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THE POTENTIAL OF USING BIOMATERIALS FOR SUSTAINABLE TREATMENT OF USED ENGINE OIL

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Abstract: Used engine oil poses a major environmental threat due to its toxic components, including hydrocarbons and heavy metals. Conventional remediation methods are often costly and harmful to the environment, prompting the need for sustainable alternatives. This review highlights the potential of biomaterials for UEO treatment, focusing on two main strategies: adsorption and bioremediation. Adsorbent biomaterials, such as agricultural wastes (pomelo peel, rice husk, coconut shell, corn stalk), biochar, cellulose–based aerogels and chitosan, offer effective contaminant removal thanks to their porous structures and modifiable surface properties. These materials represent a promising, eco–friendly solution for used engine oil management, supporting pollution reduction and circular economy goals.
Keywords: biomaterials, used engine oil, internal combustion engine, sustainability

1. INTRODUCTION

Used engine oil (UEO) represents a significant environmental pollutant globally. Millions of liters are disposed of indiscriminately each year, finding their way into land, gutters, and various waterways, leading to widespread and severe contamination [1]. This widespread pollution necessitates urgent and effective remediation strategies.

The inherent complexity of UEO stems from its composition. It originates from a petroleum hydrocarbon base stock, to which numerous additives are incorporated to enhance performance. During its operational life within an engine, exposure to high temperatures and friction triggers chemical transformations, including oxidation and polymer breakdown. As a result, UEO accumulates a diverse array of contaminants. These include heavy metals such as aluminum, chromium, copper, iron, lead, manganese, molybdenum, zinc and cadmium. Additionally, it contains polycyclic aromatic hydrocarbons (PAHs), unburnt fuel, water, antifreeze, dust, and various combustion by–products [1]. The substantial toxicity of UEO is largely attributed to these accumulated additives and wear metals, which can significantly amplify its carcinogenic and mutagenic properties. The diverse and persistent nature of these contaminants in UEO underscores the necessity for comprehensive treatment strategies capable of addressing both organic and inorganic pollutants effectively. Traditional methods often prove expensive, inefficient, time–consuming, and environmentally detrimental, highlighting an urgent need for innovative, sustainable, and integrated solutions [2].

The environmental repercussions of used engine oil contamination are far–reaching. In soil, it increases toxicity, leading to reduced fertility and productivity, aesthetic degradation (manifesting as changes in color and texture), and the inactivation or complete die–off of beneficial soil microorganisms, alongside a reduction in organic matter content [2]. High concentrations of UEO can also impede natural biodegradation processes by limiting nutrient and oxygen availability or through the direct toxic effects of volatile hydrocarbons [2]. Furthermore, it can hinder seed germination and plant growth, causing retardation and abnormalities in various plant species [3]. When used engine oil is disposed of on land, it can migrate and seep into water bodies, forming surface films that drastically reduce oxygen penetration. This can lead to the suffocation and death of aquatic biota. Water–soluble fractions of spent engine oil can enter water systems as runoff, subsequently contaminating groundwater sources like wells, thereby posing a direct threat to drinking water supplies [3]. The slow flow patterns of groundwater contribute to the prolonged persistence of heavy metals originating from UEO. Beyond soil and water, the practice of incinerating used oil, whether by industries or for domestic purposes, results in the emission of toxic compounds such as lead, zinc, chromium, and aluminum into the atmosphere. The human health implications are equally concerning. Exposure to contaminants present in used oil (Figure 1) can lead to a range of adverse health outcomes, including reproductive health issues (e.g., anti–oestrogenic activities), embryotoxic effects, teratogenicity, and lead poisoning [3].

