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Bioremediation of Edible Oil Waste: A Review on Sustainable Approach to Reducing Environmental Impact

Urva Faisal & Faiza Arshad*
Department of Biological Sciences*, International Islamic University, Islamabad, Pakistan
Corresponding Author email: faizaarshad15@hotmail.com

Abstract

Industrial growth has intensified environmental pollution, particularly within the edible oil sector, where each stage from extraction to refining and end use is generating diverse streams of waste. A narrative literature review of edible oil processing waste was conducted, based on studies published between 1999 and 2026, to critically evaluate and highlight the types and challenges associated with this waste, as well as its environmental impacts. In parallel with production-related impacts, the review examines anthropogenic pollution from edible oil consumption, including household and food-business discharges. It also summarizes in-practice methods for extracting and refining vegetable oil, the types of industrial waste generated from these processes, detection techniques, and biological remediation strategies. Many physicochemical and biological methods, such as electrocoagulation, membrane filtration, anaerobic digestion, and microbial bioaugmentation, are gaining attraction and being applied to advance the edible oil milling process toward environmental sustainability and economic feasibility while meeting strict regulatory requirements. Several treatment technologies, such as enzymatic catalysis, algal sludge hybridization, microbial bio-granulation, and spectroscopic detection using Fourier Transform Infrared (FTIR) and Raman Spectroscopy, remain under investigation, and their outcomes are anticipated. Collectively, waste accumulation accelerates ecosystem degradation, biodiversity loss, and soil contamination. Assessing these practices is essential for improving future urban waste management and for establishing sustainable circular economy models that are viable for full-scale industrial implementation. Finally, the authors highlight that future research should integrate microbial ecology, enzyme engineering, reactor design, and circular-economy principles to develop robust, scalable, and sustainable bioremediation systems for edible-oil waste.

Keywords: Edible oil waste, Bioremediation, physicochemical and biological methods.

1. Introduction

Edible oils are chemically trihydric alcohols, specifically glycerol ($C_3H_8O_3$), combined with either saturated or unsaturated long-chain (4 – 18 carbon atoms) fatty acids to form triglycerides with the general formula $C_3H_5(OOCR)_3$ [1]. These include saturated fatty acids like palmitic acid $CH_3(CH_2)_{14}COOH$, and unsaturated fatty acids like oleic acid $CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$. Largely hydrophobic in nature and insoluble in water [2], their physical state, whether solid (fats), liquid (oils), or semisolid (grease), hereafter FOG, is determined by the degree of unsaturation. The chemical composition is complex and diverse, influenced by the biobased sources from which they are derived [3]. FOGs are also referred to as the materials removed in the oil separation units of wastewater treatment plants [4]. With rising global consumption and demand, edible oil production has become a major environmental disaster, thereby shifting the focus from simple chemical classification to waste management through bioremediation (Fig. 1) [5].

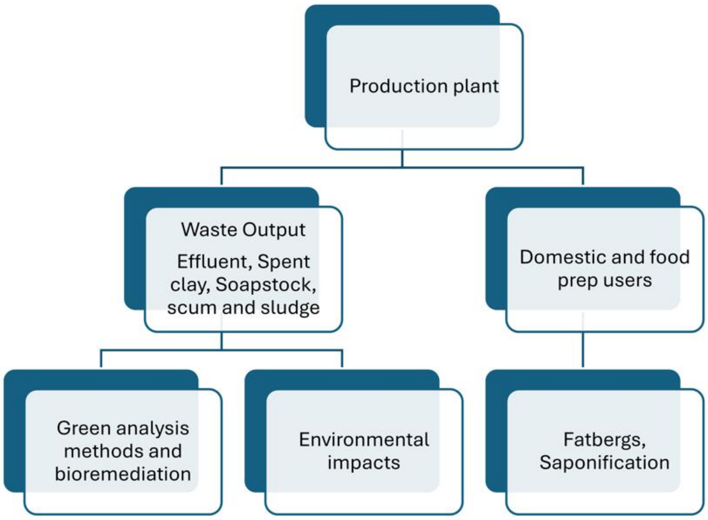

Figure 1: Overview of waste streams, impact and management.

Improper disposal of these FOGs creates operational bottlenecks within both industrial milling systems and urban municipal infrastructure [6]. Conventional systems often struggle to treat wastewater with high chemical oxygen demand (COD) and persistent lipid biofilms that inhibit normal microbial degradation [7]. Although processing facilities deploy conventional physical and chemical separation techniques, these remediation pathways are increasingly constrained by strict global discharge limits [5]. Therefore, evaluating these pathways requires prioritizing economic feasibility and global regulatory constraints, rather than technical efficiency alone [8,5].

To bridge the gap between laboratory-scale biological success and large-scale industrial implementation, the current paradigm emphasizes the deployment of green biotechnology [9]. Biological remediation approaches, including specialized microbial consortia and direct enzymatic breakdown, offer promising routes to transform low-biodegradability effluents into harmless byproducts [5]. Ultimately, the objective is to analyze these emerging biotechnologies to identify sustainable circular-economy models that are capable of full-scale industrial implementation [10].

2. Review Methodology

To ensure the review focuses on high-quality, data-driven research relevant to edible-oil waste management and microbial bioremediation, a narrative style was adopted to synthesize available information on the characteristics of oily wastewater (OWW), pollutant load, in-practice treatment methods, and pilot-scale bioremediation treatments. A targeted search was performed to screen relevant studies in major databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, PubMed, and Google Scholar. Search terms and keywords related to oily wastewater (e.g., FOG, Palm Oil Mill Effluent (POME), olive mill wastewater (OMW), domestic wastewater), bioremediation (microbial degradation, lipase, biosurfactant, biofilm), and quantitative treatment metrics (COD removal, Oil and Grease (O&G) degradation, Long-chain Fatty Acids (LCFA) inhibition) were used. Criteria were flexible and designed to ensure relevance. The overall literature selection approach is summarized in Tables 1 and 2.

Table 1: Databases and search terms used

Database	Search Terms	Purpose
Scopus	OWW, bioremediation	Core environmental studies
Web of Science	POME, lipase, COD removal	High- impact journals
ScienceDirect	FOG, microbial degradation	Applied biotechnology
PubMed	biosurfactant, anaerobic digestion	Microbial mechanisms
Google Scholar	kitchen wastewater, O&G	Supplementary sources

Table 2: Inclusion and exclusion criteria

Category	Criteria	Rationale
Inclusion	Quantitative pollutant data	Needed for comparison
Inclusion	Microbial bioremediation	Core theme
Exclusion	Chemical-only treatment	Outside scope
Exclusion	Non-oily wastewater	Not relevant
Exclusion	No quantitative data	Cannot evaluate

3.1 Industrial Sources

Edible oil production involves crude oil extraction either by mechanical means or by solvent (n-hexane) extraction. The extraction of crude palm oil uses water and steam. During this milling process, several wastewater streams are formed as fresh fruit bunches (FFB) from palm trees undergo sterilization, stripping, digestion, pressing, and clarification. Sterilization of the FFB generates large volumes of sterilizer condensate. The sludge obtained during clarification of crude palm oil and the hydrocyclone wash water used in nut-shell separation are two additional sources of acidic and viscous OWW known as Palm Oil Mill Effluent (POME) which consists of 95–96% of water, together with 2–4% of suspended solids, and 0.6–0.7% of O&G Table 3 [11,12] and challenging to treat [13] due to high Biological Oxygen Demand (BOD) and COD.

Table 3: Characteristics of each source of POME in palm oil mills

Parameters	Sterilizer condensate	Clarification ww[a]	Hydrocyclone ww[a]	POME		Raw POME
COD	47,000	64,000	15,000	15,000 – 100,000	51,000	75,900
BOD	23,000	29,000	5000	10,250 – 43,750	25,000	34,393
O&G	4000	7000	300	130 – 18,000	6000	191
pH	5.0	4.5		3.4 – 5.2	4.2	4.9
Reference		[14]		[12]	[15]	[16]

ww wastewater, all values are reported in mg/L.

During this milling process, 1.6% of oil is lost as sterilizer condensate, sludge, and wastewater produced from the hydrocyclone [11]. The solid waste left after crude oil extraction contains nearly 10 times more oil than POME, though the latter is more environmentally problematic as it forms surface films, inhibits oxygen transfer, and increases COD and biological oxygen demand (BOD) in POME. The solid waste generated consists of fibers, shells, and empty fruit bunches and is used as fuel for furnaces and agricultural applications. Whereas the liquid waste containing high organic loads (0.2 – 0.35 kg BOD m^{-3} day^{-1}) is treated through multi-stage ponding systems comprising acidification, cooling, anaerobic, aerobic, facultative, and polishing ponds in more than 80 % of the oil mills. These ponds are constructed over a large area, up to 5 hectares, and are unlined. Major drawbacks include long retention times and the need for regular sludge removal.

