2018; pp. 1–9. [CrossRef]
13. Awogbemi, O.; Onuh, E.I.; Inambao, F.L. Comparative study of properties and fatty acid composition of some neat vegetable oils and waste cooking oils. *Int. J. Low-Carbon. Technol.* **2019**, *14*, 417–425. [CrossRef]
14. Saba, T.; Estephane, J.; El Khoury, B.; El Khoury, M.; Khazma, M.; El Zakhem, H.; Aouad, S. Biodiesel production from refined sunflower vegetable oil over KOH/ZSM5 catalysts. *Renew. Energy* **2016**, *90*, 301–306. [CrossRef]
15. Foo, W.H.; Chia, W.Y.; Tang, D.Y.Y.; Koay, S.S.N.; Lim, S.S.; Chew, K.W. The conundrum of waste cooking oil: Transforming hazard into energy. *J. Hazard. Mater.* **2021**, *417*, 126129. [CrossRef]
16. Lombardi, L.; Mendecka, B.; Carnevale, E. Comparative life cycle assessment of alternative strategies for energy recovery from used cooking oil. *J. Environ. Manag.* **2018**, *216*, 235–245. [CrossRef]

17. Aniołowska, M.; Zahran, H.; Kita, A. The effect of pan frying on thermooxidative stability of refined rapeseed oil and professional blend. *J. Food Sci. Technol.* **2016**, *53*, 712–720. [CrossRef] [PubMed]
18. Teixeira, M.R.; Nogueira, R.; Nunes, L.M. Quantitative assessment of the valorisation of used cooking oils in 23 countries. *Waste Manag.* **2018**, *78*, 611–620. [CrossRef] [PubMed]
19. Olu-Arotiowa, O.A.; Odesanmi, A.A.; Adedotun, B.K.; Ajibade, O.A.; Olasesan, I.P.; Odofin, O.L.; Abass, A.O. Review on environmental impact and valourization of waste cooking oil. *LAUTECH J. Eng. Technol.* **2022**, *16*, 144–163.
20. Fingas, M. Vegetable Oil Spills. In *Handbook of Oil Spill Science and Technology*; Wiley: Hoboken, NJ, USA, 2014; pp. 79–91. [CrossRef]
21. Zahri, K.N.M.; Zulkharnain, A.; Sabri, S.; Gomez-Fuentes, C.; Ahmad, S.A. Research Trends of Biodegradation of Cooking Oil in Antarctica from 2001 to 2021: A Bibliometric Analysis Based on the Scopus Database. *Int. J. Environ. Res. Public Health* **2021**, *18*, 2050. [CrossRef]
22. Foo, W.H.; Koay, S.S.N.; Chia, S.R.; Chia, W.Y.; Tang, D.Y.Y.; Nomanbhay, S.; Chew, K.W. Recent advances in the conversion of waste cooking oil into value-added products: A review. *Fuel* **2022**, *324*, 124539. [CrossRef]
23. Cárdenas, J.; Orjuela, A.; Sánchez, D.L.; Narváez, P.C.; Katryniok, B.; Clark, J. Pre-treatment of used cooking oils for the production of green chemicals: A review. *J. Clean. Prod.* **2021**, *289*, 1215129. [CrossRef]
24. Capuano, D.; Costa, M.; Di Fraia, S.; Massarotti, N.; Vanoli, L. Direct use of waste vegetable oil in internal combustion engines. *Renew. Sustain. Energy Rev.* **2017**, *69*, 759–770. [CrossRef]
25. Carmona-Cabello, M.; Garcia, I.L.; Leiva-Candia, D.; Dorado, M.P. Valorization of food waste based on its composition through the concept of biorefinery. *Curr. Opin. Green. Sustain. Chem.* **2018**, *14*, 67–79. [CrossRef]
26. Carmona-Cabello, M.; García, I.L.; Sáez-Bastante, J.; Pinzi, S.; Koutinas, A.A.; Dorado, M.P. Food waste from restaurant sector—Characterization for biorefinery approach. *Bioresour. Technol.* **2020**, *301*, 122779. [CrossRef]
27. Carmona-Cabello, M.; Leiva-Candia, D.; Castro-Cantarero, J.L.; Pinzi, S.; Dorado, M.P. Valorization of food waste from restaurants by transesterification of the lipid fraction. *Fuel* **2018**, *215*, 492–498. [CrossRef]
28. Chrysikou, L.P.; Dagonikou, V.; Dimitriadis, A.; Bezergianni, S. Waste cooking oils exploitation targeting EU 2020 diesel fuel production: Environmental and economic benefits. *J. Clean. Prod.* **2019**, *219*, 566–575. [CrossRef]
29. D'Alessandro, B.; Bidini, G.; Zampilli, M.; Laranci, P.; Bartocci, P.; Fantozzi, F. Straight and waste vegetable oil in engines: Review and experimental measurement of emissions, fuel consumption and injector fouling on a turbocharged commercial engine. *Fuel* **2016**, *182*, 198–209. [CrossRef]
30. Hasan, M.R.; Anzar, N.; Sharma, P.; Malode, S.J.; Shetti, N.P.; Narang, J.; Kakarla, R.R. Converting biowaste into sustainable bioenergy through various processes. *Bioresour. Technol. Rep.* **2023**, *23*, 101542. [CrossRef]
31. Mannu, A.; Ferro, M.; Di Pietro, M.E.; Mele, A. Innovative applications of waste cooking oil as raw material. *Sci. Prog.* **2019**, *102*, 153–160. [CrossRef] [PubMed]
32. Namoco, C.S.; Comaling, V.C.; Buna, C.C. Utilization of used cooking oil as an alternative cooking fuel resource. *ARPN J. Eng. Appl. Sci.* **2017**, *12*, 435–442.
33. Ostadkalayeh, Z.H.; Babaeipour, V.; Pakdehi, S.G.; Sazandehchi, P. Optimization of Biodiesel Production Process from Household Waste Oil, Rapeseed, and Microalgae Oils as a Suitable Alternative for Jet Fuel. *Bioenergy Res.* **2023**, *16*, 1733–1745. [CrossRef]
34. Sahar; Sadaf, S.; Iqbal, J.; Ullah, I.; Bhatti, H.N.; Nouren, S.; Habib-ur-Rehman; Nisar, J.; Iqbal, M. Biodiesel production from waste cooking oil: An efficient technique to convert waste into biodiesel. *Sustain. Cities Soc.* **2018**, *41*, 220–226. [CrossRef]
35. Sudalai, S.; Prabakaran, S.; Varalakksmi, V.; Sai Kireeti, I.; Upasana, B.; Yuvasri, A.; Arumugam, A. A review on oilcake biomass waste into biofuels: Current conversion techniques, sustainable applications, and challenges: Waste to energy approach (WtE). *Energy Convers. Manag.* **2024**, *314*, 118724. [CrossRef]
36. Beghetto, V.; Gatto, V.; Samiolo, R.; Scolaro, C.; Brahimi, S.; Facchin, M.; Visco, A. Plastics today: Key challenges and EU strategies towards carbon neutrality: A review. *Environ. Pollut.* **2023**, *334*, 122102. [CrossRef] [PubMed]
37. Visco, A.; Scolaro, C.; Facchin, M.; Brahimi, S.; Belhamdi, H.; Gatto, V.; Beghetto, V. Agri-Food Wastes for Bioplastics: European Prospective on Possible Applications in Their Second Life for a Circular Economy. *Polymers* **2022**, *14*, 2752. [CrossRef]
38. Facchin, M.; Gatto, V.; Samiolo, R.; Conca, S.; Santandrea, D.; Beghetto, V. May 1,3,5-Triazine derivatives be the future of leather tanning? A critical review. *Environ. Pollut.* **2024**, *345*, 123472. [CrossRef] [PubMed]
39. Sole, R.; Gatto, V.; Conca, S.; Bardella, N.; Morandini, A.; Beghetto, V. Sustainable Triazine-Based Dehydro-Condensation Agents for Amide Synthesis. *Molecules* **2021**, *26*, 191. [CrossRef] [PubMed]
40. Purohit, V.B.; Pięta, M.; Pietrasik, J.; Plummer, C.M. Towards sustainability and a circular Economy: ROMP for the goal of fully degradable and chemically recyclable polymers. *Eur. Polym. J.* **2024**, *208*, 112847. [CrossRef]
41. Thushari, I.; Babel, S. Comparative study of the environmental impacts of used cooking oil valorization options in Thailand. *J. Environ. Manag.* **2020**, *310*, 114810. [CrossRef]
42. Scott, A. Oil majors back out of biofuel in Europe. *Cen. Acs. Org.* **2024**, *8*, 15.

43. Hamze, H.; Akia, M.; Yazdani, F. Optimization of biodiesel production from the waste cooking oil using response surface methodology. *Process Saf. Environ. Prot.* **2015**, *94*, 1–10. [CrossRef]
44. Ibanez, J.; Martel Martín, S.; Baldino, S.; Prandi, C.; Mannu, A. European Union Legislation Overview about Used Vegetable Oils Recycling: The Spanish and Italian Case Studies. *Processes* **2020**, *8*, 798. [CrossRef]
45. Mannu, A.; Garroni, S.; Ibanez Porras, J.; Mele, A. Available Technologies and Materials for Waste Cooking Oil Recycling. *Processes* **2020**, *8*, 366. [CrossRef]
46. Mannu, A.; Ferro, M.; Dugoni, G.C.; Panzeri, W.; Petretto, G.L.; Urgeghe, P.; Mele, A. Improving the recycling technology of waste cooking oils: Chemical fingerprint as tool for non-biodiesel application. *Waste Manag.* **2019**, *96*, 1–8. [CrossRef] [PubMed]
47. Dou, Z.; Dierenfeld, E.S.; Wang, X.; Chen, X.; Shurson, G.C. A critical analysis of challenges and opportunities for upcycling food waste to animal feed to reduce climate and resource burdens. *Resour. Conserv. Recycl.* **2024**, *203*, 107418. [CrossRef]
48. Panadare, D.C.; Rathod, V.K. Applications of Waste Cooking Oil Other Than Biodiesel: A Review. *Iran. J. Chem. Eng.* **2015**, *12*, 55–76. Available online: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.ijche.com/article_11253_54b41ee620eb7a8972ee3e37776dad5f.pdf&ved=2ahUKEwiMoK66rouIAxWPg_0HHbj0DNgQFnoECBsQAQ&usg=AOvVaw11QJ42AupQ5PiqrF-UlbHz (accessed on 10 January 2025).