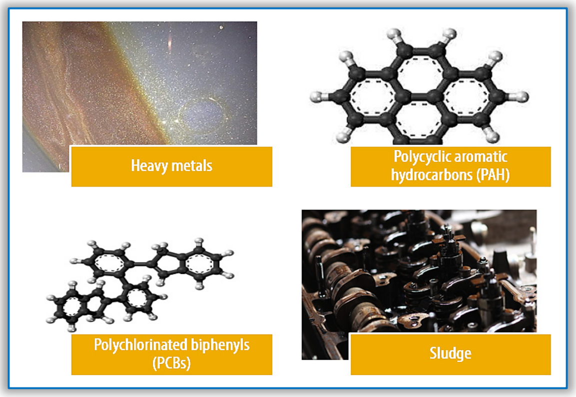

Figure 1. The main contaminants in used engine oil

In response to the severe and escalating environmental and health threats posed by UEO, there is a critical and growing demand for effective and sustainable cleaning strategies. These strategies are essential for removing oil from aquatic systems and remediating contaminated soils, driven by the imperative to protect environmental ecosystems and public health. The purpose of this paper is to explore sustainable alternatives for the treatment of used engine oil. It reviews the potential of biomaterials, particularly those used in adsorption and bioremediation processes, as eco–friendly, cost–effective solutions for removing contaminants from UEO. By highlighting natural adsorbents like biochar and cellulose–based materials, as well as microbial and enzymatic approaches, the paper aims to provide a comprehensive understanding of current advancements, limitations, and future directions in biomaterial–based used engine oil remediation.

2. ADSORBENT BIOMATERIALS FOR USED ENGINE OIL TREATMENT

The global shift towards biomaterial–based approaches for used engine oil treatment is fundamentally driven by a dual imperative: to achieve superior environmental outcomes and to realize enhanced cost efficiencies compared to conventional methods. This indicates a strategic pivot in waste management paradigms. Sustainable solutions are increasingly favored due to their inherently low environmental impact, biodegradability, and demonstrated cost–effectiveness when compared to conventional physicochemical treatment methods [4]. Biomaterial–based approaches offer distinct advantages, including their cost–effectiveness, environmental sustainability, and the capacity to completely mineralize organic pollutants, thereby transforming them into less harmful substances. This means that the objective is not merely the removal of pollutants, but their removal through methods that minimize ecological footprint, valorize waste, and are economically viable in the long term, thereby embodying a holistic sustainability objective [4].

Adsorption is recognized as a highly efficient and promising approach for removing oil contaminants from various sources, fundamentally involving the adherence of pollutants to the surface of an adsorbent material. An ideal adsorbent should possess a high oil adsorption capacity, the ability to selectively separate oil from water, rapid adsorption kinetics, and the capacity to float on water for easy recovery. Furthermore, it must be recyclable, environmentally friendly, and reasonably inexpensive. Natural materials, particularly agricultural wastes, fulfill many of these criteria due to their abundance, frequent availability as residues, inherent biodegradability, and intrinsic oil absorbency [5].

Natural and modified agricultural wastes

The effectiveness of agricultural wastes as adsorbents stems from their porous structure, which provides a wealth of binding sites for pollutants. Their complex chemical composition, including cellulose, hemicellulose, lignin, pectin, and a variety of functional groups (such as hydroxyl, carboxyl, amino, phenolic, aldehydic, ketonic, and sulphydryl groups), enables the binding of metal ions and other contaminants. This binding occurs through diverse mechanisms, including complexation, ion exchange, physical adsorption, and surface micro–precipitation [6]. Crucially, hydrophobicity is a key property that ensures selective oil adsorption while repelling water [5].

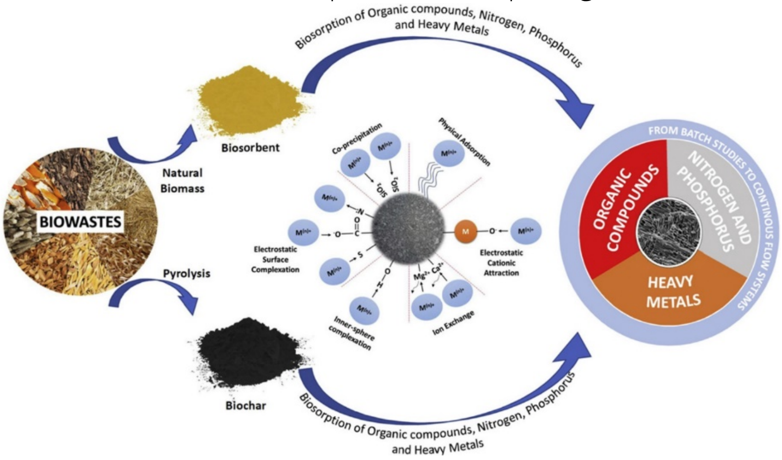

Figure 2. Flow of the biosorption process from biowaste [8]