Other conventional strategies that could achieve 81% COD removal include open-tank anaerobic digestion for 20 days, followed by aerobic polishing, which can further reduce COD and BOD, and clarified supernatant is discharged into water streams [9]. In contrast, closed biodigesters with>95% COD removal efficiency at a 17-day retention time can also recover biogas, and their effluent is used for irrigation.
Vegetable oils extracted from soybean, sesame, sunflower, corn, canola, and cottonseed use a water-based refining method to remove phospholipids, monoacylglycerols, diacylglycerols, free fatty acids (FFA), color and pigments. During the refining of cottonseed and palm oil, hot water or acid [17] is used for degumming (to remove phospholipids), and FFA are removed either by distillation or by treatment with caustic soda. Subsequently, bleaching of earthy clay, usually Bentonite, is performed under vacuum at high temperatures to decolorize and deodorize [18,19]. However, over 95% of the Malaysian Palm oil mills, due to the low phospholipid content of palm oil, are refined through a chemical-free process where FFA are removed by steam distillation during deodorization [20]. The refining results in the formation of dark mucilage containing saponified fatty acids, gummy substances, and oil pigments. Further processing of this mucilage during degumming and neutralization generates a blend of water, salt, and oil soap stocks rich in fatty acids. The clay used for pigment removal absorbs fats [21] (up to 30% by weight), forming "oily mud," which is another major source of industrial FOGs. Nearly 40% of the water used in the process is removed, along with some minor components such as antioxidants and vitamins (carotenes and tocopherols), and the remaining water becomes the carrier of fats and oils, carbohydrates, phenolic compounds, and suspended solids [22]. Its direct discharge, along with minor components such as antioxidants and vitamins (carotenes and tocopherols), causes soil clogging, waterlogging, and vegetation loss, while release into waterways leads to aquatic pollution [12]. These industrial FOGs are concentrated and exhibit consistent characteristics within single manufacturing plants, compared to those of sewage-based greases, though fluctuations in hydraulic flow and the concentrations of the FOGs present are also important factors [23]. For this section of the review, we focus on FOGs in oil refinery effluents. Biologically treated POME from ponding systems can be further polished using techniques such as ultrafiltration, coagulation, and adsorption to remove suspended solids [24]. In contrast, Raw POME can be converted into high-quality water through chemical and physical pre-treatments such as coagulation with ferric chloride, flocculation with acrylamide, sedimentation, and activated carbon adsorption followed by ultrafiltration and reverse osmosis [25,26]. Another tertiary treatment used Fenton oxidation to polish biologically treated POME, thereby enhancing organic matter degradation and color reduction [27]. All these polishing methods are effective, although their operating conditions still need further optimization.
FOGs present in edible oil industrial effluents are removed via in-practice pre-treatment systems (such as grease traps, physicochemical treatment, and dissolved air flotation systems) prior to biological treatment at stations. However, these processes employ costly reagents and have limited efficiency in removing dissolved and emulsified O&G; furthermore, challenging sludge is produced as a by-product. During biological treatment, oils and grease retained in the wastewater post-pre-treatment decrease substrate transfer rates to microbes due to the formation of a lipid coat surrounding biological floc, with an increased ratio of filamentous microorganisms and floating sludge, resulting in decreased sedimentation rates and reduced TPs efficiency. LCFAs produced by fat hydrolysis also inhibit microbial activity [7]. Therefore, this low-biodegradable effluent is treated with processes such as coagulation/flocculation, electrocoagulation, reverse osmosis, flocculation/membrane filtration, air flotation, microfiltration, and enzymatic catalysis, which are costly and less efficient [28], before its release into natural water bodies due to environmental concerns [29]. Chemically treated effluent has restricted uses due to increased mineralization and salination. Biological treatment, either aerobic or anaerobic, received less attention and could serve as an economical and efficient alternative [22].
POME is typically treated through two main steps: (1) pre-treatment to reduce oil, grease, and suspended solids, and (2) advanced treatment to lower contaminants like BOD and COD to discharge standards [30]. The typical workflow for the vegetable- oil refinery wastewater treatment in the treatment plant (TP) consists of agitating the effluent and pH stabilization, followed by chemical dosing (acid, alkali, alum) and flocculation. High FOG levels decrease aeration efficiency and must be removed before the aeration tank because they disrupt biological treatment. They form a surface film that blocks oxygen transfer, inhibits aerobic microbes, causes foaming and scum, reduces sludge settling, and overloads the system with slow-to-degrade fats. The wastewater then passes through a dissolved- air flotation (DAF) unit, where oil, grease, and suspended solids are separated by flotation and skimmed off. The scum is the floatable material collected from the surface of primary and secondary settling tanks in wastewater TPs, and its oil content could be as high as 60% [31]. The skimmed O&G from the DAF unit is collected as float sludge and sent to sludge- handling units such as drying beds or dewatering systems. The dried oily sludge is either disposed off (landfill/incineration) or, in some cases, the oil is recovered for low- grade reuse. The clarified water is pumped to an aeration tank for biological degradation of dissolved organic matter and, finally, to a secondary clarifier, where biomass settles. Treated water is discharged for reuse, while sludge is recycled or sent to drying beds. Apparently, these TPs have high operational costs and low efficiency [8]. This whole process has been summarized in a flow chart, which is presented in Figure 2.

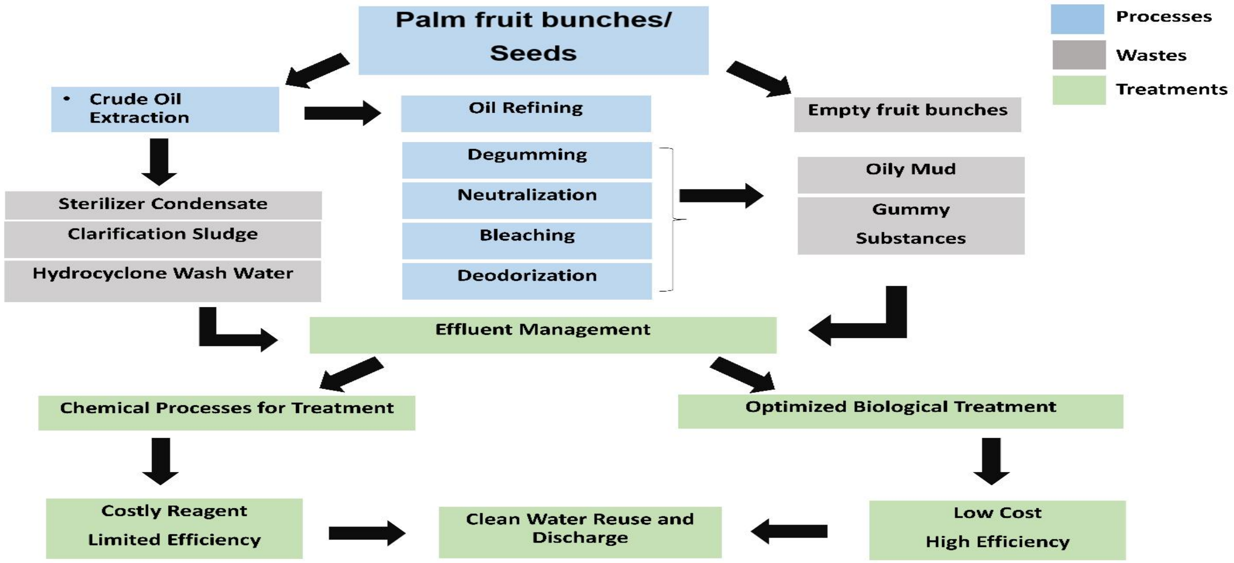

Figure 2. Summarized process of edible oil extraction

3.2. Food service providers (FSPs) and domestic sources

Disposal of used highly processed edible oil [32], butter, poultry and meat drippings, residual oils and fats, lipid-rich food like spoiled milk and dairy products, infant formulas, and fish oil supplements directly down the sink are the main domestic sources of FOGs [33]. Polyunsaturated Fatty Acids (like linoleic, linolenic, and arachidonic acids), common ingredients of cooking oil, undergo hydrolysis and release a higher percentage of FFA [34] in sewer pipelines. Modern domestic hygiene has moved back toward lipid-based products. Today's households are increasingly using products containing fatty acids derived from microalgae and yeasts rather than traditional animal fats [34]. In-sink grinders pulverize food, though fats persist and interact with common household cleaning agents, facilitating saponification in sewer pipes. Households lack a filtration system, resulting in all of the domestic FOGs entering the municipal infrastructure without mitigation. Small-scale establishments involved in food preparation, like small stalls and corner shops at both national and international levels [35], lack proper infrastructure like Grease Interceptors (GI) [36] as required by law and regulatory frameworks to collect and dispose of FOGs, which boosts the oily content of municipal wastewater. The current design of GIs does not support full removal of FOGs as claimed by manufacturers [37], and particles smaller than 150 µm can enter the sewer [38]. Higher microbial activity in the GI environment was reported in a lab-scale study where FFA concentrations increased significantly [39], indicating that GIs may promote FOG deposits in sewers by increasing FFA production [5].

FOGs, when present in sewage, can combine with suspended solids, pose challenges to wastewater management, and are the leading cause of sewer pipe blockages, thereby increasing maintenance costs [5]. They undergo physical and chemical changes inside the sewer system [40], e.g., they transform into a semisolid or solid grease that adheres to the interior of the pipe and eventually thickens with time, constricting the pipelines [41]. Pipe material also influences accumulation, with rougher surfaces such as concrete promoting greater adhesion than smoother plastic pipes [6]. Sometimes they float and accumulate in the upper layers, being less dense than water and forming fatbergs [42], interacting physically with other non-biodegradable items, gradually increasing in size, and eventually obstructing wastewater flow. They can saponify, reacting chemically with minerals either naturally present in water [43] or leached from concrete-built sewage pipelines [44, 45, 46] or carried in mineral-rich industrial discharge [47], producing soap-like, rigid deposits that stick to sewage lines [48]. Beyond physical blockages, they create environments that promote microbial proliferation, generating methane (CH_4) and hydrogen sulfide (H_2S) [49] within sewer networks, making them unintended sources of greenhouse gases. Biofilm formation on the interiors of PVC pipes increases surface roughness, reduces shear stress, and promotes sedimentation, thereby contributing to FOG buildup [50]. Globally, 50-70% of sewer blockages require coordinated technical and regulatory actions [5].

4. Environmental Effects/ Human Health Risk

The physical impacts of FOGs could be greater than their toxicity on the terrestrial environment. Anthropogenic discharge through unplanned urbanization and industrialization is a major driver of river water contamination [51]. In general, storm runoff and, in particular, fatberg accumulation in sewage pipelines cause sewer overflows that release untreated wastewater into the aquatic and terrestrial environments. Not only do they contaminate the topsoil, but the polluted water can also seep into the groundwater and degrade the water table. The FOGs, being less dense than water, float and make a surface sheen, impeding oxygen exchange and blocking sunlight, thus reducing photosynthesis in aquatic plants and algae and disturbing the food chain. Crude oil exports by sea can lead to spills, which raise the chemical and biological oxygen demand in marine ecosystems.