49. Salemdeeb, R.; zu Ermgassen, E.K.H.J.; Kim, M.H.; Balmford, A.; Al-Tabbaa, A. Environmental and health impacts of using food waste as animal feed: A comparative analysis of food waste management options. *J. Clean. Prod.* **2017**, *140*, 871–880. [CrossRef] [PubMed]
50. Sarker, A.; Ahmmed, R.; Ahsan, S.M.; Rana, J.; Ghosh, M.K.; Nandi, R. A comprehensive review of food waste valorization for the sustainable management of global food waste. *Sustain. Food Technol.* **2024**, *2*, 48–69. [CrossRef]
51. Bardella, N.; Facchin, M.; Fabris, E.; Baldan, M.; Beghetto, V. Waste Cooking Oil as Eco-Friendly Rejuvenator for Reclaimed Asphalt Pavement. *Materials* **2024**, *17*, 1477. [CrossRef] [PubMed]
52. Wang, C.; Xue, L.; Xie, W.; You, Z.; Yang, X. Laboratory investigation on chemical and rheological properties of bio-asphalt binders incorporating waste cooking oil. *Constr. Build. Mater.* **2018**, *167*, 348–358. [CrossRef]
53. Staroń, A.; Chwastowski, J.; Kijania-Kontak, M.; Wiśniewski, M.; Staroń, P. Bio-enriched composite materials derived from waste cooking oil for selective reduction of odour intensity. *Sci. Rep.* **2024**, *14*, 16311. [CrossRef]
54. Zhang, R.; Wang, J.; Kang, H. Effect of waste cooking oil on the performance of EVA modified asphalt and its mechanism analysis. *Sci. Rep.* **2024**, *14*, 14072. [CrossRef]
55. Onn, M.; Jalil, M.J.; Mohd Yusoff, N.I.S.; Edward, E.B.; Wahit, M.U. A comprehensive review on chemical route to convert waste cooking oils to renewable polymeric materials. *Ind. Crops Prod.* **2024**, *211*, 118194. [CrossRef]
56. Singh, N.; Agarwal, P.; Porwal, J.; Porwal, S.K. Evaluation of multifunctional green copolymer additives–doped waste cooking oil–extracted natural antioxidant in biolubricant formulation. *Biomass Convers. Biorefin.* **2024**, *14*, 761–770. [CrossRef]
57. Marriam, F.; Irshad, A.; Umer, I.; Asghar, M.A.; Atif, M. Vegetable oils as bio-based precursors for epoxies. *Sustain. Chem. Pharm.* **2023**, *31*, 100935. [CrossRef]
58. Singh, N.; Agarwal, P.; Porwal, S.K. Natural Antioxidant Extracted Waste Cooking Oil as Sustainable Biolubricant Formulation in Tribological and Rheological Applications. *Waste Biomass Valorization* **2022**, *13*, 3127–3137. [CrossRef] [PubMed]
59. Wierzchowska, K.; Derewiaka, D.; Zieniuk, B.; Nowak, D.; Fabiszewska, A. Whey and post-frying oil as substrates in the process of microbial lipids obtaining: A value-added product with nutritional benefits. *Eur. Food Res. Technol.* **2023**, *249*, 2675–2688. [CrossRef]
60. Lhuissier, M.; Couvert, A.; Amrane, A.; Kane, A.; Audic, J.L. Characterization and selection of waste oils for the absorption and biodegradation of VOC of different hydrophobicities. *Chem. Eng. Res. Des.* **2018**, *138*, 482–489. [CrossRef]
61. Worthington, M.J.H.; Kucera, R.L.; Albuquerque, I.S.; Gibson, C.T.; Sibley, A.; Slattery, A.D.; Campbell, J.A.; Alboaiji, S.F.K.; Muller, K.A.; Young, J.; et al. Laying Waste to Mercury: Inexpensive Sorbents Made from Sulfur and Recycled Cooking Oils. *Chem. Eur. J.* **2017**, *23*, 16219–16230. [CrossRef] [PubMed]
62. European Commission. Available online: https://commission.europa.eu/index_en (accessed on 15 December 2024).
63. European Law Portal. Available online: https://eur-lex.europa.eu/homepage.html?locale=en (accessed on 18 December 2024).
64. The European Alliance of News Agencies. Available online: https://www.newsalliance.org/ (accessed on 15 December 2024).
65. European Environment Agency. Available online: https://www.eea.europa.eu/en (accessed on 15 December 2024).
66. European Chemicals Agency. Available online: https://echa.europa.eu/it/home (accessed on 15 December 2024).
67. Statista. Available online: https://www.statista.com/ (accessed on 15 December 2024).
68. Eurostat Portal. Available online: https://ec.europa.eu/eurostat (accessed on 15 December 2024).
69. Zhao, Y.; Zhu, K.; Li, J.; Zhao, Y.; Li, S.; Zhang, C.; Xiao, D.; Yu, A. High-efficiency production of bisabolene from waste cooking oil by metabolically engineered Yarrowia lipolytica. *Microb. Biotechnol.* **2021**, *14*, 2497–2513. [CrossRef] [PubMed]
70. Khedaywi, T.; Melhem, M. Effect of Waste Vegetable Oil on Properties of Asphalt Cement and Asphalt Concrete Mixtures: An Overview. *Int. J. Pavement Res. Technol.* **2024**, *17*, 280–290. [CrossRef]

71. Math, M.C.; Kumar, S.P.; Chetty, S.V. Technologies for biodiesel production from used cooking oil—A review. *Sustain. Energy Dev.* **2010**, *14*, 339–345. [CrossRef]
72. Manikandan, G.; Kanna, P.R.; Taler, D.; Sobota, T. Review of Waste Cooking Oil (WCO) as a Feedstock for Biofuel—Indian Perspective. *Energies* **2023**, *16*, 1739. [CrossRef]
73. Matušinec, J.; Hrabec, D.; Šomplák, R.; Nevrlý, V.; Pecha, J.; Smejkalová, V.; Redutskiy, Y. Cooking oil and fat waste management: A review of the current state. *Chem. Eng. Trans.* **2020**, *81*, 763–768. [CrossRef]
74. Monika; Banga, S.; Pathak, V.V. Biodiesel production from waste cooking oil: A comprehensive review on the application of heterogenous catalysts. *Energy Nexus* **2023**, *10*, 100209. [CrossRef]
75. Nanda, S.; Rana, R.; Hunter, H.N.; Fang, Z.; Dalai, A.K.; Kozinski, J.A. Hydrothermal catalytic processing of waste cooking oil for hydrogen-rich syngas production. *Chem. Eng. Sci.* **2019**, *195*, 935–945. [CrossRef]
76. Nascimento, L.; Ribeiro, A.; Ferreira, A.; Valério, N.; Pinheiro, V.; Araújo, J.; Vilarinho, C.; Carvalho, J. Turning waste cooking oils into biofuels—Valorization technologies: A review. *Energies* **2022**, *15*, 116. [CrossRef]
77. Ortner, M.E.; Müller, W.; Schneider, I.; Bockreis, A. Environmental assessment of three different utilization paths of waste cooking oil from households. *Resour. Conserv. Recycl.* **2016**, *106*, 59–67. [CrossRef]
78. Rocha-Meneses, L.; Hari, A.; Inayat, A.; Yousef, L.A.; Alarab, S.; Abdallah, M.; Shanableh, A.; Ghenai, C.; Shanmugam, S.; Kikas, T. Recent advances on biodiesel production from waste cooking oil (WCO): A review of reactors, catalysts, and optimization techniques impacting the production. *Fuel* **2023**, *348*, 128514. [CrossRef]
79. Tamošiūnas, A.; Gimžauskaitė, D.; Aikas, M.; Uscila, R.; Praspaliauskas, M.; Eimontas, J. Gasification of Waste Cooking Oil to Syngas by Thermal Arc Plasma. *Energies* **2019**, *12*, 2612. [CrossRef]
80. Xu, L.; Li, Y.; Liao, M.; Song, Q.; Wang, C.; Weng, J.; Zhao, M.; Gao, N. Catalytic pyrolysis of waste cooking oil for hydrogen-rich syngas production over bimetallic Fe-Ru/ZSM-5 catalyst. *Fuel Process. Technol.* **2023**, *247*, 107812. [CrossRef]
81. Sabino, J.; Liborio, D.O.; Arias, S.; Gonzalez, J.F.; Barbosa, C.M.B.M.; Carvalho, F.R.; Frety, R.; Barros, I.C.L.; Pacheco, J.G.A. Hydrogen-Free Deoxygenation of Oleic Acid and Industrial Vegetable Oil Waste on CuNiAl Catalysts for Biofuel Production. *Energies* **2023**, *16*, 6131. [CrossRef]
82. Suzihaque, M.U.H.; Alwi, H.; Kalthum Ibrahim, U.; Abdullah, S.; Haron, N. Biodiesel production from waste cooking oil: A brief review. *Mater. Today Proc.* **2022**, *63*, S490–S495. [CrossRef]
83. Aransiola, E.F.; Ojumu, T.V.; Oyekola, O.O.; Madzimbamuto, T.F.; Ikhu-Omoregbe, D.I.O. A review of current technology for biodiesel production: State of the art. *Biomass Bioenergy* **2014**, *61*, 276–297. [CrossRef]