To enhance their oleophilic (oil–attracting) and hydrophobic (water–repelling) properties, and thus improve overall adsorption performance, biosorbents derived from agricultural wastes are frequently subjected to physical or chemical treatments [5]. Chemical treatment involves the use of various chemical agents, such as acids (e.g., citric acid, nitric acid, phosphoric acid, sulfuric acid), alkalis (e.g., sodium hydroxide), or salts (e.g., potassium carbonate, sodium bicarbonate). These treatments aim to increase the number and accessibility of surface functional groups, develop the adsorbent's contact surface, increase its porosity, remove impurities, or enhance its inherent hydrophobicity. For instance, sodium hydroxide treatment can improve effectiveness by promoting the formation of galactouronic acid groups. Common physical modification methods include drying, pulverization (grinding into smaller particles), and pyrolysis [7]. Some advanced approaches integrate both physical and chemical methods, such as carbonization followed by chemical activation, to synergistically enhance pore opening and increase surface area [7].

The effectiveness of agricultural waste biosorbents is highly dependent on their intrinsic physical properties, such as porosity, density, and surface area, and their chemical composition, particularly the presence and accessibility of functional groups. These properties can be significantly enhanced through targeted physical and chemical modifications, indicating that the raw material is merely a foundation upon which performance is engineered [7]. This means that effective utilization of these biomaterials requires a deep understanding of material science and surface chemistry, moving beyond simple material selection to active material engineering.

The utilization of agricultural waste offers a dual benefit of waste valorization, reducing the environmental burden from agricultural residues, and effective pollution treatment. This positions them as highly sustainable and economically attractive solutions. However, this sustainability is contingent upon ensuring that the modification processes themselves remain energy–efficient and environmentally benign, preventing a shift of environmental burdens. The advantages of agricultural wastes can be lost if the cost of treatment outweighs the benefits due to energy–intensive and environmentally unfriendly processes, or if chemical modifiers introduce potentially toxic substances to water [5]. Therefore, true sustainability is not merely about the raw material's origin but encompasses the entire lifecycle, including the environmental impact and cost of its processing and modification.

A wide variety of natural and modified agricultural wastes can effectively adsorb used engine oil and its contaminants, as detailed below [5], [9–13]:

- Pomelo peel (PP): This material exhibits a natural gradient porous structure with pore sizes ranging from 10 to 1000 μm, and an average of 151±31 μm. Its low density allows it to float on water, and it possesses inherent hydrophobicity, evidenced by water contact angles between 105° and 115°. Pomelo peel rapidly absorbs various oils (e.g., canola oil, diesel, gasoline) with high capacities; granular PP, for example, demonstrated absorption capacities of 8.45 g/g for diesel, 7.8 g/g for gasoline, and 8.3 g/g for canola oil at 10°C. While effective, modification with NaOH can sometimes inadvertently reduce absorption capacity if it damages the fragile structural integrity of the peel. Beyond oil, pomelo peel can also effectively remove heavy metals like Pb(II) with a high efficiency of 96.12%.
- Animal hair, modified palm fibers, and polyurethane particles: These materials have been successfully utilized as adsorbent pads for oil removal from water, achieving a notable maximum absorption capacity of 3333 mg/g under optimal conditions (40°C, pH 7, 10 minutes contact time).
- Animal bones (ABs) and Anise residues (ARs): In comparative studies, animal bones exhibited superior oil removal capacity (45 mg/g, 94% removal efficiency) compared to anise residues (30 mg/g, 70% removal efficiency).
- Corn stalk: This agricultural waste has demonstrated biosorption efficiency for both crude and diesel oils, showing higher sorption for the lower viscosity diesel (29.3 g oil) compared to crude oil (23.9 g for 3mm film thickness). Furthermore, the addition of bacterial doses to corn stalk pads has been shown to enhance oil elimination.
- Rice husk (RH): Rice husk is an effective material for removing heavy metals (e.g., Pb, Cd, Zn, Ni, As) from water, with chemically treated RH generally exhibiting better adsorption efficiency than its untreated counterpart. It can also be effectively floated on oil–contaminated water to absorb oil, which is then skimmed off for removal. Modified forms, such as rice husk activated carbon (RHAC) loaded with ZnO nanoparticles, have been developed to further enhance performance.
- Coconut shell and palm kernel shell activated carbons: Activated carbons produced from these agricultural wastes have proven effective in removing certain heavy metals, including zinc, chromium, cadmium, and magnesium, from used engine oil. Specifically, coconut shell activated carbon showed efficacy for lead removal, though neither material was found suitable for the removal of copper or iron.
- Barley straw: Chemical modification through esterification with citric acid significantly improved the zinc sorption capacity of barley straw, while modification with methanol was found to reduce its effectiveness.
- Algal biomass (e.g., *Enteromorpha intestinalis*): This abundantly available biomass serves as a low–cost and environmentally friendly adsorbent for both crude and used engine oil. Studies indicate that it exhibits better adsorption for higher viscosity spent oil and is more efficient in seawater compared to freshwater.