Used edible oil (UEO) is a significant source of waste produced by both food businesses and households. Discharging it in landfills risks soil health, as it breaks down and releases harmful substances in its leachate, which can degrade soil composition and alter microbial activity. Edible oil is rich in polyunsaturated fatty acids, which, on heating, convert to trans-unsaturated fatty acids, and the volatile fraction contains low-molecular-weight polar organic compounds, which, on further oxidation, release Polycyclic Aromatic Hydrocarbons (PAHs), which are hazardous, mutagenic, and carcinogenic. Repeated heating of edible oils further generates free radicals, which are a leading cause of cell death and oxidative stress and are linked to various human health issues. High-temperature use of edible oil generates hydroperoxides and mono- and diglycerides due to hydrolysis and oxidation [52]. All these hazardous compounds can enter the underground water table if UEO is disposed of on land without treatment. The heterogeneous waste generated from production to consumption can be divided into various categories; each presents unique challenges and consequences (Table 4).

Table 4: Summary of major waste streams, typical composition and environmental impact

Waste Stream	Typical Composition	Environmental Impacts
Effluents	High FOG, COD, BOD, suspended solids, phenolics, LCFA, residual proteins, carbohydrates	Water pollution, oxygen depletion, toxicity to microbes, membrane fouling, sludge bulking, inhibition of methanogenesis
Solid Waste	Biomass, residual oil, proteins, minerals	Slow decomposition and greenhouse gas emission, soil contamination, leaching
Spent Earth	Bleaching clays, 20–40% adsorbed oil, pigments, PAHs, metals	Hazardous waste; spontaneous combustion risk; soil and groundwater contamination; release of carcinogenic compounds; difficult landfill disposal
Sludge	Concentrated FOG, microbial biomass, polymerized fats, organic solids, nutrients	Methane emissions, odor, pathogen load, and soil contamination if applied untreated
UCO	Oxidized fats, polymerized triglycerides, FFA, food residues, water	Sewer FOG and blockages, overflows, increased municipal treatment costs, rancid odors, pathogen growth, fire hazards due to methanogenesis
Volatile Emissions	Aldehydes, ketones, hydrocarbons, short- chain volatile compounds are released during heating/refining	Indoor air pollution, respiratory irritation, occupational health risks, and contribution to photochemical smog

5. Bioremediation

As discussed above, various methods have been used to treat OWW. These include ponding systems, tank digestion with aeration, and combined physicochemical and biological processes, but each has drawbacks such as long retention times, high land requirements, chemical use, and inconsistent nutrient removal.

Bioremediation is a broader biological approach that uses microorganisms (bacteria, fungi, algae) to degrade organic and colored compounds, as well as FOGs, present in all types of wastewaters under aerobic or anaerobic conditions, as indicated above. Diverse bioremediation strategies are being used to treat O&G in POME and restaurant wastewater. These are cost- effective, environmentally friendly, and adaptable to a wide range of pollutants. The choice of strategy depends on contaminant type, site conditions, and desired treatment speed. These strategies range from simple natural attenuation to engineered systems like bioreactors and bio-granules. Bioreactors [53] are controlled systems that optimize microbial activity to achieve rapid wastewater treatment, while biogranules [54] are dense microbial clusters that enable high degradation rates. Their stability and rapid settling make them ideal for treating high-strength wastewater such as POME. Bioremediation employs natural microbial and enzymatic processes that degrade OWW safely and sustainably, while chemical treatment relies on harsh reagents that produce toxic residues and environmental hazards Figure 3.

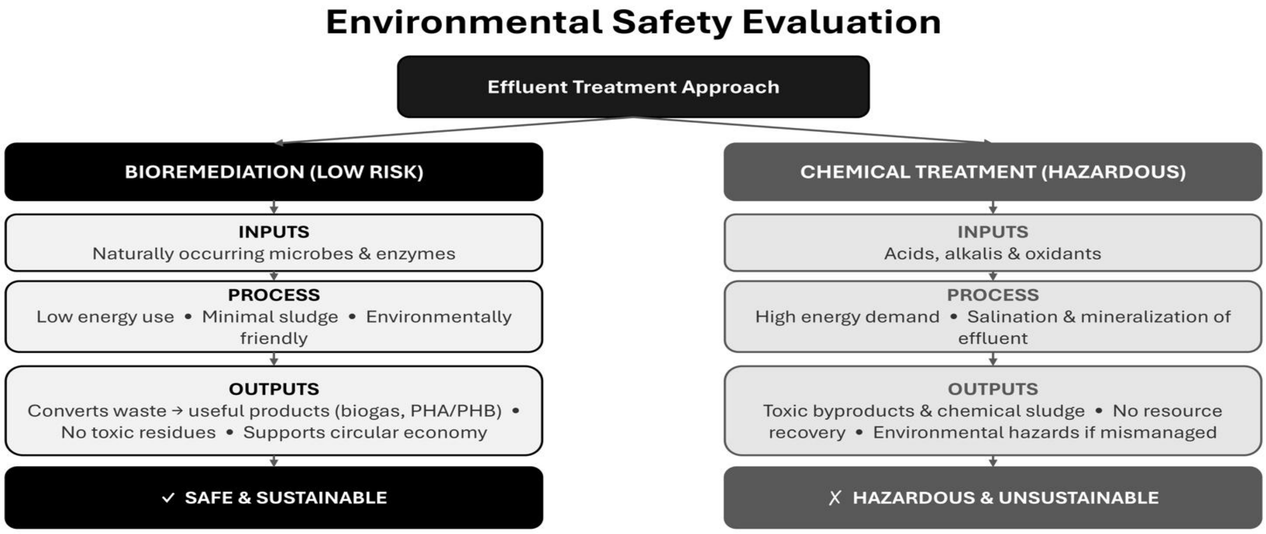

Figure 3. Bioremediation Compared with Conventional Chemical Treatment

This review gathered data on the potential microorganisms being investigated for use in degrading FOGs and converting them into harmless CO_2, H_2O, biomass, and other useful products like biogas and biopolymers. Scientists involved in this area of research use a single [55] or a combination of different species in a “consortium”; some hydrolyze the fats into fatty acids, and others excel at beta-oxidation of these fatty acids. The former step inhibits the accumulation of LCFA, while the later helps in maintaining the pH and microbial colony. In some applications, Lipase, secreted by microbes [56] such as bacteria, yeast, and fungi, can hydrolyze the fats and glycerides to FFA and glycerol and produce new substances with potential industrial applications [57]. These lipases can function at elevated temperatures, across a range of pH levels, and in various organic solvents, catalyzing reactions at the lipid-water interface. In industrial settings, isolated enzymes, crude lipase and esterase, are directly added to effluents to overcome the sluggish bacterial work. These enzymes act like chemical "scissors," cutting the ester bonds of triglycerides. This "liquefies" the grease, making it much easier for the indigenous bacteria already in the sewer to finish the job. This process is faster than waiting for bacteria to grow and secrete their own enzymes. Yeast and fungi, two prominent microorganisms, produce extracellular lipolytic enzymes, which make the process more cost-effective [58, 59]. Chemical hydrolysis requires concentrated alkalis and acids under high temperature, and the use of dichloromethane to extract the organic phase makes it difficult and requires precise control over the process [60].

Aerobic treatment is a promising alternative because it rapidly reduces carbon and nitrogen levels, effectively removes pollutants, and can improve the suitability of treated OWW for use as fertilizer by shifting its pH from acidic to alkaline [61]. Technologies based on aerobic treatment depend heavily on the metabolic capabilities of the microbial community, especially when dealing with high- strength effluents such as POME. Vijayaraghavan et al. tested the aerobic digestion of the raw and anaerobically treated POME with microbial biomass in activated sludge [62] in a bioreactor and reported COD removal efficiency up to 83% after 36 h of hydraulic retention time [63]. An indigenous strain of *Bacillus cereus* KJ605415 identified in POME can completely degrade O&G under aerobic conditions at pH 6 and 30 °C after 7 days of incubation [64].

In contrast, Raw POME and other oily industrial wastewaters showed a reduction of BOD from 3,200 mg/L to below 40 mg/L, while lipid content declined from 25,000 mg/L to approximately 80 mg/L on inoculating with a bacterial consortium comprising *Bacillus subtilis*, *Bacillus licheniformis*, *Bacillus amyloliquefaciens*, *Serratia marsescens*, *Pseudomonas aeruginosa,* and *Staphylococcus aureus* [65]. In another study, consortia comprising Bacillus cereus and Bacillus subtilis isolated from raw POME removed more than 90% of the organic load in the bioreactor [15].

Wastewater from olive oil manufacturing had total dissolved solids (TDS), COD, and O&G concentrations of 10,032, 9,174, and 914.8 mg/L, respectively [66]. In a lab-based study, a 12 L filter reactor containing oil mill waste was inoculated with activated sludge and bioaugmented with *Phanerochaete chrysosporium* or *Trametes versicolor* under anaerobic conditions, which digested the organic matter of oil mill waste and produced biogas [67]. *Candida tropicalis* ATCC 750 showed strong ability to detoxify 68% of organic waste and approximately 40% of phenolic contents in OMW and generate valuable products, making this process a promising alternative to traditional methods for treating OMW in bioreactors and producing appreciable quantities of lipase and protease [68]. In another lab-scale study, a combination of triacylglycerol acylhydrolases (a type of lipase), produced by bacterial strains, *Micrococcus lylae* (strain DSM 20315) and a *Corynebacterium aurimucosum* strain, was used to study the hydrolysis of fats and oils. Among these, *Corynebacterium* is known for producing biosurfactants, thus playing a crucial role in emulsifying available fats and accelerating degradation [69]. The bioremediation efficiency of purified lipase combined with a bacterial consortium consisting of Acinetobacter junii VSJK-R6, Pseudomonas composti VSJK-R8, and Pseudomonas aeruginosa VSJK-R9 was evaluated on restaurant wastewater supplemented with NH_4Cl and K_2HPO_4 to promote microbial growth. While the bacterial consortium alone was effective, adding the purified lipase enzyme significantly "boosted" the degradation process. *Pseudomonas aeruginosa* is also known to produce biosurfactants [70]. The enzyme acted as a catalyst to break down complex fats into simpler fatty acids that the bacteria could then easily consume. The combined treatment led to a substantial decrease in oil content. Using purified lipase from a native strain (*P. aeruginosa* VSJK-R9) makes the treatment highly specific and environmentally friendly, offering a viable alternative to harsh chemical cleaners or expensive mechanical dredging of sewer lines [71].