84. Tsoutsos, T.; Tournaki, S.; Gkouskos, Z.; Paraíba, O.; Giglio, F.; García, P.Q.; Braga, J.; Adrianos, H.; Filice, M. Quality Characteristics of Biodiesel Produced from Used Cooking Oil in Southern Europe. *Chem. Eng.* **2019**, *3*, 19. [CrossRef]
85. Caldeira, C.; Freire, F.; Olivetti, E.A.; Kirchain, R.; Dias, L.C. Analysis of cost-environmental trade-offs in biodiesel production incorporating waste feedstocks: A multi-objective programming approach. *J. Clean. Prod.* **2019**, *216*, 64–73. [CrossRef]
86. Cordero-Ravelo, V.; Schallenberg-Rodriguez, J. Biodiesel production as a solution to waste cooking oil (WCO) disposal. Will any type of WCO do for a transesterification process? A quality assessment. *J. Environ. Manag.* **2018**, *228*, 117–129. [CrossRef] [PubMed]
87. Cadillo-Benalcazar, J.J.; Bukkens, S.G.F.; Ripa, M.; Giampietro, M. Why does the European Union produce biofuels? Examining consistency and plausibility in prevailing narratives with quantitative storytelling. *Energy Res. Soc. Sci.* **2021**, *71*, 101810. [CrossRef]
88. Outili, N.; Kerras, H.; Meniai, A.H. Recent conventional and non-conventional WCO pretreatment methods: Implementation of green chemistry principles and metrics. *Curr. Opin. Green. Sustain. Chem.* **2023**, *41*, 100794. [CrossRef]
89. Ripa, M.; Cadillo-Benalcazar, J.J.; Giampietro, M. Cutting through the biofuel confusion: A conceptual framework to check the feasibility, viability and desirability of biofuels. *Energy Strategy Rev.* **2021**, *35*, 100642. [CrossRef]
90. Caldeira, C.; Queirós, J.; Freire, F. Biodiesel from Waste Cooking Oils in Portugal: Alternative Collection Systems. *Waste Biomass Valorization* **2015**, *6*, 771–779. [CrossRef]
91. Directive (EU) 2023/2413, 2023. Amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as Regards the Promotion of Energy from Renewable Sources, and Repealing Council Directive (EU) 2015/652, European Parliament and of the Council. Available online: http://data.europa.eu/eli/dir/2023/2413/oj (accessed on 3 August 2024).
92. Directive 75/439/EEC, 1975. Disposal of Waste Oils, The Council of the European Communities. Available online: http://data.europa.eu/eli/dir/1975/439/oj (accessed on 20 September 2024).
93. Directive 2014/955/EU, 2014. Commission Decision of 18 December 2014 amending Decision 2000/532/EC on the List of Waste Pursuant to Directive 2008/98/EC of the European Parliament and of the Council Text with EEA relevance, European Parliament and of the Council. Available online: http://data.europa.eu/eli/dec/2014/955/oj (accessed on 3 February 2024).
94. Directive 75/442/EEC, 1975. Council Directive 75/442/EEC of 15 July 1975 on waste, The council of the European Communities. Available online: http://data.europa.eu/eli/dir/1975/442/oj (accessed on 15 October 2024).

95. Directive 2008/98/EC, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives (Text with EEA Relevance), European Parliament and of the Council. Available online: http://data.europa.eu/eli/dir/2008/98/oj (accessed on 25 December 2024).
96. Directive (EU) 2018/851, 2018. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste (Text with EEA Relevance), European Parliament and of the Council. Available online: http://data.europa.eu/eli/dir/2018/851/oj (accessed on 3 December 2024).
97. Borrello, M.; Caracciolo, F.; Lombardi, A.; Pascucci, S.; Cembalo, L. Consumers' Perspective on Circular Economy Strategy for Reducing Food Waste. *Sustainability* **2017**, *9*, 141. [CrossRef]
98. United States Environmental Agency. Available online: https://www.epa.gov/oil-spills-prevention-and-preparedness-regulations/facility-response-plan-frp-overview (accessed on 24 January 2025).
99. US Congress Government. Available online: https://www.congress.gov/congressional-report/104th-congress/house-report/262/1 (accessed on 24 January 2025).
100. Federal Regulations. Available online: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-D/part-112?toc=1 (accessed on 24 January 2025).
101. Beghetto, V.; Bardella, N.; Samiolo, R.; Gatto, V.; Conca, S.; Sole, R.; Molin, G.; Gattolin, A.; Ongaro, N. By-products from mechanical recycling of polyolefins improve hot mix asphalt performance. *J. Clean. Prod.* **2021**, *318*, 128627. [CrossRef]
102. CONOE Annual Report 2018. Available online: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=http://www.conoe.it/wp-content/uploads/2018/11/ANNUAL-REPORT-2018.pdf&ved=2ahUKEwiB-v_3touIAxVJ8LsIHS8kAKAQFnoECBUQAQ&usg=AOvVaw0pNXsTRFSIaiWl9aUnWgPQ (accessed on 23 November 2024).
103. De Feo, G.; Di Domenico, A.; Ferrara, C.; Abate, S.; Sesti Osseo, L. Evolution of Waste Cooking Oil Collection in an Area with Long-Standing Waste Management Problems. *Sustainability* **2020**, *12*, 8578. [CrossRef]
104. De Feo, G.; Ferrara, C.; Giordano, L.; Ossèo, L.S. Assessment of Three Recycling Pathways for Waste Cooking Oil as Feedstock in the Production of Biodiesel, Biolubricant, and Biosurfactant: A Multi-Criteria Decision Analysis Approach. *Recycling* **2023**, *8*, 64. [CrossRef]
105. Foo, W.H.; Koay, S.S.N.; Tang, D.Y.Y.; Chia, W.Y.; Chew, K.W.; Show, P.L. Safety control of waste cooking oil: Transforming hazard into multifarious products with available pre-treatment processes. *Food Mater. Res.* **2022**, *2*, 1–11. [CrossRef]
106. Bazina, N.; He, J. Analysis of fatty acid profiles of free fatty acids generated in deep-frying process. *J. Food Sci. Technol.* **2018**, *55*, 3085–3092. [CrossRef] [PubMed]
107. Park, J.-M.; Kim, J.-M. Monitoring of Used Frying Oils and Frying Times for Frying Chicken Nuggets Using Peroxide Value and Acid Value. *Korean J. Food Sci. Anim. Resour.* **2016**, *36*, 612–616. [CrossRef]
108. Kulkarni, M.G.; Dalai, A.K. Waste Cooking OilAn Economical Source for Biodiesel: A Review. *Ind. Eng. Chem. Res.* **2006**, *45*, 2901–2913. [CrossRef]
109. Awogbemi, O.; Von Kallon, D.V.; Aigbodion, V.S.; Panda, S. Advances in biotechnological applications of waste cooking oil. *CSCEE* **2021**, *4*, 100158. [CrossRef]
110. Fabiszewska, U.A.; Białecka-Florjańczyk, E. Factors influencing synthesis of extracellular lipases by yarrowia lipolytica in medium containing vegetable oils. *J. Microbiol. Biotechnol. Food Sci.* **2014**, *4*, 231–237. [CrossRef]
111. Liepins, J.; Balina, K.; Soloha, R.; Berzina, I.; Lukasa, L.K.; Dace, E. Glycolipid biosurfactant production from waste cooking oils by yeast: Review of substrates, producers and products. *Fermentation* **2021**, *7*, 136. [CrossRef]
112. Wadekar, S.; Kale, S.; Lali, A.; Bhowmick, D.; Pratap, A. Sophorolipid Production by Starmerella bombicola (ATCC 22214) from Virgin and Waste Frying Oils, and the Effects of Activated Earth Treatment of the Waste Oils. *J. Am. Oil Chem. Soc.* **2012**, *89*, 1029–1039. [CrossRef]
113. Carmona-Cabello, M.; Sáez-Bastante, J.; Pinzi, S.; Dorado, M.P. Optimization of solid food waste oil biodiesel by ultrasound-assisted transesterification. *Fuel* **2019**, *255*, 115817. [CrossRef]
114. EN 14214. International Standard that Describes the Minimum Requirements for Biodiesel Production from Vegetable Oils. Available online: https://www.chemeurope.com/en/encyclopedia/EN_14214.html (accessed on 23 August 2024).