Advanced bio–based adsorbents

Advanced bio–based materials like aerogels, chitosan, and various nanomaterials offer high–performance alternatives for oil treatment, often leveraging unique structural and surface properties. The superior performance of these advanced biomaterials, particularly in terms of high adsorption capacity, selectivity, and potential for reusability, stems from their engineered or intrinsic nanostructure and tailored surface chemistry. This signifies a move beyond simple natural materials to sophisticated, designed solutions. The effectiveness is rooted in their precise structural and chemical attributes at the nanoscale, with tailored and specialized designs and functionalization indicating a deliberate engineering approach to enhance performance.

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While highly effective in performance, the complex synthesis pathways and potentially higher production costs associated with some advanced biomaterials (e.g., specific nanomaterials, complex aerogel fabrication) might present significant challenges for their widespread, cost–effective industrial application.

Table 1. Comparative adsorption capacities and key properties of selected agricultural waste biosorbents for used engine oil [9–17]

Biosorbent type	Modification (if any)	Oil type treated	Maximum adsorption capacity/ removal efficiency	Key properties/ Mechanism
Pomelo peel (PP)	Granular	Diesel oil	8.45 g/g (at 10°C)	Porous structure, hydrophobicity, low density
Pomelo peel (PP)	Granular	Gasoline oil	7.8 g/g (at 10°C)	Porous structure, hydrophobicity, low density
Pomelo peel (PP)	None (dried PP)	Diesel oil	7.1 g/g (at 10°C)	Porous structure, hydrophobicity, low density
Pomelo peel (PP)	None (dried PP)	Gasoline oil	5.68 g/g (at 10°C)	Porous structure, hydrophobicity, low density
Pomelo peel (PP)	None	Pb contaminated oil	96.12% removal	Functional groups, pH sensitivity
Animal hair	None	Used engine oil	3333 mg/g	Adsorption process
Modified palm fibers	Modified	Used engine oil	3333 mg/g	Adsorption process
Polyurethane particles	None	Used engine oil	3333 mg/g	Adsorption process
Animal bones (ABs)	None	Used engine oil	45 mg/g (94% removal)	Adsorption process
Anise residues (ARs)	None	Used engine oil	30 mg/g (70% removal)	Adsorption process
Corn stalk	None	Diesel oil	29.3 ± 5.7 g oil	Lower viscosity, biosorption efficiency
Rice husk (RH)	Chemically treated	Heavy metals (Pb, Cd, Zn, Ni, As)	Improved adsorption efficiency	Functional groups, porous structure
Rice husk (RH)	None	Used engine oil	Effective absorption	Floats on water
Coconut shell Activated carbon	Chemical activation (K_2CO_3, $NaHCO_3$)	Zinc, Chromium, Cadmium, Magnesium, Lead	Effective removal	Large active surface area, porous structures
Palm kernel shell Activated carbon	Chemical activation (K_2CO_3, $NaHCO_3$)	Zinc, Chromium, Cadmium, Magnesium	Effective removal	Large active surface area, porous structures
Barley straw	Esterification with citric acid	Zinc	Significantly improved sorption capacity	Chemical modification
Algal biomass	None	Used engine oil	Better adsorption than crude oil	Low cost, environmentally friendly, abundant
Biochar	None	Used engine oil	1220 g/kg (optimum capacity)	Porous nature, hydrophobicity

This necessitates further research into developing scalable, energy–efficient, and environmentally friendly production methods. The complexity of these processes suggests higher costs, and the need for future research to improve efficiency and scalability, including developing hybrid carbon materials, nanocomposites, and environmentally friendly synthesis methods, directly points to current limitations in widespread adoption [14].