El-Masry et al. [72] achieved complete removal of FOG, COD, and BOD using a *Pseudomonas*- based sand biofilm consisting of a two-unit bioreactor in heavily polluted vegetable wastewater containing 7535 ppm of FOG, 525 ppm BOD, and 1660 ppm COD. They found such immobile systems to be highly stable, robust, scalable, and able to easily manage hydraulic fluctuations. The consortium of *Pseudomonas* sp., lipase-producing and *Pseudomonas diminuta* hydrolyses the fats [72]. The *Serratia marcescens* SA30 has been reported to remove FOG from palm oil industrial wastewater [73]. After 60 days of treating anaerobically digested palm oil mill effluent with the same strain, flocculent biomass transformed into bio-granules that settled well and improved treatment efficiency [74]. By using a mix of two or more than two strains applied in situ or at the point of collection, researchers demonstrated that the synergistic use of *Pseudomonas putida* and *Bacillus amyloliquefaciens* improved oil degradation by lipase hydrolysis and β-oxidation under anaerobic digestion, which further showed an enhanced degradation under aerobic conditions of recalcitrant fatty acids [75].

The fermented broth produced after oil degradation, resulting from the combined activity of *Rhodotorula mucilaginosa*, *Candida rugosa* CCMA 00371, and *Bacillus subtilis* CCMA 0085, is suitable for application in waste treatment systems [76]. Mixed cultures of Bacillus spp. and their variants, particularly Bacillus cereus variants, were applied to sunflower production plant effluent, and superior degradation of FOG and associated organic wastes was achieved, making them ideal candidates for industrial bioaugmentation [77].

Studies are available on remediating kitchen oily waste using lipases from *Candida albicans* (ATCC10231), *Aspergillus sclerotigenum* (MK732096.1), and *Aspergillus niger* (MG654699.1) [78]. Affandi et al. reported that *S. marcescens* achieved 91% O&G degradation at pH 7.0 after 12 days of incubation with a 14.6 kg O&G loading per day, due to its high adherence to hydrocarbons and biosurfactant production in used cooking oil [64]. The lipase-producing bacterium *Pseudomonas aeruginosa* LP602 showed greater lipid-degradation capacity than other bacteria when tested for the treatment of oily kitchen wastewater [65].

In a simulated experiment, the effect of LCFA like oleic acid was observed, which can undermine the performance of the anaerobic membrane bioreactors. Moderate levels of LCFA support COD removal and methane production. However, high LCFA accumulation coats biomass and membranes, slowing hydrolysis, suppressing methanogens by inhibiting the proliferation of the genus *Methanosarcina*, increasing VFA buildup, and accelerating membrane fouling. As a result, reactor stability, biogas yield, and treatment efficiency decline sharply at high lipid loading [79]. In another study, sludge settling performance was reduced when oleic acid was absent, promoting the proliferation of Zoogloea and suggesting an altered microbial population in the presence of LCFA in wastewater [80]. The inoculation of activated sludge with multiculture photosynthetic microalgae (*Pleurochloris keutzingium* and *Chlorella vulgaris*) not only promoted biomass production but also improved the bioavailability of FOG as a carbon source. Biochemical analysis indicated increased lipid and carbohydrate synthesis, thereby reducing reliance on energy-intensive aeration and highlighting the potential of these environmentally sustainable wastewater streams containing FOG for biofuel applications [81]. Many of these laboratory-scale studies outperform physicochemical methods; however, applicability on a commercial scale is challenging. Cost, operational reliability, and long-term sustainability remain the deciding factors for their successful applications in oil mills.

Microbes can use O&G in wastewater as a carbon source instead of pure glucose and can produce granules of poly-hydroxybutyric acid (PHB), commonly known as bioplastics. Cells produce it under conditions of nutrient limitation (nitrogen, phosphorus, oxygen, or magnesium) and store it in the cytoplasm. The selection of microorganisms depends on their ability to store PHB and utilize the cheap substrate, such as O&G, present in OWWs under non-sterile conditions in the reactor. PHB has properties comparable to petroleum-based plastics such as polypropylene (PP), but unlike conventional plastics, it is fully biodegradable in the environment [82]. Supplementing POME with 20 g/L molasses, *Caldibacillus thermoamylovorans* strain PHA005 produced 59.9 ± 0.5% cell dry mass (CDM) after 96 h, demonstrating a 1.8-fold improvement over the unsupplemented effluent [83]. Bioplastics are gaining increasing attention as sustainable alternatives to conventional plastics [84-87]. In another study, production of the bioplastic polyhydroxyalkanoate (PHA) was reported through a fed-batch POME (aerobic–anaerobic) fermentation process in bioreactors for nearly six days using the bacterial strain *Pseudomonas aeruginosa*. Mumtaz et. Al [10] provided an insight into the biochemical pathway involved in bioplastic production from organic acids generated during acid-phase anaerobic digestion of POME [10]. The average yield of PHA production was 5.25% by weight [88] along with a reduction of COD and BOD. Some other bacterial strains such as *Pseudomonas aeruginosa* and *Bacillus subtilis* have been reported to produce PHA when raised on glucose obtained from sources other than POME [89]. These strains, together with *Aspergillus niger*, have also been investigated for POME bioremediation [90], and a few strains, like Bacillus subtilis [15] and Aspergillus niger [91], have been found indigenously in POME. Strategies are still being developed to optimize conditions for efficient PHA production [92], and one approach is the genetic modification of selected microbes for producing bioplastics at an industrial scale [93]. The bioremediation efficiency of different microbial strains across multiple wastewater types, including POME, raw POME, OMW, palm oil industrial wastewater, kitchen wastewater, vegetable wastewater, and kitchen oily waste, was compared (Fig. 4).

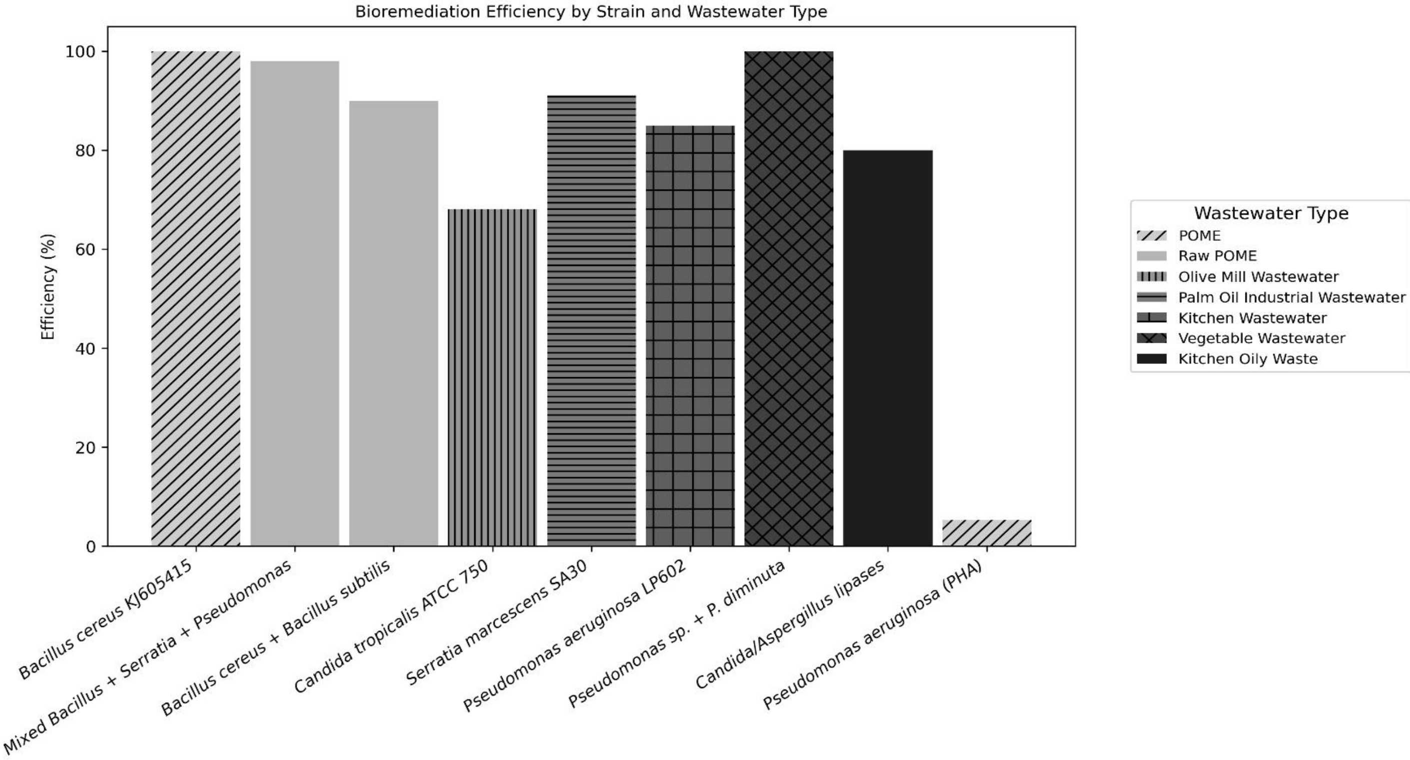

Figure 4. Quantitative performance matrix of different microbial strains across different wastewater streams

6. Quality assessment and Quantification

COD, BOD, and suspended solids are physicochemical parameters used to assess the organic load of a sample matrix. COD reflects total pollution, including non-biodegradable compounds, whereas BOD indicates the potential impact of biodegradable organic matter on aquatic life through oxygen depletion. O&G are biodegradable pollutants; their presence is separately detected. During seed oil extraction, refining, and use in homes and restaurants, assessing the quality and quantity of O&G in effluents from oil mills, grease traps, and household drains is essential for monitoring mill efficiency and ensuring discharge levels remain within permissible limits. For better environmental management, the discharge limits are being revised in different countries, and recent figures are presented in Table 5.