115. Hussein, R.Z.K.; Attia, N.K.; Fouad, M.K.; ElSheltawy, S.T. Experimental investigation and process simulation of biolubricant production from waste cooking oil. *Biomass Bioenergy* **2021**, *144*, 105850. [CrossRef]
116. Liang, M.-Y.; Ma, C.; Qin, W.-Q.; Mtui, H.I.; Wang, W.; Liu, J.; Yang, S.-Z.; Mu, B.-Z. A synergetic binary system of waste cooking oil-derived bio-based surfactants and its interfacial performance for enhanced oil recovery. *Colloids and Surfaces C: Environ. Asp.* **2024**, *2*, 100039. [CrossRef]
117. Jia, P.; Zhang, M.; Hu, L.; Song, F.; Feng, G.; Zhou, Y. A Strategy for Nonmigrating Plasticized PVC Modified with Mannich base of Waste Cooking Oil Methyl Ester. *Sci. Rep.* **2018**, *8*, 1589. [CrossRef] [PubMed]
118. Suzuki, A.H.; Botelho, B.G.; Oliveira, L.S.; Franca, A.S. Sustainable synthesis of epoxidized waste cooking oil and its application as a plasticizer for polyvinyl chloride films. *Eur. Polym. J.* **2018**, *99*, 142–149. [CrossRef]

119. Zheng, T.; Wu, Z.; Xie, Q.; Fang, J.; Hu, Y.; Lu, M.; Xia, F.; Nie, Y.; Ji, J. Structural modification of waste cooking oil methyl esters as cleaner plasticizer to substitute toxic dioctyl phthalate. *J. Clean. Prod.* **2018**, *186*, 1021–1030. [CrossRef]
120. Moretti, C.; Junginger, M.; Shen, L. Environmental life cycle assessment of polypropylene made from used cooking oil. *Resour. Conserv. Recycl.* **2020**, *157*, 104750. [CrossRef]
121. Tremblay-Parrado, K.K.; Astrain, C.G.; Avérous, L. Click chemistry for the synthesis of biobased polymers and networks derived from vegetable oils. *Green Chem.* **2021**, *23*, 4296–4327. [CrossRef]
122. Huang, J.; Huo, Y.; Su, Q.; Lu, D.; Wu, Y.; Dong, X.; Gao, Y. Sustainable high-strength alkali-activated slag concrete is achieved by recycling emulsified waste cooking oil. *Front. Mater.* **2024**, *11*, 1–13. [CrossRef]
123. Ingrassia, L.P.; Lu, X.; Ferrotti, G.; Canestrari, F. Renewable materials in bituminous binders and mixtures: Speculative pretext or reliable opportunity? Resour. *Conserv. Recycl.* **2019**, *144*, 209–222. [CrossRef]
124. Ozdemir, K.D.; Dokandari, A.P.; Raufi, H.; Topal, A.; Sengoz, B. Feasibility and mixture performance assessment of waste oil based rejuvenators in high-RAP asphalt mixtures. *Mater. Res. Express* **2023**, *10*, 045306. [CrossRef]
125. Sun, D.; Lu, T.; Xiao, F.; Zhu, X.; Sun, G. Formulation and aging resistance of modified bio-asphalt containing high percentage of waste cooking oil residues. *J. Clean. Prod.* **2017**, *161*, 1203–1214. [CrossRef]
126. Straits Research. Bio-Lubricants Market Size, Share & Trends Analysis Report By Base Oil Type (Vegetable Oils, Animal Fats), By Application (Chainsaw Oils, Hydraulic Fluids), By End-User (Industrial, Commercial Transport, Passenger Vehicles) and By Region(North America, Europe, APAC, Middle East and Africa, LATAM) Forecasts, 2023-2031 [WWW Document]. 2024. Available online: https://straitsresearch.com/report/bio-lubricants-market#:~:text=The%20global%20bio-lubricants%20market,the%20forecast%20period%202023-2031 (accessed on 19 August 2024).
127. Joshi, J.R.; Bhanderi, K.K.; Patel, J.V. Waste cooking oil as a promising source for bio lubricants—A review. *J. Indian Chem. Soc.* **2023**, *100*, 100820. [CrossRef]
128. Khodadadi, M.R.; Malpartida, I.; Tsang, C.-W.; Lin, C.S.K.; Len, C. Recent advances on the catalytic conversion of waste cooking oil. *Mol. Catal.* **2020**, *494*, 111128. [CrossRef]
129. Kutluk, B.G.; Kutluk, T.; Kapucu, N. Enzymatic Synthesis of Trimethylolpropane-Bases Biolubricants from Waste Edible Oil Biodiesel Using Different Types of Biocatalysis. *Iran. J. Chem. Chem. Eng.* **2022**, *41*, 3234–3243. [CrossRef]
130. Mukherjee, S.; Chandar, T.; Pradhan, S.; Prasad, L. Lubricant from Waste Cooking Oil. In *Lubricants from Renewable Feedstocks*; Wiley: Hoboken, NJ, USA, 2024; pp. 291–335. [CrossRef]
131. Zhang, W.; Ji, H.; Song, Y.; Ma, S.; Xiong, W.; Chen, C.; Chen, B.; Zhang, X. Green preparation of branched biolubricant by chemically modifying waste cooking oil with lipase and ionic liquid. *J. Clean. Prod.* **2020**, *274*, 122918. [CrossRef]
132. Borugadda, V.B.; Goud, V.V. Improved thermo-oxidative stability of structurally modified waste cooking oil methyl esters for bio-lubricant application. *J. Clean. Prod.* **2016**, *112*, 4515–4524. [CrossRef]
133. Chowdhury, A.; Mitra, D.; Biswas, D. Biolubricant synthesis from waste cooking oil via enzymatic hydrolysis followed by chemical esterification. *JCTB* **2023**, *88*, 139–144. [CrossRef]
134. Dabai, U.M.; Owuna, J.F.; Sokoto, A.M.; Abubakar, L.A. Assessment of Quality Parameters of Ecofriendly Biolubricant from Waste Cooking Palm Oil. *Asian J. Appl. Chem. Res.* **2018**, *1*, 1–11. [CrossRef]
135. Bahadi, M.; Salimon, J.; Derawi, D. Synthesis of di-trimethylolpropane tetraester-based biolubricant from Elaeis guineensis kernel oil via homogeneous acid-catalyzed transesterification. *Renew. Energy* **2021**, *171*, 981–993. [CrossRef]
136. Carvalho, W.C.A.; Luiz, J.H.H.; Fernandez-Lafuente, R.; Hirata, D.B.; Mendes, A.A. Eco-friendly production of trimethylolpropane triesters from refined and used soybean cooking oils using an immobilized low-cost lipase (Eversa>® Transform 2.0) as heterogeneous catalyst. *Biomass Bioenergy* **2021**, *155*, 106302. [CrossRef]
137. Ivan-Tan, C.T.; Islam, A.; Yunus, R.; Taufiq-Yap, Y.H. Screening of solid base catalysts on palm oil based biolubricant synthesis. *J. Clean. Prod.* **2017**, *148*, 441–451. [CrossRef]
138. Owuna, F.J.; Dabai, M.U.; Sokoto, M.A.; Dangoggo, S.M.; Bagudo, B.U.; Birnin-Yauri, U.A.; Hassan, L.G.; Sada, I.; Abubakar, A.L.; Jibrin, M.S. Chemical modification of vegetable oils for the production of biolubricants using trimethylolpropane: A review. *Egypt. J. Pet.* **2020**, *29*, 75–82. [CrossRef]
139. Liu, Y.; Liu, M.Y.; Fan, X.G.; Wang, L.; Liang, J.Y.; Jin, X.Y.; Che, R.J.; Ying, W.Y.; Chen, S.P. 4D printing of multifunctional photocurable resin based on waste cooking oil. *ACS Sustain. Chem. Eng.* **2022**, *10*, 16344–16358. [CrossRef]
140. Wang, E.; Ma, X.; Tang, S.; Yan, R.; Wang, Y.; Riley, W.W.; Reaney, M.J.T. Synthesis and oxidative stability of trimethylolpropane fatty acid triester as a biolubricant base oil from waste cooking oil. *Biomass Bioenergy* **2014**, *66*, 371–378. [CrossRef]
141. Lakkoju, B.; Vemulapalli, V. Synthesis and characterization of triol based bio-lubricant from waste cooking oil. *AIP Conf. Proc.* **2020**, *2297*, 020002. [CrossRef]
142. Bashiri, S.; Ghobadian, B.; Dehghani Soufi, M.; Gorjian, S. Chemical modification of sunflower waste cooking oil for biolubricant production through epoxidation reaction. *Mater. Sci. Energy Technol.* **2021**, *4*, 119–127. [CrossRef]
143. Li, W.; Wang, X. Bio-lubricants derived from waste cooking oil with improved oxidation stability and low-temperature properties. *J. Oleo. Sci.* **2015**, *64*, 367–374. [CrossRef]

144. Jahromi, H.; Adhikari, S.; Roy, P.; Shelley, M.; Hassani, E.; Oh, T.-S. Synthesis of Novel Biolubricants from Waste Cooking Oil and Cyclic Oxygenates through an Integrated Catalytic Process. ACS Sustain. *Chem. Eng.* **2021**, *9*, 13424–13437. [CrossRef]