— Cellulose–based aerogels: Aerogels are recognized as exceptionally light, strong, and porous solid materials, synthesized by replacing the liquid component of a gel with a gas. Cellulose–based aerogels uniquely combine the renewability, biocompatibility, and biodegradability of cellulose with advantageous properties such as extremely low density (e.g., 0.04 g cm³), high porosity (e.g., 96%), and a large specific surface area. They demonstrate significant hydrophobicity (e.g., a water contact angle of 141°) and exhibit selective adsorption of oils while actively repelling water. A reed–based cellulose aerogel, for instance, showed a superior crude oil adsorption capacity of 35 g. The ability of cellulose–based gels to absorb large volumes of oil while maintaining their structural integrity makes them highly attractive alternatives to traditional, often less efficient or more environmentally damaging, oil spill cleanup methods. The general preparation process involves three key steps: dissolving or dispersing cellulose (or its derivatives), forming a cellulose gel through a sol–gel process, and then drying the gel while largely preserving its three–dimensional porous structure. Further modification, such as with methyltrimethoxysilane, can be applied to enhance specific properties [15].

— Chitosan and its derivatives: Chitosan, a natural polymer derived from chitin, has demonstrated superior oil removal capabilities compared to conventional adsorbents like activated carbon and bentonite. It achieved an impressive 99% residual oil removal from palm oil mill effluent

(POME) at a low dosage (0.5 g) and under acidic pH conditions (4.0–5.0). Its inherent biodegradability and high affinity for emulsified oil droplets make chitosan a promising candidate for wastewater treatment, potentially serving as an eco–friendly replacement for synthetic flocculants [16].

— Nanomaterials derived from biomass: One–dimensional (1D) materials such as carbon nanotubes, metallic nanowires, nanofibers, and nanorods, along with two–dimensional (2D) materials like graphene, graphitic carbon nitride (g–C_3N_4) and MoS_2, offer distinct advantages. These include high length–to–diameter ratios, exceptionally large specific surface areas, and the potential for targeted hydrophobic surface modifications, which enable selective oil adsorption while repelling water. Three–dimensional (3D) porous nanostructures, including magnetic nanoparticles, magnetic nanocomposites, and magnetic hydrogels, combine high porosity, precise functional group arrangement, and magnetic responsivity. These features facilitate multi–level adsorption, effective contaminant removal, and convenient magnetic separation. Beyond direct adsorption, nanoparticles can also significantly enhance bioremediation processes by acting as emulsifiers. This increases the oil–water interfacial area and provides surfaces for microbial attachment, thereby boosting the bioavailability of oil and leading to increased degradation rates by microorganisms [17].

3. BIOCHAR

Biochar is a versatile and sustainable adsorbent for used engine oil, with properties tunable by production conditions and modifications. It is a stable, carbon–rich substance produced from organic material (biomass, including agricultural, aquaculture, wood, and fiber processing wastes) through pyrolysis, a process where biomass is heated without oxygen, resulting in a charred black material. The specific properties of biochar are highly dependent on the feedstock used, the preparation method, and crucially, the pyrolysis temperature, which is typically below 700°C for biochar, distinguishing it from activated carbon which is often produced above 700°C. Higher pyrolysis temperatures (e.g., exceeding 600°C) generally result in biochar that is more stable, more hydrophobic, and possesses higher specific surface areas and increased microporosity. The mineral content and pH of the resulting biochar can vary greatly depending on the feedstock used; for instance, poultry litter biochar has a higher mineral content, and pH values can range from 4.6 to 9.3 depending on the source material. As temperature increases, the porosity and particle size of biochar also tend to increase, with smaller particles generally having a larger surface area and better cation exchange capacity (CEC) [18].

Figure 3. The use of biochar in treating used engine oil

Key properties that contribute to biochar's excellent performance as an adsorbent include its porous nature, high carbon content, large specific surface area (SSA), inherent hydrophobicity, and the ease with which its surface can be functionalized. The composition of biochar in terms of carbon, nitrogen, sulfur, and oxygen also affects its chemical properties. Biochar with a hydrogen–to–carbon (H/C) ratio of less than or equal to 0.7 and an oxygen–to–carbon (O/C) ratio of approximately 0.4 demonstrates remarkable stability and can persist in soil for over a millennium [18].