Table 5: Discharge limits in selected countries

	Parameters			
Countries	**COD**	**BOD_5**	**Oil and grease**	**References**
America	125	25	25 – 35 (EPA-America)	[102].
Russia	15 - 30	2 - 4	n/a	
Belarus	70 – 125	15 - 35	n/a	
Switzerland	45 - 60	15- 20	n/a	
China	50	n/a	10 in surface waters, 100 in sewage system (EPA-America)	
Dubai	100	30- 50	n/a	
EU	125	25	n/a	
Germany	75 -150	15-40	n/a	
Sweden	n/a	13	n/a	
Denmark	n/a	10	n/a	
HELCOM signatory countries	n/a	15- 25	n/a	
Malaysia	n/a	100	50	[103]
Thailand	<1000	<100	<25	[15]

All values are recorded here in mg/L. The values were established on TPs and fall within the range depending on the water category, population equivalent, and eutrophication. BOD5: Biochemical Oxygen Demand over 5 days. EPA: Environmental Protection Agency. n/a Not available.

The standard quantification method 5520 is used with detection limits in the mg/L range and modified depending on the sample type [94]. Volatile and non-chlorinated solvents such as n-hexane are used in the Partition-Gravimetric Method and Soxhlet Extraction. Despite its widespread use as a solvent, n-hexane is associated with several environmental, fire, and health risks. Because it is volatile, it contributes to air pollution by forming ground-level ozone. In case of spill or runoff, it can be absorbed by aquatic organisms. It is also neurotoxic to both wildlife and humans, especially workers exposed to it in industrial settings, potentially causing nerve damage and cognitive issues. The intake limit has not been defined by any food regulatory authority [95]. The reported LD50 value is high (28,710 mg/kg for rats) [96]. These risks underscore the importance of effective regulation to protect people directly involved in the workplace and the environment. Nevertheless, the toxic effects of n-hexane [95- 98] on occupational health and the environment have been known for more than 50 years, and it is still used in routine O&G analysis. Greener alternatives should be developed to reduce and replace n-hexane. The non-destructive spectroscopic techniques like Raman and FTIR Spectroscopy can be used to quantify O&G. Several researchers have used FTIR to identify the stages of FFA and FOG formation in sewers, and it offers a fast, reliable, and solvent-free method for detecting various stages of FOG formation [99, 100] with potential for extension to quantification purposes. The use of a solvent and its evaporation during the quantification of oils and greases can be minimized by coupling extraction with FTIR analysis. Chemometric analysis can be combined with spectral data to identify meaningful patterns by reducing dimensionality and grouping samples by shared spectral features, enabling accurate estimates of oil concentration [101].

7. Future Recommendations

Lipase-based treatments to overcome sluggish microbial communities become more expensive when upscaling to industrial level due to cost-associated challenges in enzyme purification. Systematic optimization of microbial interactions, stability under fluctuating pH and temperature, and resilience to inhibitory compounds like LCFA remain limited. High LCFA levels coat biomass and membranes, thereby accelerating fouling, reducing hydrolysis, and suppressing methanogens. Strategies to reduce LCFA toxicity or develop LCFA-tolerant strains remain insufficiently explored. Further development is needed to improve enzyme-based treatments by addressing enzyme stability and immobilization. Research should prioritize reusable, immobilized, and heat-tolerant enzymes/lipases, and hybrid systems where enzymes accelerate hydrolysis and microbes complete mineralization. Greater research attention is needed to optimize indigenous microbial communities, thereby reducing reliance on extracellular lipases. For instance, mixed Bacillus–Serratia–Pseudomonas consortia achieved >98 % COD removal [65], while Candida tropicalis detoxified 68 % of organic matter and reduced phenolics by 40 % [68].

The unique solvent properties of Supercritical Fluids (SCFs), particularly CO_2 [104, 105], allow efficient removal of FOGs without generating toxic residues or secondary pollution. Integrating recyclable, non-toxic, and energy-efficient SCFs with bioremediation can decrease LCFA toxicity, enhance biodegradability, and support circular economy valorization by enabling clean recovery of lipids for biogas, biosurfactants, and bioplastics. SCFs offer a green alternative to conventional chemical treatments and may play a significant role in next-generation sustainable wastewater management systems.

Despite the well-established hazards associated with the UEO, standardized protocols for kitchen-scale or sewer-line bioremediation are not receiving the same attention as industrial waste. Few strains like Serratia marcescens [64] and Pseudomonas aeruginosa [65] show robust performance in domestic wastewater; there is a pressing need to design standardized protocols for domestic grease traps, sewer line bioaugmentation, and restaurant-scale biological dosing systems. Microbe- or enzyme-based formulations could substantially reduce urban FOG formation and improve municipal wastewater management. Strategies are still being developed to optimize promising valorization pathways of PHA and PHB production. Altogether, these gaps highlight the need for future investigation on optimized, self-reliant and LCFA-resilient consortia and integrated bioremediation valorization frameworks.

The International Union for Conservation of Nature published a report in 2024 on the future of vegetable oils and emphasized the adoption of environmentally friendly technologies across the oil sector, from oil-crop to industrial processes. Bioremediation is recommended due to its ability to degrade hydrophobic lipids through microbial hydrolysis and β-oxidation without producing chemical sludges and aligns with these sustainability objectives by offering unharmed, non-toxic, and circular approaches for managing OWW [106]. Advanced biological systems such as lipase-mediated hydrolysis, anaerobic digestion, and algal bacterial consortia should be adopted to enhance degradation kinetics and support circular economy valorization.

8. Conclusion

The review demonstrates the severity of challenging effluent from edible oil production units due to high pollutant loads of FOGs, LCFA, and complex organic matter. The severity of the pollutant load from oil resource waste necessitates advanced biological treatment systems as an environmentally friendly solution. Although numerous biological (consortium-based) and enzymatic approaches have been explored to outperform physicochemical methods well at laboratory scale, the real challenge arises when these approaches are scaled to industrial or municipal settings. Cost, operational reliability, and long-term sustainability remain the deciding factors in real-world implementation. This highlights the need for long-term monitoring and techno-economic assessments to validate the feasibility of pilot-scale demonstrations in wastewater environments.

Municipalities worldwide impose limits on the discharge of O&G (50 to 100 mg L^{-1} in Singapore and Malaysia) and mandate businesses to install grease traps, as pollution from industrial wastewater has become a global issue, posing environmental and health risks to ecosystems. Conventional methods have been developed over decades to combat this threat but have proven ineffective. Advanced treatment innovations provide an efficient method for removing pollutants. Furthermore, the application of combined technologies to fully remediate toxic pollutants from rising OWW has recently gained attention. The application of supercritical fluids, their extraction efficiency, and use at the industrial scale are potential alternatives to conventional extraction processes. Although existing oil extraction and refining systems are difficult to modify, eco-friendly improvements should be developed for current operations and incorporated into the design of new vegetable oil processing facilities. Nearly 37% of the world's farmland is dedicated to oil crop fields and is expected to rise by a further 14% to meet the increasing demand, risking biodiversity and driving deforestation. Adopting sustainable practices, protecting natural habitats from expansion, improving crop yields and prioritizing food uses are all strategies that should be adopted to meet the future demand for edible vegetable oils. This article provides a broad overview of FOGs entering the environment and discusses various available bioremediation strategies that could be adapted for their effective management. Turning OWW into other products by integrating algal–bacterial systems and valorization pathways can create a circular economy system where waste becomes a resource, supporting sustainable industrial and environmental practices.

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References

1. Winkler-Moser, J. K., & Mehta, B. M. (2015). Chemical composition of fat and oil products. In *Handbook of Food Chemistry* (pp. 365–402). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-36605-5_32
2. Mohana, A. A., Roddick, F., Maniam, S., Gao, L., & Pramanik, B. K. (2023). Component analysis of fat, oil and grease in wastewater: Challenges and opportunities. *Analytical Methods*, *15*(39), 5112–5128. https://doi.org/10.1039/D3AY01222K
3. Hasenhuettl, G. L. (2016). Fats and fatty oils. In *Kirk-Othmer Encyclopedia of Chemical Technology* (pp. 1–37). Wiley. https://doi.org/10.1002/0471238961.0601201908011905.a01.pub3
4. 4 .Alibardi, L., Strazzabosco, A., & Cossu, R. (2025). Characterisation and anaerobic digestion of fat, oil and grease (FOG) waste from wastewater treatment plants. *Journal of Environmental Management*, *375*, 124193. https://doi.org/10.1016/j.jenvman.2025.124193
5. Ahmed, N., Straub, A., & Ali, M. (2026). Fats, oil, and grease (FOG) in wastewater: Sources, mechanisms, control, and removal strategies. *International Journal of Environmental Science and Technology*, *23*(2), 161. https://doi.org/10.1007/s13762-025-06977-2
6. Yusuf, H. H., Roddick, F., Jegatheesan, V., Gao, L., & Pramanik, B. K. (2023). Tackling fat, oil, and grease (FOG) build-up in sewers: Insights into deposit formation and sustainable in-sewer management techniques. *Science of The Total Environment*, *904*, 166761. https://doi.org/10.1016/j.scitotenv.2023.166761
7. Cammarota, M. C., & Freire, D. M. G. (2006). A review on hydrolytic enzymes in the treatment of wastewater with high oil and grease content. *Bioresource Technology*, *97*(17), 2195–2210. https://doi.org/10.1016/j.biortech.2006.02.030
8. Rajkumar, K., Muthukumar, M., & Sivakumar, R. (2010). Novel approach for the treatment and recycle of wastewater from soya edible oil refinery industry—An economic perspective. *Resources, Conservation and Recycling*, *54*(10), 752–758. https://doi.org/10.1016/j.resconrec.2009.12.005
9. Liew, W. L., Kassim, Mohd. A., Muda, K., Loh, S. K., & Affam, A. C. (2015). Conventional methods and emerging wastewater polishing technologies for palm oil mill effluent treatment: A review. *Journal of Environmental Management*, *149*, 222–235. https://doi.org/10.1016/j.jenvman.2014.10.016
10. Mumtaz, T., Yahaya, N. A., Abd-Aziz, S., Abdul Rahman, N., Yee, P. L., Shirai, Y., & Hassan, M. A. (2010). Turning waste to wealth-biodegradable plastics polyhydroxyalkanoates from palm oil mill effluent – A Malaysian perspective. *Journal of Cleaner Production*, *18*(14), 1393–1402. https://doi.org/10.1016/j.jclepro.2010.05.016
11. Chew, C. L., Ng, C. Y., Hong, W. O., Wu, T. Y., Lee, Y.-Y., Low, L. E., Kong, P. S., & Chan, E. S. (2021). Improving sustainability of palm oil production by increasing oil extraction rate: A review. *Food and Bioprocess Technology*, *14*(4), 573–586. https://doi.org/10.1007/s11947-020-02555-1
12. Mohammad, S., Baidurah, S., Kobayashi, T., Ismail, N., & Leh, C. P. (2021). Palm oil mill effluent treatment processes—A review. *Processes*, *9*(5), 739. https://doi.org/10.3390/pr9050739
13. Soo, P. L., Bashir, M. J. K., & Wong, L.-P. (2022). Recent advancements in the treatment of palm oil mill effluent (POME) using anaerobic biofilm reactors: Challenges and future perspectives. *Journal of Environmental Management*, *320*, 115750. https://doi.org/10.1016/j.jenvman.2022.115750