145. Turco, R.; Tesser, R.; Vitiello, R.; Russo, V.; Andini, S.; Di Serio, M. Synthesis of Biolubricant Basestocks from Epoxidized Soybean Oil. *Catalysts* **2017**, *7*, 309. [CrossRef]
146. Borah, M.J.; Das, A.; Das, V.; Bhuyan, N.; Deka, D. Transesterification of waste cooking oil for biodiesel production catalyzed by Zn substituted waste egg shell derived CaO nanocatalyst. *Fuel* **2019**, *242*, 345–354. [CrossRef]
147. Ghafar, F.; Sapawe, N.; Dzazita Jemain, E.; Safwan Alikasturi, A.; Masripan, N. Study on The Potential of Waste Cockle Shell Derived Calcium Oxide for Biolubricant Production. *Mater. Today Proc.* **2019**, *19*, 1346–1353. [CrossRef]
148. Guimarães, J.R.; Miranda, L.P.; Fernandez-Lafuente, R.; Tardioli, P.W. Immobilization of Eversa® Transform via CLEA Technology Converts It in a Suitable Biocatalyst for Biolubricant Production Using Waste Cooking Oil. *Molecules* **2021**, *26*, 193. [CrossRef]
149. Sarno, M.; Iuliano, M.; Cirillo, C. Optimized procedure for the preparation of an enzymatic nanocatalyst to produce a bio-lubricant from waste cooking oil. *Chem. Eng. J.* **2019**, *377*, 120273. [CrossRef]
150. Su, Y.; Lin, H.; Zhang, S.; Yang, Z.; Yuan, T. One-Step Synthesis of Novel Renewable Vegetable Oil-Based Acrylate Prepolymers and Their Application in UV-Curable Coatings. *Polymers* **2020**, *12*, 1165. [CrossRef] [PubMed]
151. Ahmad, A.; Kuching Sarawak, P.; Hafizah Naihi, M. Analysis of Produced Bio-Surfactants from Waste Cooking Oil and Pure Coconut. *IJISRT* **2019**, *4*, 682–685, ISSN 2456-2165.
152. De, S.; Malik, S.; Ghosh, A.; Saha, R.; Saha, B. A review on natural surfactants. *RSC Adv.* **2015**, *5*, 65757–65767. [CrossRef]
153. Inès, M.; Dhouha, G. Glycolipid biosurfactants: Potential related biomedical and biotechnological applications. *Carbohydr. Res.* **2015**, *416*, 59–69. [CrossRef] [PubMed]
154. Miao, Y.; To, M.H.; Siddiqui, M.A.; Wang, H.; Lodens, S.; Chopra, S.S.; Kaur, G.; Roelants, S.L.K.W.; Lin, C.S.K. Sustainable biosurfactant production from secondary feedstock—Recent advances, process optimization and perspectives. *Front. Chem.* **2024**, *12*, 1327113. [CrossRef] [PubMed]
155. Rawat, N.; Alam, P.; Bhonsle, A.K.; Ngomade, S.B.L.; Agarwal, T.; Singh, R.K.; Atray, N. Valorization of used cooking oil into bio-based surfactant: Modeling and optimization using response surface methodology. *Biomass Convers. Biorefin.* **2024**, *5*, 1–14. [CrossRef]
156. Zhang, Q.Q.; Cai, B.X.; Xu, W.J.; Gang, H.Z.; Liu, J.F.; Yang, S.Z.; Mu, B.Z. The rebirth of waste cooking oil to novel bio-based surfactants. *Sci. Rep.* **2015**, *5*, 9971. [CrossRef]
157. Market Research Engine. Biosurfactants Market Research. 2022. Available online: https://www.marketresearchengine.com/biosurfactants-market?srsltid=AfmBOopWbMrQRk5GEZTHLe-xSaQJk4fBT84YEX_zBlJ5Rqe64EyXE1tJ (accessed on 12 August 2024).
158. Jahan, R.; Bodratti, A.M.; Tsianou, M.; Alexandridis, P. Biosurfactants, natural alternatives to synthetic surfactants: Physicochemical properties and applications. *Adv. Colloid. Interface Sci.* **2020**, *275*, 102061. [CrossRef] [PubMed]
159. Jiménez-Peñalver, P.; Koh, A.; Gross, R.; Gea, T.; Font, X. Biosurfactants from Waste: Structures and Interfacial Properties of Sophorolipids Produced from a Residual Oil Cake. *J. Surfactants Deterg.* **2020**, *23*, 481–486. [CrossRef]
160. Sharma, K.; Toor, S.S.; Brandão, J.; Pedersen, T.H.; Rosendahl, L.A. Optimized conversion of waste cooking oil into ecofriendly bio-based polymeric surfactant- A solution for enhanced oil recovery and green fuel compatibility. *J. Clean. Prod.* **2021**, *294*, 126214. [CrossRef]
161. Cameotra, S.S.; Makkar, R.S. Biosurfactant-enhanced bioremediation of hydrophobic pollutants. *Pure Appl. Chem.* **2010**, *82*, 97–116. [CrossRef]
162. Gaur, V.K.; Sharma, P.; Sirohi, R.; Varjani, S.; Taherzadeh, M.J.; Chang, J.-S.; Yong Ng, H.; Wong, J.W.C.; Kim, S.-H. Production of biosurfactants from agro-industrial waste and waste cooking oil in a circular bioeconomy: An overview. *Bioresour. Technol.* **2022**, *343*, 126059. [CrossRef]
163. Gautam, K.; Sharma, P.; Gaur, V.K.; Gupta, P.; Pandey, U.; Varjani, S.; Pandey, A.; Wong, J.W.C.; Chang, J.S. Oily waste to biosurfactant: A path towards carbon neutrality and environmental sustainability. *Environ. Technol. Innov.* **2023**, *30*, 103095. [CrossRef]
164. Nurdin, S.; Yunus, R.M.; Nour, A.H.; Gimbun, J.; Aisyah Azman, N.N.; Sivaguru, M.V. Restoration of waste cooking oil (WCO) using alkaline hydrolysis technique (ALHYT) for future biodetergent 11. *ARPN J. Eng. Appl. Sci.* **2016**, *11*, 6405–6410; ISSN 1819-6608.
165. Yusuff, A.S.; Porwal, J.; Bhonsle, A.K.; Rawat, N.; Atray, N. Valorization of used cooking oil as a source of anionic surfactant fatty acid methyl ester sulfonate: Process optimization and characterization studies. *Biomass Convers. Biorefin.* **2023**, *13*, 8903–8914. [CrossRef]
166. Permadani, R.L.; Ibadurrohman, M.; Slamet. Utilization of waste cooking oil as raw material for synthesis of Methyl Ester Sulfonates (MES) surfactant. In *IOP Conference Series: Earth and Environmental Science*; Institute of Physics Publishing: Bristol, UK, 2018. [CrossRef]

167. Jin, Y.; Tian, S.; Guo, J.; Ren, X.; Li, X.; Gao, S. Synthesis, Characterization and Exploratory Application of Anionic Surfactant Fatty Acid Methyl Ester Sulfonate from Waste Cooking Oil. *J. Surfactants Deterg.* **2016**, *19*, 467–475. [CrossRef]
168. Lucchetti, M.G.; Paolotti, L.; Rocchi, L.; Boggia, A. The Role of Environmental Evaluation within Circular Economy: An Application of Life Cycle Assessment (LCA) Method in the Detergents Sector. *Environ. Clim. Technol.* **2019**, *23*, 238–257. [CrossRef]
169. Dong, Q.; Li, X.; Dong, J. Synthesis of branched surfactant via ethoxylation of oleic acid derivative and its surface properties. *Chem. Eng. Sci.* **2022**, *258*, 117747. [CrossRef]
170. Khalaf, M.M.; Tantawy, A.H.; Soliman, K.A.; Abd El-Lateef, H.M. Cationic gemini-surfactants based on waste cooking oil as new 'green' inhibitors for N80-steel corrosion in sulphuric acid: A combined empirical and theoretical approaches. *J. Mol. Struct.* **2020**, *1203*, 127442. [CrossRef]
171. Guerrero-Hernández, L.; Meléndez-Ortiz, H.I.; Cortez-Mazatan, G.Y.; Vaillant-Sánchez, S.; Peralta-Rodríguez, R.D. Gemini and Bicephalous Surfactants: A Review on Their Synthesis, Micelle Formation, and Uses. *Int. J. Mol. Sci.* **2022**, *23*, 1798. [CrossRef] [PubMed]
172. Bocqué, M.; Voirin, C.; Lapinte, V.; Caillol, S.; Robin, J.J. Petro-based and bio-based plasticizers: Chemical structures to plasticizing properties. *J. Polym. Sci. A Polym. Chem.* **2016**, *54*, 11–33. [CrossRef]
173. Silviana; Anggoro, D.D.; Kumoro, A.C. Waste cooking oil utilisation as bio-plasticiser through epoxidation using inorganic acids as homogeneous catalysts. *Chem. Eng. Trans.* **2017**, *56*, 1861–1866. [CrossRef]
174. Carlos, K.S.; de Jager, L.S.; Begley, T.H. Investigation of the primary plasticisers present in polyvinyl chloride (PVC) products currently authorised as food contact materials. *Food Addit.* **2018**, *35*, 1214–1222. [CrossRef]
175. Friday Etuk, I.; Ekwere Inyang, U. Applications of Various Plasticizers in the Plastic Industry-Review. *IJEMT* **2024**, *10*, 38–55.