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For biochar, the adsorbtion process is driven by its unique physicochemical properties. Biochar's porous nature, high carbon content, large specific surface area and inherent hydrophobicity provide numerous active sites for contaminants to bind. The mechanisms of adsorption can involve various physical and chemical processes, including ion exchange, complexation, electrostatic attraction, and surface precipitation, particularly for heavy metals. Organic pollutants, such as hydrocarbons, are primarily adsorbed through physisorption and chemisorption, where the oil molecules are trapped within the porous arrays and interact with the biochar's surface functional groups. The presence of functional groups like hydroxyl, carboxyl, and amine on the biochar surface enhances its ability to bind with various contaminants [19].

The efficiency of biochar's adsorption process is influenced by several key factors. These include the contact time between the oil and biochar, temperature, the concentration of contaminants in the oil, the pH of the solution, and the particle size of the biochar. For instance, increasing contact time generally allows more pollutants to bind until equilibrium is reached. Temperature can affect both the rate and capacity of adsorption, with optimal temperatures varying depending on the specific oil and biochar type. The initial concentration of contaminants also plays a role, as higher concentrations can lead to increased adsorption capacity until the active sites on the biochar become saturated. pH is crucial, as it influences the surface charge of the adsorbent and the speciation of metal ions, thereby affecting binding affinity. Smaller biochar particle sizes typically offer a larger surface area, which can enhance adsorption efficiency. To understand and predict the adsorption behavior, researchers utilize adsorption isotherm models (such as Langmuir and Freundlich) and kinetic models (like pseudo–first–order and pseudo–second–order), which describe the relationship between the adsorbed amount and the equilibrium concentration, and the rate of adsorption, respectively. These models provide critical insights into the adsorption mechanism, surface properties, and the overall applicability of biochar for treating used engine oil [19].

Biochar is considered an environmentally friendly, sustainable, and cost–effective substitute for waste management, climate protection, soil improvement, and wastewater treatment. The preparation of biochar does not involve the use of harmful chemicals and can be prepared simply from any bio–waste, making it a "green adsorbent." Its wide availability and ease of collection of raw materials further enhance its appeal. The economic viability and overall sustainability of biochar production extend beyond its direct application as an adsorbent. Its profitability is increasingly tied to its potential as a carbon offset and the value derived from co–products such as bio–oil and pyrolysis gas. Converting biomass into biochar effectively halts much of the decomposition of biomass that would have led to the release of carbon dioxide (CO_2) and other greenhouse gases, thereby storing carbon more stably in soils (approximately 50% of the original carbon is stored in biochar compared to 3% retained after burning and less than 20% after decomposition). The assumed carbon offset value for biochar is projected to increase from $20 per metric ton in 2015 to $60 in 2030. Bio–oil, a dense liquid also created through pyrolysis, can be refined into "green" gasoline and diesel, further contributing to the economic viability. This suggests that biochar's role in used engine oil treatment can be integrated into broader sustainable energy and waste management strategies, enhancing its appeal as a holistic solution [18].

4. BIOREMEDIATION APPROACHES FOR USED ENGINE OIL DEGRADATION

Bioremediation is a biological treatment method that harnesses the metabolic capabilities of microorganisms to degrade and mineralize organic contaminants present in used engine oil. This approach offers several distinct advantages over conventional physicochemical treatments, being non–invasive, relatively simple to implement, cost–effective, and environmentally sustainable. It can be applied effectively over large contaminated areas and aims to transform pollutants into non–toxic end products, thereby restoring environmental integrity [1].

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Microbial bioremediation

The success of microbial bioremediation is critically dependent on optimizing a complex interplay of environmental factors and leveraging specific microbial capabilities. This highlights that successful bioremediation is not merely about identifying a degrading microbe but about creating and maintaining an optimal microenvironment for its activity.