14. Mohd Yusof, M. A. Bin, Chan, Y. J., Chong, C. H., & Chew, C. L. (2023). Effects of operational processes and equipment in palm oil mills on characteristics of raw palm oil mill effluent (POME): A comparative study of four mills. *Cleaner Waste Systems*, *5*, 100101. https://doi.org/10.1016/j.clwas.2023.100101
15. Dominic, D., & Baidurah, S. (2022). Recent developments in biological processing technology for palm oil mill effluent treatment—A review. *Biology*, *11*(4), 525. https://doi.org/10.3390/biology11040525
16. Bala, J. D., Lalung, J., & Ismail, N. (2015). Studies on the reduction of organic load from palm oil mill effluent (POME) by bacterial strains. *International Journal of Recycling of Organic Waste in Agriculture*, *4*(1), 1–10. https://doi.org/10.1007/s40093-014-0079-6
17. Menezes Dos Passos, R., Sousa, R., Ferreira, B., Caldas Batista, E. A., Meirelles, A. J. A., Maximo, G. J., Ferreira, M. C., & Sampaio, K. A. (2019). Degumming alternatives for edible oils and biodiesel production. *Food and Public Health*, *2019*(5), 139–147. https://doi.org/10.5923/j.fph.20190905.01
18. El-Hamidi, M. Z. F. A. ; S. A. (2020). Edible oil production in Egypt: An overview. *Current Science International*. https://doi.org/10.36632/csi/2020.9.4.58
19. Nur Sulihatimarsyila, A. W., Lau, H. L. N., Nabilah, K. M., & Nur Azreena, I. (2019). Refining process for production of refined palm-pressed fibre oil. *Industrial Crops and Products*, *129*, 488–494. https://doi.org/10.1016/j.indcrop.2018.12.034
20. Gibon, V., De Greyt, W., & Kellens, M. (2007). Palm oil refining. *European Journal of Lipid Science and Technology*, *109*(4), 315–335. https://doi.org/10.1002/ejlt.200600307
21. Rossi, M., Gianazza, M., Alamprese, C., & Stanga, F. (2003). The role of bleaching clays and synthetic silica in palm oil physical refining. *Food Chemistry*, *82*(2), 291–296. https://doi.org/10.1016/S0308-8146(02)00551-4
22. Reddy, K., Drysdale, G., & Bux, F. (2004). Evaluation of activated sludge treatment and settleability in remediation of edible oil effluent. *Water SA*, *29*(3). https://doi.org/10.4314/wsa.v29i3.4924
23. Berninghaus, A. E., & Radniecki, T. S. (2022). Shock loads change the resistance, resiliency, and productivity of anaerobic co-digestion of municipal sludge and fats, oils, and greases. *Journal of Cleaner Production*, *362*, 132447. https://doi.org/10.1016/j.jclepro.2022.132447
24. Abolore Idris, M., Saedi Jami, M., & Aremu Muyibi, S. (2010). Tertiary treatment of biologically treated palm oil mill effluent (POME) using UF membrane system: Effect of MWCO and transmembrane pressure. *International Journal of Chemical and Environmental Engineering 1*(2) (2010), 108-112.
25. Ahmad, A. L., Chong, M. F., Bhatia, S., & Ismail, S. (2006). Drinking water reclamation from palm oil mill effluent (POME) using membrane technology. *Desalination*, *191*(1–3), 35–44. https://doi.org/10.1016/j.desal.2005.06.033
26. Gao, W., Liang, H., Ma, J., Han, M., Chen, Z., Han, Z., & Li, G. (2011). Membrane fouling control in ultrafiltration technology for drinking water production: A review. *Desalination*, *272*(1–3), 1–8. https://doi.org/10.1016/j.desal.2011.01.051
27. Aris, A., Boon Siew, O., Suh Kee, K., & Ujang, Z. (2018). Tertiary treatment of palm oil mill effluent using fenton oxidation. *Malaysian Journal of Civil Engineering*, *20*(1). https://doi.org/10.11113/mjce.v20.15753
28. Long, J. H., Aziz, T. N., Reyes, F. L. de los, & Ducoste, J. J. (2012). Anaerobic co-digestion of fat, oil, and grease (FOG): A review of gas production and process limitations. *Process Safety and Environmental Protection*, *90*(3), 231–245. https://doi.org/10.1016/j.psep.2011.10.001
29. Kaya, D., & Hung, Y.-T. (2021). *Advances in Treatment of Vegetable Oil Refining Wastes* (pp. 325–375). https://doi.org/10.1007/978-3-030-54626-7_8
30. Alhaji, M. H., Sanaullah, K., Lim, S.-F., Khan, A., Hipolito, C. N., Abdullah, M. O., Bhawani, S. A., & Jamil, T. (2016). Photocatalytic treatment technology for palm oil mill effluent (POME) – A review. *Process Safety and Environmental Protection*, *102*, 673–686. https://doi.org/10.1016/j.psep.2016.05.020
31. Bi, C., Min, M., Nie, Y., Xie, Q., Lu, Q., Deng, X., Anderson, E., Li, D., Chen, P., & Ruan, R. (2015). Process development for scum to biodiesel conversion. *Bioresource Technology*, *185*, 185–193. https://doi.org/10.1016/j.biortech.2015.01.081
32. Yusuf, H. H., Roddick, F., Jegatheesan, V., & Pramanik, B. K. (2025). Influence of improper disposal on FOG deposition: Rheological behaviour and pumping power requirements in sewer systems. *Water Research*, *278*, 123404. https://doi.org/10.1016/j.watres.2025.123404
33. Husain, I. A. F., Alkhatib, M. F., Jammi, M. S., Mirghani, M. E. S., Zainudin, Z. Bin, & Hoda, A. (2014). Problems, control, and treatment of fat, oil, and grease (FOG): A review. *Journal of Oleo Science*, *63*(8), 747–752. https://doi.org/10.5650/jos.ess13182
34. Cerone, M., & Smith, T. K. (2021). A brief journey into the history of and future sources and uses of fatty acids. *Frontiers in Nutrition*, *8*. https://doi.org/10.3389/fnut.2021.570401
35. Hernández-Montelongo, R., Gutiérrez-Pulido, H., García-Sandoval, J. P., & Alvarado-Mendoza, A. G. (2026). Fats, oils, and grease (fog) management in the restaurant sector of the Guadalajara Metropolitan Area, Mexico. *Resources*, *15*(3), 35. https://doi.org/10.3390/resources15030035