176. Greco, A.; Ferrari, F.; Maffezzoli, A. UV and thermal stability of soft PVC plasticized with cardanol derivatives. *J. Clean. Prod.* **2017**, *164*, 757–764. [CrossRef]
177. He, Z.; Lu, Y.; Lin, C.; Jia, H.; Wu, H.; Cao, F.; Ouyang, P. Designing anti-migration furan-based plasticizers and their plasticization properties in poly (vinyl chloride) blends. *Polym. Test.* **2020**, *91*, 106793. [CrossRef]
178. Sahnoune Millot, M.; Devémy, J.; Chennell, P.; Pinguet, J.; Dequidt, A.; Sautou, V.; Malfreyt, P. Leaching of plasticizers from PVC medical devices: A molecular interpretation of experimental migration data. *J. Mol. Liq.* **2024**, *396*, 123965. [CrossRef]
179. Cheng, Y.; Miao, D.; Kong, L.; Jiang, J.; Guo, Z. Preparation and Performance Test of the Super-Hydrophobic Polyurethane Coating Based on Waste Cooking Oil. *Coatings* **2019**, *9*, 861. [CrossRef]
180. Feng, G.; Ma, Y.; Zhang, M.; Jia, P.; Liu, C.; Zhou, Y. Synthesis of Bio-base Plasticizer Using Waste Cooking Oil and Its Performance Testing in Soft Poly(vinyl chloride) Films. *J. Bioresour. Bioprod.* **2019**, *4*, 99–110. [CrossRef]
181. Jia, P.; Ma, Y.; Kong, Q.; Xu, L.; Hu, Y.; Hu, L.; Zhou, Y. Graft modification of polyvinyl chloride with epoxidized biomass-based monomers for preparing flexible polyvinyl chloride materials without plasticizer migration. *Mater. Today Chem.* **2019**, *13*, 49–58. [CrossRef]
182. Thirupathiah, G.; Satapathy, S.; Palanisamy, A. Studies on epoxidised castor oil as co-plasticizer with epoxidised soyabean oil for PVC processing. *J. Renew. Mater.* **2019**, *7*, 775–785. [CrossRef]
183. Cai, D.-L.; Yue, X.; Hao, B.; Ma, P.-C. A sustainable poly(vinyl chloride) plasticizer derivated from waste cooking oil. *J. Clean. Prod.* **2020**, *274*, 122781. [CrossRef]
184. Liu, D.; Jiang, P.; Nie, Z.; Wang, H.; Dai, Z.; Deng, J.; Cao, Z. Synthesis of an efficient bio-based plasticizer derived from waste cooking oil and its performance testing in PVC. *Polym. Test.* **2020**, *90*, 106625. [CrossRef]
185. Ma, D.-X.; Yin, G.-Z.; Ye, W.; Jiang, Y.; Wang, N.; Wang, D.-Y. Exploiting Waste towards More Sustainable Flame-Retardant Solutions for Polymers: A Review. *Materials* **2024**, *17*, 2266. [CrossRef]
186. Tan, J.; Zhang, S.; Lu, T.; Li, R.; Zhong, T.; Zhu, X. Design and synthesis of ethoxylated esters derived from waste frying oil as anti-ultraviolet and efficient primary plasticizers for poly(vinyl chloride). *J. Clean. Prod.* **2019**, *229*, 1274–1282. [CrossRef]
187. Polaczek, K.; Kurańska, M.; Auguścik-Królikowska, M.; Prociak, A.; Ryszkowska, J. Open-cell polyurethane foams of very low density modified with various palm oil-based bio-polyols in accordance with cleaner production. *J. Clean. Prod.* **2021**, *290*, 125875. [CrossRef]
188. Gadhave, R.V.; Mahanwar, P.A.; Gadekar, P.T. Bio-Renewable Sources for Synthesis of Eco-Friendly Polyurethane Adhesives—Review. *Open J. Polym. Chem.* **2017**, *7*, 57–75. [CrossRef]
189. Sarim, M.; Alavi Nikje, M.M.; Dargahi, M. Preparation and Characterization of Polyurethane Rigid Foam Nanocomposites from Used Cooking Oil and Perlite. *Int. J. Polym. Sci.* **2023**, *1*, 1–13. [CrossRef]
190. Mangal, M.; Rao, C.V.; Banerjee, T. Bioplastic: An eco-friendly alternative to non-biodegradable plastic. *Polym. Int.* **2023**, *72*, 984–996. [CrossRef]
191. Orjuela, A.; Clark, J. Green chemicals from used cooking oils: Trends, challenges, and opportunities. *Curr. Opin. Green. Sustain. Chem.* **2020**, *26*, 100369. [CrossRef]
192. Salleh, W.N.F.W.; Tahir, S.M.; Mohamed, N.S. Synthesis of waste cooking oil-based polyurethane for solid polymer electrolyte. *Polym. Bull.* **2018**, *75*, 109–120. [CrossRef]

193. Sawpan, M.A. Polyurethanes from vegetable oils and applications: A review. *J. Polym. Res.* **2018**, *25*, 184. [CrossRef]
194. Delavarde, A.; Savin, G.; Derkenne, P.; Boursier, M.; Morales-Cerrada, R.; Nottelet, B.; Pinaud, J.; Caillol, S. Sustainable polyurethanes: Toward new cutting-edge opportunities. *Prog. Polym. Sci.* **2024**, *151*, 101805. [CrossRef]
195. Maulana, S.; Wibowo, E.S.; Mardawati, E.; Iswanto, A.H.; Papadopoulos, A.; Lubis, M.A.R. Eco-Friendly and High-Performance Bio-Polyurethane Adhesives from Vegetable Oils: A Review. *Polymers* **2024**, *16*, 1613. [CrossRef] [PubMed]
196. Paciorek-Sadowska, J.; Borowicz, M.; Isbrandt, M.; Czupryński, B.; Apiecionek, Ł. The Use of Waste from the Production of Rapeseed Oil for Obtaining of New Polyurethane Composites. *Polymers* **2019**, *11*, 1431. [CrossRef] [PubMed]
197. Pu, M.; Fang, C.; Zhou, X.; Wang, D.; Lin, Y.; Lei, W.; Li, L. Recent Advances in Environment-Friendly Polyurethanes from Polyols Recovered from the Recycling and Renewable Resources: A Review. *Polymers* **2024**, *16*, 1889. [CrossRef]
198. Asare, M.A.; de Souza, F.M.; Gupta, R.K. Waste to Resource: Synthesis of Polyurethanes from Waste Cooking Oil. *Ind. Eng. Chem. Res.* **2022**, *61*, 18400–18411. [CrossRef]
199. Kurańska, M.; Banaś, J.; Polaczek, K.; Banaś, M.; Prociak, A.; Kuc, J.; Uram, K.; Lubera, T. Evaluation of application potential of used cooking oils in the synthesis of polyol compounds. *J. Environ. Chem. Eng.* **2019**, *7*, 103506. [CrossRef]
200. Malewska, E.; Polaczek, K.; Kurańska, M. Impact of Various Catalysts on Transesterification of Used Cooking Oil and Foaming Processes of Polyurethane Systems. *Materials* **2022**, *15*, 7807. [CrossRef]
201. Raofuddin, D.N.A.; Azmi, I.S.; Jalil, M.J. Catalytic Epoxidation of Oleic Acid Derived from Waste Cooking Oil by In Situ Peracids. *J. Polym. Environ.* **2024**, *32*, 803–814. [CrossRef]
202. Sánchez, B.S.; Benitez, B.; Querini, C.A.; Mendow, G. Transesterification of sunflower oil with ethanol using sodium ethoxide as catalyst. Effect of the reaction conditions. *Fuel Process. Technol.* **2015**, *131*, 29–35. [CrossRef]
203. Kurańska, M.; Malewska, E. Waste cooking oil as starting resource to produce bio-polyol—Analysis of transesteryfication process using gel permeation chromatography. *Ind. Crops Prod.* **2021**, *162*, 113294. [CrossRef]
204. Kurańska, M.; Benes, H.; Polaczek, K.; Trhlikova, O.; Walterova, Z.; Prociak, A. Effect of homogeneous catalysts on ring opening reactions of epoxidized cooking oils. *J. Clean. Prod.* **2019**, *230*, 162–169. [CrossRef]
205. Skleničková, K.; Abbrent, S.; Halecký, M.; Kočí, V.; Beneš, H. Biodegradability and ecotoxicity of polyurethane foams: A review. *Crit. Rev. Environ. Sci. Technol.* **2022**, *52*, 157–202. [CrossRef]
206. Ul Haq, I.; Akram, A.; Nawaz, A.; Zohu, X.; Abbas, S.Z.; Xu, Y.; Rafatullah, M. Comparative analysis of various waste cooking oils for esterification and transesterification processes to produce biodiesel. *Green. Chem. Lett. Rev.* **2021**, *14*, 462–473. [CrossRef]
207. Moreno, D.; Velasco, M.; Malagón-Romero, D. Production of polyurethanes from used vegetable oil-based polyols. *Chem. Eng. Trans.* **2020**, *79*, 337–342. [CrossRef]
208. Lubis, M.; Prayogo, M.A.; Harahap, M.B.; Iriany; Ginting, M.H.S.; Lazuardi, I.N.; Akbar, R. The effect of fibre loading on characterization and mechanical properties of polyurethane foam composites derived waste cooking oil, polyol and toluene diisocyanate with adding filler sugar palm (Arenga pinnata) fibre. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1122*, 012109. [CrossRef]
209. Paraskar, P.M.; Prabhudesai, M.S.; Hatkar, V.M.; Kulkarni, R.D. Vegetable oil based polyurethane coatings—A sustainable approach: A review. *Prog. Org. Coat.* **2021**, *156*, 106267. [CrossRef]
210. Silva, R.; Barros-Timmons, A.; Quinteiro, P. Life cycle assessment of fossil- and bio-based polyurethane foams: A review. *J. Clean. Prod.* **2023**, *430*, 139697. [CrossRef]
211. Castro-Osma, J.A.; Martínez, J.; de la Cruz-Martínez, F.; Caballero, M.P.; Fernández-Baeza, J.; Rodríguez-López, J.; Otero, A.; Lara-Sánchez, A.; Tejeda, J. Development of hydroxy-containing imidazole organocatalysts for CO2 fixation into cyclic carbonates. *Catal. Sci. Technol.* **2018**, *8*, 1981–1987. [CrossRef]
212. Werlinger, F.; Caballero, M.P.; Trofymchuk, O.S.; Flores, M.E.; Moreno-Villoslada, I.; de la Cruz-Martínez, F.; Castro-Osma, J.A.; Tejeda, J.; Martínez, J.; Lara-Sánchez, A. Turning waste into resources. Efficient synthesis of biopolyurethanes from used cooking oils and CO2. *J. CO2 Util.* **2024**, *79*, 102659. [CrossRef]
213. Onn, M.; Mustafa, H.; Azman, H.A.; Ahmad, Z.; Wahit, M.U. Synthesis and Characterization of Photocrosslinkable Acrylic Prepolymers from Waste Palm Frying Oil. *Chem. Eng. Trans.* **2023**, *106*, 379–384. [CrossRef]
214. Wu, B.; Sufi, A.; Ghosh Biswas, R.; Hisatsune, A.; Moxley-Paquette, V.; Ning, P.; Soong, R.; Dicks, A.P.; Simpson, A.J. Direct Conversion of McDonald's Waste Cooking Oil into a Biodegradable High-Resolution 3D-Printing Resin. *ACS Sustain. Chem. Eng.* **2020**, *8*, 1171–1177. [CrossRef]
215. Wu, W.; Deng, X.; Tian, S.; Wang, S.; He, Y.; Zheng, B.; Xin, K.; Zhou, Z.; Tang, L. Whole-Waste synthesis of Kilogram-Scale Macropores adsorbent materials for Wide-Range oil and heavy metal removal. *Sep. Purif. Technol.* **2025**, *354*, 128750. [CrossRef]
216. Voet, V.S.D.; Guit, J.; Loos, K. Sustainable Photopolymers in 3D Printing: A Review on Biobased, Biodegradable, and Recyclable Alternatives. *Macromol. Rapid Commun.* **2021**, *42*, e2000475. [CrossRef]
217. Heriyanto, H.; Suhendi, E.; Asyuni, N.F.; Shahila, I.K. Effect of Bayah natural zeolite for purification of waste cooking oil as feedstock of alkyd resin. *Tek. J. Sains Dan Teknologi* **2022**, *18*, 49. [CrossRef]
218. Silvianti, F.; Wijayanti, W.; Sudjarwo, W.A.A.; Dewi, W.B. Synthesis of Alkyd Resin Modified with Waste Palm Cooking Oil as Precursor Using Pretreatment with Zeolite Adsorbent. *Sci. Technol. Indones.* **2018**, *3*, 119–122. [CrossRef]

219. Markets and Markets. Epoxy Resin Market by Physical Form, Raw Materilas, Application, End-Use Industry and Region- Global Forecast to 2028. 2024. Available online: https://www.marketsandmarkets.com/Market-Reports/epoxy-resins-market-762.html (accessed on 10 January 2025).
220. Jaengmee, T.; Pongmuksuwan, P.; Kitisatorn, W. Development of bio-based epoxy resin from palm oil. *Mater. Today Proc.* **2022**, *52*, 2357–2360. [CrossRef]
221. Chong, K.L.; Lai, J.C.; Rahman, R.A.; Adrus, N.; Al-Saffar, Z.H.; Hassan, A.; Lim, T.H.; Wahit, M.U. A review on recent approaches to sustainable bio-based epoxy vitrimer from epoxidized vegetable oils. *Ind. Crops Prod.* **2022**, *189*, 115857. [CrossRef]
222. Gonçalves, F.A.M.M.; Santos, M.; Cernadas, T.; Ferreira, P.; Alves, P. Advances in the development of biobased epoxy resins: Insight into more sustainable materials and future applications. *Int. Mater. Rev.* **2022**, *67*, 119–149. [CrossRef]
223. Fernandes, F.C.; Kirwan, K.; Wilson, P.R.; Coles, S.R. Sustainable Alternative Composites Using Waste Vegetable Oil Based Resins. *J. Polym. Environ.* **2019**, *27*, 2464–2477. [CrossRef]
224. Wang, Z.; Pei, Q.; Li, K.; Wang, Z.; Huo, X.; Wang, Y.; Zhang, X.; Kong, S. Molecular Dynamics Simulation of the Rejuvenation Performance of Waste Cooking Oil with High Acid Value on Aged Asphalt. *Molecules* **2024**, *29*, 2830. [CrossRef] [PubMed]
225. Xu, N.; Wang, H.; Wang, H.; Kazemi, M.; Fini, E. Research progress on resource utilization of waste cooking oil in asphalt materials: A state-of-the-art review. *J. Clean. Prod.* **2023**, *385*, 135427. [CrossRef]
226. Baranowska, W.; Rzepna, M.; Ostrowski, P.; Lewandowska, H. Radiation and Radical Grafting Compatibilization of Polymers for Improved Bituminous Binders—A Review. *Materials* **2024**, *17*, 1642. [CrossRef]
227. Chamaa, A.; Khatib, J.; Elkordi, A. A review on the use of vegetable oil and its waste in construction applications. *BAU J. Sci. Technol.* **2020**, *1*, 1–10. [CrossRef]
228. Chandrasekar, M.; Kavitha Kathikeyan, S.; Snekha, G.; Vinothini, A. Experimental Investigation on Usage of Waste Cooking Oil (WCO) in Concrete Making and Adopting Innovative Curing Method. *Int. J. Eng. Res.* **2016**, *5*, 146–151. [CrossRef]
229. Jain, S.; Chandrappa, A.K. Influence of Blended Waste Cooking Oils on the Sustainable Asphalt Rejuvenation Considering Secondary Aging. *Int. J. Pavement Res. Technol.* **2024**, *1*, 1–11. [CrossRef]
230. Uz, V.E.; Gökalp, İ. Sustainable recovery of waste vegetable cooking oil and aged bitumen: Optimized modification for short and long term aging cases. *Waste Manag.* **2020**, *110*, 1–9. [CrossRef] [PubMed]
231. Wang, Y.; Su, J.; Liu, L.; Liu, Z.; Sun, G. Waste cooking oil based capsules for sustainable self-healing asphalt pavement: Encapsulation, characterization and fatigue-healing performance. *Constr. Build. Mater.* **2024**, *425*, 136032. [CrossRef]
232. Ji, H.; Li, B.; Li, X.; Han, J.; Liu, D.; Dou, H.; Fu, M.; Yao, T. Waste cooking oil as a sustainable solution for UV-aged asphalt binder: Rheological, chemical and molecular structure. *Constr. Build. Mater.* **2024**, *420*, 135149. [CrossRef]
233. Al Mamun, A.; Wahhab, H.I.A.-A.; Dalhat, M.A. Comparative laboratory evaluation of waste cooking oil rejuvenated asphalt concrete mixtures for high contents of reclaimed asphalt pavement. *Int. J. Pavement Eng.* **2020**, *21*, 1297–1308. [CrossRef]
234. Taherkhani, H.; Noorian, F. Laboratory investigation on the properties of asphalt concrete containing reclaimed asphalt pavement and waste cooking oil as recycling agent. *Int. J. Pavement Eng.* **2021**, *22*, 539–549. [CrossRef]
235. Al-Omari, A.A.; Khedaywi, T.S.; Khasawneh, M.A. Laboratory characterization of asphalt binders modified with waste vegetable oil using SuperPave specifications. *Int. J. Pavement Res. Techn.* **2018**, *11*, 68–76. [CrossRef]