36. Sultana, N., Roddick, F. A., & Pramanik, B. K. (2024). Fat, oil and grease wastewater and dishwashers: Uncovering the link to FOG deposition. *Science of The Total Environment*, *907*, 168032. https://doi.org/10.1016/j.scitotenv.2023.168032
37. Sultana, N., Roddick, F., Jefferson, B., Gao, L., Bergmann, D., Papalois, J., Guo, M., Tzimourtas, K., & Pramanik, B. K. (2024). Effectiveness of grease interceptors in food service establishments for controlling fat, oil and grease deposition in the sewer system. *Science of The Total Environment*, *912*, 169441. https://doi.org/10.1016/j.scitotenv.2023.169441
38. Chan, H. (2010). Removal and recycling of pollutants from Hong Kong restaurant wastewaters. *Bioresource Technology*, *101*(17), 6859–6867. https://doi.org/10.1016/j.biortech.2010.03.104
39. He, X., & Yan, T. (2016). Impact of microbial activities and hydraulic retention time on the production and profile of long chain fatty acids in grease interceptors: A laboratory study. *Environmental Science: Water Research & Technology*, *2*(3), 474–482. https://doi.org/10.1039/C6EW00013D
40. Gross, M. A., Jensen, J. L., Gracz, H. S., Dancer, J., & Keener, K. M. (2017). Evaluation of physical and chemical properties and their interactions in fat, oil, and grease (FOG) deposits. *Water Research*, *123*, 173–182. https://doi.org/10.1016/j.watres.2017.06.072
41. Hu, Z., Yadav, S., Hassell, K., Gao, L., & Pramanik, B. K. (2025). Fat, oil and grease - induced sewer blockages: Mechanisms, modelling and monitoring strategies. *Water Research*, *286*, 124215. https://doi.org/10.1016/j.watres.2025.124215
42. Wallace, T., Gibbons, D., O'Dwyer, M., & Curran, T. P. (2017). International evolution of fat, oil and grease (FOG) waste management – A review. *Journal of Environmental Management*, *187*, 424–435. https://doi.org/10.1016/j.jenvman.2016.11.003
43. Ingin, Y. P., Mahringer, D., & El-Athman, F. (2024). Hardness properties of calcium and magnesium ions in drinking water. *Applied Food Research*, *4*(2), 100600. https://doi.org/10.1016/j.afres.2024.100600
44. He, X., de los Reyes, F. L., & Ducoste, J. J. (2017). A critical review of fat, oil, and grease (FOG) in sewer collection systems: Challenges and control. *Critical Reviews in Environmental Science and Technology*, *47*(13), 1191–1217. https://doi.org/10.1080/10643389.2017.1382282
45. Kusum, S. A., Pour-Ghaz, M., & Ducoste, J. J. (2020). Reducing fat, oil, and grease (FOG) deposits formation and adhesion on sewer collection system structures through the use of fly ash replaced cement-based materials. *Water Research*, *186*, 116304. https://doi.org/10.1016/j.watres.2020.116304
46. Wang, Y., Hu, J., Kou, D., Li, W., & Liu, Y. (2025). Comparative assessment of concrete degradation in sewage pipelines: Biogenic vs. mineral sulfuric acid and sewage liquid. *Case Studies in Construction Materials*, *23*, e05169. https://doi.org/10.1016/j.cscm.2025.e05169
47. Panagopoulos, A. (2022). Study and evaluation of the characteristics of saline wastewater (brine) produced by desalination and industrial plants. *Environmental Science and Pollution Research*, *29*(16), 23736–23749. https://doi.org/10.1007/s11356-021-17694-x
48. Ahmad, I., Abdullah, N., Koji, I., Yuzir, A., Ahmad, M. D., Rachmadona, N., Al-Dailami, A., Show, P. L., & Khoo, K. S. (2023). Micro and macro analysis of restaurant wastewater containing fat, oil, grease (FOG): An approach based on prevention, control, and sustainable management. *Chemosphere*, *325*, 138236. https://doi.org/10.1016/j.chemosphere.2023.138236
49. Sudiartha, G. A. W., & Imai, T. (2025). Harnessing conductive materials to reshape sewer microbiomes and mitigate corrosion from sulfide and hydrogen sulfide formation. *Scientific Reports*, *15*(1), 21382. https://doi.org/10.1038/s41598-025-06099-2
50. Otsuka, T., Yamazaki, H., Ankyu, E., Ahamed, T., Anda, M., & Noguchi, R. (2020). Elucidation of the mechanism of blockage in sewer pipes by fatty acid deposition and suspended solid. *Water*, *12*(8), 2291. https://doi.org/10.3390/w12082291
51. Alfee, S. L., & Bloor, M. C. (2025). A global review of river sediment contamination and remobilization through climate change-induced flooding. *Sustainable Environment*, *11*(1). https://doi.org/10.1080/27658511.2024.2440957
52. Kumar, A., Bhayana, S., Singh, P. K., Tripathi, A. D., Paul, V., Balodi, V., & Agarwal, A. (2025). Valorization of used cooking oil: Challenges, current developments, life cycle assessment and future prospects. *Discover Sustainability*, *6*(1), 119. https://doi.org/10.1007/s43621-025-00905-7
53. Lidén, G. (2002). Understanding the bioreactor. *Bioprocess and Biosystems Engineering*, *24*(5), 273–279. https://doi.org/10.1007/s004490100263
54. 5 Milferstedt, K., Hamelin, J., Park, C., Jung, J., Hwang, Y., Cho, S.-K., Jung, K.-W., & Kim, D.-H. (2017). Biogranules applied in environmental engineering. *International Journal of Hydrogen Energy*, *42*(45), 27801–27811. https://doi.org/10.1016/j.ijhydene.2017.07.176
55. Bhumibhamon, O., Koprasertsak, A., & Funthong, S. (2002). Biotreatment of high fat and oil wastewater by lipase producing microorganisms. In *Nat. Sci.)* (Vol. 36).

56. Bharathi, D., & Rajalakshmi, G. (2019). Microbial lipases: An overview of screening, production and purification. *Biocatalysis and Agricultural Biotechnology*, *22*, 101368. https://doi.org/10.1016/j.bcab.2019.101368
57. Haba, E., Bresco, O., Ferrer, C., Marqués, A., Busquets, M., & Manresa, A. (2000). Isolation of lipase-secreting bacteria by deploying used frying oil as selective substrate. *Enzyme and Microbial Technology*, *26*(1), 40–44. https://doi.org/10.1016/S0141-0229(99)00125-8
58. Mandari, V., Nema, A., & Devarai, S. K. (2020). Sequential optimization and large-scale production of lipase using tri-substrate mixture from *Aspergillus niger* MTCC 872 by solid state fermentation. *Process Biochemistry*, *89*, 46–54. https://doi.org/10.1016/j.procbio.2019.10.026
59. Melani, N. B., Tambourgi, E. B., & Silveira, E. (2020). Lipases: From production to applications. *Separation & Purification Reviews*, *49*(2), 143–158. https://doi.org/10.1080/15422119.2018.1564328
60. Peters, M. A., Alves, C. T., Wang, J., & Onwudili, J. A. (2022). Subcritical water hydrolysis of fresh and waste cooking oils to fatty acids followed by esterification to fatty acid methyl esters: Detailed characterization of feedstocks and products. *ACS Omega*, *7*(50), 46870–46883. https://doi.org/10.1021/acsomega.2c05972
61. Ganapathy, B., Yahya, A., & Ibrahim, N. (2019). Bioremediation of palm oil mill effluent (POME) using indigenous *Meyerozyma guilliermondii*. *Environmental Science and Pollution Research*, *26*(11), 11113–11125. https://doi.org/10.1007/s11356-019-04334-8
62. Lee, W. S., Chua, A. S. M., Yeoh, H. K., Nittami, T., & Ngoh, G. C. (2015). Strategy for the biotransformation of fermented palm oil mill effluent into biodegradable polyhydroxyalkanoates by activated sludge. *Chemical Engineering Journal*, *269*, 288–297. https://doi.org/10.1016/j.cej.2015.01.103
63. Vijayaraghavan, K., Ahmad, D., & Ezani Bin Abdul Aziz, M. (2007). Aerobic treatment of palm oil mill effluent. *Journal of Environmental Management*, *82*(1), 24–31. https://doi.org/10.1016/j.jenvman.2005.11.016
64. Affandi, I. E., Suratman, N. H., Abdullah, S., Ahmad, W. A., & Zakaria, Z. A. (2014). Degradation of oil and grease from high-strength industrial effluents using locally isolated aerobic biosurfactant-producing bacteria. *International Biodeterioration & Biodegradation*, *95*(PA), 33–40. https://doi.org/10.1016/j.ibiod.2014.04.009
65. Prasad, M. , M. K. (2011). Comparative study on biodegradation of lipid-rich wastewater using lipase producing bacterial species. In *Indian Journal of Biotechnology* (Vol. 10).
66. Hellal, M., Aboutaleb, E., & kamel, G. (2018). Investigation of effective treatment techniques for olive mill wastewater. *Egyptian Journal of Chemistry*, *61*(3), 320–330. https://doi.org/10.21608/ejchem.2018.2655.1224
67. Dhouib, A., Ellouz, M., Aloui, F., & Sayadi, S. (2006). Effect of bioaugmentation of activated sludge with white-rot fungi on olive mill wastewater detoxification. *Letters in Applied Microbiology*, *42*(4), 405–411. https://doi.org/10.1111/j.1472-765X.2006.01858.x
68. Dias, B., Lopes, M., Ramôa, R., Pereira, A. S., & Belo, I. (2021). *Candida tropicalis* as a promising oleaginous yeast for olive mill wastewater bioconversion. *Energies*, *14*(3), 640. https://doi.org/10.3390/en14030640
69. Alkhatib, M. F. R., Nedjai, R., Kabbashi, N. A., & Hamdaqa, N. F. M. (2026). Optimization of fat, oil, and grease (FOG) biodegradation using consortium of bacteria. *International Journal of Environmental Science and Technology*, *23*(3), 214. https://doi.org/10.1007/s13762-025-06948-7
70. Wong, J.-Y., Ngieng, N.-S., Husaini, A., Saat, R., & Hussain, H. (2025). Influence of pH on the biodegradation efficiency of fats, oils, and grease by biosurfactant-producing bacterial consortia. *Biodegradation*, *36*(4), 50. https://doi.org/10.1007/s10532-025-10146-0
71. Sutar, V. P., Mali, G. V., Upadhye, V., Singh, V. K., & Sinha, R. P. (2023). Purification of lipase from *Pseudomonas aeruginosa* VSJK R-9 and its application in combination with the lipolytic consortium for bioremediation of restaurant wastewater. *Applied Biochemistry and Biotechnology*, *195*(3), 1888–1903. https://doi.org/10.1007/s12010-022-04230-x
72. El-Masry, M. H., El-Bestawy, E., & El-Adl, N. I. (2004). Bioremediation of vegetable oil and grease from polluted wastewater using a sand biofilm system. *World Journal of Microbiology and Biotechnology*, *20*(6), 551–557. https://doi.org/10.1023/B:WIBI.0000043162.17813.17
73. Abdullah, S., Husna, F., Nor, M., & Khamidun, M. H. (2021). Biodegradation of oil & grease from agro-food industry by immobilised *Serratia marcescens* SA30 (Biodegradasi Minyak dan Gris dari Industri Agro-Makanan oleh Serratia marcescens SA30 yang Dipegunkan). In *Malaysian Journal of Analytical Sciences 25*(2).
74. Nuid, M., Aris, A., Abdullah, S., Fulazzaky, M. A., & Muda, K. (2023). Bioaugmentation and enhanced formation of biogranules for degradation of oil and grease: Start-up, kinetic and mass transfer studies. *Journal of Environmental Management*, *341*, 118032. https://doi.org/10.1016/j.jenvman.2023.118032
75. Ke, X., Hua, X., Sun, J.-C., Zheng, R.-C., & Zheng, Y.-G. (2021). Synergetic degradation of waste oil by constructed bacterial consortium for rapid in-situ reduction of kitchen waste. *Journal of Bioscience and Bioengineering*, *131*(4), 412–419. https://doi.org/10.1016/j.jbiosc.2020.12.005
76. Melo, M. M., dos Reis, K. C., Pires, J. F., das Neves, T. T., Schwan, R. F., & Silva, C. F. (2021). Bio-hydrolysis of used soybean oil: Environmental-friendly technology using microbial consortium. *Biodegradation*, *32*(5), 551–562. https://doi.org/10.1007/s10532-021-09951-0