236. Jalkh, R.; El-Rassy, H.; Chehab, G.R.; Abiad, M.G. Assessment of the Physico-Chemical Properties of Waste Cooking Oil and Spent Coffee Grounds Oil for Potential Use as Asphalt Binder Rejuvenators. *Waste Biomass Valorization* **2018**, *9*, 2125–2132. [CrossRef]
237. Ahmed, R.B.; Hossain, K. Waste cooking oil as an asphalt rejuvenator: A state-of-the-art review. *Constr. Build. Mater.* **2020**, *230*, 116985. [CrossRef]
238. Elahi, Z.; Mohd Jakarni, F.; Muniandy, R.; Hassim, S.; Ab Razak, M.S.; Ansari, A.H.; Ben Zair, M.M. Waste Cooking Oil as a Sustainable Bio Modifier for Asphalt Modification: A Review. *Sustainability* **2021**, *13*, 11506. [CrossRef]
239. Elahi, Z.; Jakarni, F.M.; Muniandy, R.; Hassim, S.; Ab Razak, M.S.; Ansari, A.H. Influence of novel modified waste cooking oil beads on rheological characteristics of bitumen. *Constr. Build. Mater.* **2024**, *414*, 134829. [CrossRef]
240. Zahoor, M.; Nizamuddin, S.; Madapusi, S.; Giustozzi, F. Sustainable asphalt rejuvenation using waste cooking oil: A comprehensive review. *J. Clean. Prod.* **2021**, *278*, 123304. [CrossRef]
241. Alkuime, H.; Kassem, E.; Alshraiedeh, K.A.; Bustanji, M.; Aleih, A.; Abukhamseh, F. Performance Assessment of Waste Cooking Oil-Modified Asphalt Mixtures. *Appl. Sci.* **2024**, *14*, 1228. [CrossRef]
242. Chen, M.; Xiao, F.; Putman, B.; Leng, B.; Wu, S. High temperature properties of rejuvenating recovered binder with rejuvenator, waste cooking and cotton seed oils. *Constr. Build. Mater.* **2014**, *59*, 10–16. [CrossRef]
243. Huo, Y.; Dong, X.; Gao, Y.; Xu, X.; Zeng, L.; Wu, Y.; Zhao, Y.; Yang, Y.; Su, Q.; Huang, J.; et al. Effects of cooking oil on the shrinkage-reducing of high-strength concrete. *Results Mater.* **2024**, *23*, 100602. [CrossRef]
244. Joni, H.H.; Al-Rubaee, R.H.A.; Al-zerkani, M.A. Rejuvenation of aged asphalt binder extracted from reclaimed asphalt pavement using waste vegetable and engine oils. *Case Stud. Constr. Mater.* **2019**, *11*, e00279. [CrossRef]
245. Xinxin, C.; Xuejuan, C.; Boming, T.; Yuanyuan, W.; Xiaolong, L. Investigation on Possibility of Waste Vegetable Oil Rejuvenating Aged Asphalt. *Appl. Sci.* **2018**, *8*, 765. [CrossRef]

246. Azahar, W.N.A.W.; Jaya, R.P.; Hainin, M.R.; Bujang, M.; Ngadi, N. Mechanical performance of asphaltic concrete incorporating untreated and treated waste cooking oil. *Constr. Build. Mater.* **2017**, *150*, 653–663. [CrossRef]
247. Oldham, D.; Rajib, A.; Dandamudi, K.P.R.; Liu, Y.; Deng, S.; Fini, E.H. Transesterification of Waste Cooking Oil to Produce A Sustainable Rejuvenator for Aged Asphalt. *Resour. Conserv. Recy.* **2021**, *168*, 105297. [CrossRef]
248. Sun, Z.; Yi, J.; Huang, Y.; Feng, D.; Guo, C. Properties of asphalt binder modified by bio-oil derived from waste cooking oil. *Constr. Build. Mater.* **2016**, *102*, 496–504. [CrossRef]
249. Enfrin, M.; Gowda, A.; Giustozzi, F. Low-cost chemical modification of refined used cooking oil to produce long-lasting bio-asphalt pavements. *Resour. Conserv. Recycl.* **2024**, *204*, 107493. [CrossRef]
250. Yi, X.; Dong, R.; Shi, C.; Yang, J.; Leng, Z. The influence of the mass ratio of crumb rubber and waste cooking oil on the properties of rubberised bio-rejuvenator and rejuvenated asphalt. *Road Mater. Pavement Des.* **2023**, *24*, 578–591. [CrossRef]
251. Liu, Y.; Yu, Z.; Lv, C.; Meng, F.; Yang, Y. Preparation of waste cooking oil emulsion as shrinkage reducing admixture and its potential use in high performance concrete: Effect on shrinkage and mechanical properties. *J. Build. Eng.* **2020**, *32*, 101488. [CrossRef]
252. Tarnpradab, T.; Unyaphan, S.; Takahashi, F.; Yoshikawa, K. Tar removal capacity of waste cooking oil absorption and waste char adsorption for rice husk gasification. *Biofuels* **2016**, *7*, 401–412. [CrossRef]
253. Cappello, M.; Brunazzi, E.; Rossi, D.; Seggiani, M. Absorption of n-butyl acetate from tannery air emissions by waste vegetable oil/water emulsions. *J. Environ. Chem. Eng.* **2024**, *12*, 112443. [CrossRef]
254. Dong, R.; Zhao, M.; Tang, N. Characterization of crumb tire rubber lightly pyrolyzed in waste cooking oil and the properties of its modified bitumen. *Constr. Build. Mater.* **2019**, *195*, 10–18. [CrossRef]
255. Aldagari, S.; Kabir, S.F.; Lamanna, A.; Fini, E.H. Functionalized Waste Plastic Granules to Enhance Sustainability of Bituminous Composites. *Resour. Conserv. Recycl.* **2022**, *183*, 106353. [CrossRef]
256. Mousavi, M.; Fini, E.H. Preventing emissions of hazardous organic compounds from bituminous composites. *J. Clean. Prod.* **2022**, *344*, 131067. [CrossRef]
257. Yi, X.; Dong, R.; Tang, N. Development of a novel binder rejuvenator composed by waste cooking oil and crumb tire rubber. *Constr. Build. Mater.* **2020**, *236*, 117621. [CrossRef]
258. Gallart-Sirvent, P.; Martín, M.; Villorbina, G.; Balcells, M.; Solé, A.; Barrenche, C.; Cabeza, L.F.; Canela-Garayoa, R. Fatty acid eutectic mixtures and derivatives from non-edible animal fat as phase change materials. *RSC Adv.* **2017**, *7*, 24133–24139. [CrossRef]
259. Kahwaji, S.; White, M.A. Edible Oils as Practical Phase Change Materials for Thermal Energy Storage. *Appl. Sci.* **2019**, *9*, 1627. [CrossRef]
260. Afonso, I.S.; Nobrega, G.; Lima, R.; Gomes, J.R.; Ribeiro, J.E. Conventional and Recent Advances of Vegetable Oils as Metalworking Fluids (MWFs): A Review. *Lubricants* **2023**, *11*, 160. [CrossRef]
261. Landi, F.A.F.; Fabiani, C.; Pisello, A.L. Palm oil for seasonal thermal energy storage applications in buildings: The potential of multiple melting ranges in blends of bio-based fatty acids. *J. Energy Storage* **2020**, *29*, 101431. [CrossRef]
262. Chen, D.; Chen, M.; Zhao, Y.; Zhang, Y.; Wu, Y.; Zhang, J.; Yang, X. Waste cooking oil applicable phase change capsules to improve thermoregulation of foamed concrete. *Constr. Build. Mater.* **2024**, *432*, 136538. [CrossRef]
263. Irsyad, M.; Amrizal; Harmen; Amrul; Susila Es, M.D.; Diva Putra, A.R. Experimental study of the thermal properties of waste cooking oil applied as thermal energy storage. *Results Eng.* **2023**, *18*, 101080. [CrossRef]
264. Okogeri, O.; Stathopoulos, V.N. What about greener phase change materials? A review on biobased phase change materials for thermal energy storage applications. *Int. J. Thermofluids* **2021**, *10*, 100081. [CrossRef]
265. Gatto, V.; Conca, S.; Bardella, N.; Beghetto, V. Efficient Triazine Derivatives for Collagenous Materials Stabilization. *Materials* **2021**, *14*, 3069. [CrossRef]
266. Zhao, Y.; Chen, M.; Wu, S.; Xu, H.; Wan, P.; Zhang, J. Preparation and characterization of phase change capsules containing waste cooking oil for asphalt binder thermoregulation. *Constr. Build. Mater.* **2023**, *395*, 132311. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.