77. Roets-Dlamini, Y., Moonsamy, G., Lalloo, R., & Ramchuran, S. (2022). Use of *Bacillus* spp in the bioremediation of fats, oils and greases (FOG's), and other waste substrates in food processing effluents. *Biocatalysis and Agricultural Biotechnology*, *42*, 102351. https://doi.org/10.1016/j.bcab.2022.102351
78. Safdar, A., Ismail, F., Imran, M., Zia, M. A., Parveen, S., & Bibi, T. (2025). Purification of optimally produced extracellular fungal lipases and their role in the remediation of oil-rich kitchen wastewater. *Journal of Microbiological Methods*, *238*, 107288. https://doi.org/10.1016/j.mimet.2025.107288
79. Zhang, N., Wu, C., Zhang, J., Han, S., Peng, Y., & Song, X. (2023). Impacts of lipids on the performance of anaerobic membrane bioreactors for food wastewater treatment. *Journal of Membrane Science*, *666*, 121104. https://doi.org/10.1016/j.memsci.2022.121104
80. Chen, Z., Gao, C., Hu, X., Gao, Y., Zhou, J., & Peng, Y. (2025). Effects of oleic acid on activated sludge systems: Performance, extracellular polymeric substances (EPS) and microbial communities. *Journal of Environmental Chemical Engineering*, *13*(3), 116582. https://doi.org/10.1016/j.jece.2025.116582
81. Javed, F., & Al-Zuhair, S. (2025). Role of microalgae and activated sludge in the removal of fats, oils, and grease (FOG) in municipal wastewater. *Chemical Engineering Journal Advances*, *22*, 100737. https://doi.org/10.1016/j.ceja.2025.100737
82. Primasari, B., Ibrahim, S., Annuar, M. S. M., & Remmie, L. X. I. (2011). Aerobic treatment of oily wastewater: Effect of aeration and sludge concentration to pollutant reduction and PHB accumulation. *World Academy of Science, Engineering and Technology*, *54*.
83. Binhayeeding, N., Choonut, A., Saimmai, A., & Sangkharak, K. (2026). Waste-to-value: Two-step bioconversion of palm oil mill effluent into biodiesel and polyhydroxybutyrate. *Renewable Energy*, *263*, 125488. https://doi.org/10.1016/j.renene.2026.125488
84. Costa, A., Encarnação, T., Tavares, R., Todo Bom, T., & Mateus, A. (2023). Bioplastics: Innovation for green transition. *Polymers*, *15*(3), 517. https://doi.org/10.3390/polym15030517
85. Ghasemlou, M., Barrow, C. J., & Adhikari, B. (2024). The future of bioplastics in food packaging: An industrial perspective. *Food Packaging and Shelf Life*, *43*, 101279. https://doi.org/10.1016/j.fpsl.2024.101279
86. Islam, M., Xayachak, T., Haque, N., Lau, D., Bhuiyan, M., & Pramanik, B. K. (2024). Impact of bioplastics on environment from its production to end-of-life. *Process Safety and Environmental Protection*, *188*, 151–166. https://doi.org/10.1016/j.psep.2024.05.113
87. Rosenboom, J.-G., Langer, R., & Traverso, G. (2022). Bioplastics for a circular economy. *Nature Reviews Materials*, *7*(2), 117–137. https://doi.org/10.1038/s41578-021-00407-8
88. Ulia, H., Samah, S. D., & Nurmalasari, E. (2025). The Production of polyhydroxyalkanoate (PHA) bioplastic from palm oil mill effluent (POME) using *Pseudomonas aeruginosa*. *Jurnal Kimia Sains Dan Aplikasi*, *28*(7), 387–395. https://doi.org/10.14710/jksa.28.7.387-395
89. Iftikhar, N., Quddus, F., Nadeem, N., Ali, I., Raza, M. U., & Zaid, M. (2024). Production of polyhydroxyalkanoates (PHA) by bacillus and pseudomonas on cheap carbon substrates. *Brazilian Archives of Biology and Technology*, *67*. https://doi.org/10.1590/1678-4324-2024230082
90. Loretta, O. O., & E, S. (2016). In vitro biodegradation of palm oil mill effluent (POME) by *Bacillus subtilis, Pseudomonas aeruginosa* and *Aspergillus niger. Journal of Bioremediation & Biodegradation*, *7*(4). https://doi.org/10.4172/2155-6199.1000361
91. Bala, J. D., Lalung, J., Al-Gheethi, A. A. S., Kaizar, H., & Ismail, N. (2018). Reduction of organic load and biodegradation of palm oil mill effluent by aerobic indigenous mixed microbial consortium isolated from palm oil mill effluent (POME). *Water Conservation Science and Engineering*, *3*(3), 139–156. https://doi.org/10.1007/s41101-018-0043-9
92. Muhammadi, Shabina, Afzal, M., & Hameed, S. (2015). Bacterial polyhydroxyalkanoates-eco-friendly next generation plastic: Production, biocompatibility, biodegradation, physical properties and applications. *Green Chemistry Letters and Reviews*, *8*(3–4), 56–77. https://doi.org/10.1080/17518253.2015.1109715
93. Favaro, L., Basaglia, M., & Casella, S. (2019). Improving polyhydroxyalkanoate production from inexpensive carbon sources by genetic approaches: A review. *Biofuels, Bioproducts and Biorefining*, *13*(1), 208–227. https://doi.org/10.1002/bbb.1944
94. Baird, R. R. E. , and E. A. (2017). Standard methods for the examination of water and wastewaters. *Water Environment Federation, Chair Eugene W. Rice, American Public Health Association Andrew D. Eaton, American Water Works Association*, (1), 71–90.
95. Kumar, B., & Deak, C. (2025). Occupational and environmental risks of n-hexane in industries: A review on risk and regulatory perspectives. *Chemical Engineering Transactions*, *115*, 37–42. https://doi.org/10.3303/CET25115007
96. Damásio, R. A. P., Abed, K., & Meyer, J. (2025). Risk assessment, environmental and health hazards of hexane (HEX) and ethyl acetate (EtOAc): A review. *Journal of Pharmaceutical Research International*, *37*(12), 55–69. https://doi.org/10.9734/jpri/2025/v37i127777

97. Kumar, P., & Pandey, S. K. (2025). Exploring hexane's impact: Toxicological insights, challenges, and forward-looking perspectives. In *Hazardous Chemicals* (pp. 453–465). Elsevier. https://doi.org/10.1016/B978-0-323-95235-4.00037-2
98. Lanska, D. J. (1999). Limitations of occupational air contaminant standards, as exemplified by the neurotoxin n-hexane. *Journal of Public Health Policy*, *20*(4), 441. https://doi.org/10.2307/3343130
99. Shin, H., Han, S., & Hwang, H. (2015). Analysis of the characteristics of fat, oil, and grease (FOG) deposits in sewerage systems in the case of Korea. *Desalination and Water Treatment*, *54*(4–5), 1318–1326. https://doi.org/10.1080/19443994.2014.910141
100. Tang, L. Y., Wong, N. H., Chieng, T. A., Kiu, A. K. J., Choo, C. S., Li, Y., Tan, C. P., Yaser, A. Z., Khaerudini, D. S., Chen, G. H., & Sunarso, J. (2024). Physicochemical characteristics of grease-trap wastewater with different potential mechanisms of FOG solid formation, separation, and accumulation inside grease traps. *Water Research*, *256*, 121607. https://doi.org/10.1016/j.watres.2024.121607
101. Motahari, H., Mousavi, S. S., & Haghighi, P. (2023). Raman, FTIR, and UV–Vis spectroscopic investigation of some oils and their hierarchical agglomerative clustering (HAC). *Food Analytical Methods*, *16*(7), 1237–1251. https://doi.org/10.1007/s12161-023-02481-w
102. Preisner, M., Neverova-Dziopak, E., & Kowalewski, Z. (2020). An analytical review of different approaches to wastewater discharge standards with particular emphasis on nutrients. *Environmental Management*, *66*(4), 694–708. https://doi.org/10.1007/s00267-020-01344-y
103. Latif Ahmad, A., Ismail, S., & Bhatia, S. (2003). Water recycling from palm oil mill effluent (POME) using membrane technology. *Desalination*, *157*(1–3), 87–95. https://doi.org/10.1016/S0011-9164(03)00387-4
104. Bojanić, N., Teslić, N., Rakić, D., Brdar, M., Fišteš, A., Zeković, Z., Bodroža-Solarov, M., & Pavlić, B. (2019). Extraction kinetics modeling of wheat germ oil supercritical fluid extraction. *Journal of Food Processing and Preservation*, *43*(9). https://doi.org/10.1111/jfpp.14098
105. Promraksa, A., Siripatana, C., Rakmak, N., & Chusri, N. (2020). Modeling of supercritical CO2 extraction of palm oil and tocopherols based on volumetric axial dispersion. *The Journal of Supercritical Fluids*, *166*, 105021. https://doi.org/10.1016/j.supflu.2020.105021
106. Meijaard, E., Virah-Sawmy, M., Newing, H. S., Ingram, V., Holle, M. J. M., Pasmans, T., Omar, S., van den Hombergh, H., Unus, N., Fosch, A., Ferraz de Arruda, H., Allen, J., Tsagarakis, K., Ogwu, M. C., Diaz-Ismael, A., Hance, J., Moreno, Y., O'Keeffe, S., Slavin, J., . . . Sheil, D. (2024). *Exploring the future of vegetable oils : Oil crop implications : Fats, forests, forecasts, and futures*. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/KFJA1910

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