Hydrocarbonoclastic bacteria play a pivotal role in this process. Specific strains identified include Pseudomonas oleovorans strain NMA, which demonstrated remarkable degradation efficiency of 98–99% within 7 days, utilizing used engine oil as its sole carbon and energy source and effectively transforming major components like methyl hexane, pyrene, and phytane. Other highly effective bacterial genera and species reported include Pseudomonas alcaligenes LR14 (59% degradation), Klebsiella aerogenes CR21 (62%), Klebsiella pneumonia CR23 (58%), Bacillus coagulans CR31 (45%), Pseudomonas putrefacience CR33 (68%), as well as Nocardia, Acinetobacter, Flavobacterium, Micrococcus, Arthrobacter, Corynebacterium, Achromobacter, Rhodococcus, Alcaligenes, Mycobacterium, Burkholderia, Collimonas, Dietzia, Gordonia, Ralstonia, Sphingomonas, Variovorax, and Enterobacter species. Research indicates that microbial consortia (mixtures of different species) are often more effective at degrading petroleum hydrocarbons than single isolates due to synergistic effects. This suggests that a multi–species approach might be superior, as different microorganisms can target different components of the complex oil mixture or work together to enhance degradation [1].

Hydrocarbon–utilizing fungi are also significant contributors to bioremediation. Genera such as Aspergillus, Cephalosporium, Penicillium, Cunninghamella, Fusarium, Mucor, Phanerochaete, Rhodotorula, Sporobolomyces, and Trichoderma have been identified. Specific effective species include Talaromyces flavus, which recorded the highest percentage of spent engine oil biodegradation at 69.66% for 5% UEO contamination, and Aspergillus glaucus, which showed 66.16% degradation for 10% UEO contamination. Certain yeast species, including Candida lipolytica, Rhodotorula mucilaginosa, Geotrichum sp, and Trichosporon mucoides, have also been reported to possess the ability to degrade petroleum compounds [4].

Two major bioremediation approaches are employed. Bioaugmentation involves the introduction or "seeding" of known oil–degrading microorganisms (e.g., specific bacterial or fungal isolates) into a contaminated environment to enhance or supplement the activity of the indigenous microbial community.

Biostimulation focuses on stimulating the growth and metabolic activity of existing, indigenous oil–degrading microorganisms by providing essential nutrients that may be limiting their optimal growth, primarily nitrogen and phosphorus. A critical aspect of biostimulation is the role of biosurfactant–producing microorganisms. Biosurfactants are surface–active agents that lower the surface tension of hydrocarbons, thereby enhancing their bioavailability either through solubilization or surface modification, making them more accessible for microbial degradation. The ability of biosurfactants to overcome the inherent insolubility of oil is a key mechanism by which microbes facilitate degradation [4].

Optimal environmental conditions are paramount for effective bioremediation. The growth rate of oil–degrading bacteria is frequently limited by the availability of macronutrients like nitrogen and phosphorus. A carbon:nitrogen:phosphorus (C:N:P) ratio of 100:10:2 is commonly reported as sufficient for optimal microbial growth and biodegradation. Hydrocarbon biodegradation is predominantly an aerobic process, necessitating the presence of molecular oxygen for the initial catabolic steps mediated by oxygenase enzymes. Temperature significantly influences both the rate of degradation and the composition of the microbial community. An optimal temperature range, typically 30–40°C, favors the metabolic activities of numerous microbial species within a consortium, thereby increasing the overall degradation rate. pH plays a crucial role in microbial

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growth and enzyme activity. Most bacteria exhibit optimal growth within a narrow pH range of 6.7 to 7.5. In soil environments, a pH range of 7 to 8 generally supports optimal microbial degradation. Water is indispensable for microbial growth, constituting a large proportion of cell cytoplasm and serving as the fundamental solvent for enzymatic reactions and material transport. Lastly, high concentrations of hydrocarbons can inhibit biodegradation, either by creating nutrient or oxygen limitations or through the toxic effects exerted by volatile hydrocarbons on microbial populations.
While microbial bioremediation is promising, the scalability of bioaugmentation (introducing external microbes) can be economically and ecologically unsustainable in field applications, and biostimulation can inadvertently lead to eutrophication. These are significant practical limitations that extend beyond the basic effectiveness of bioremediation. This points to a critical need for advanced strategies, such as slow–release nutrient formulations, encapsulating agents for microbes, and the development of genetically engineered microorganisms (GEMs), to achieve sustainable and efficient large–scale bioremediation. These proposed solutions indicate that current research is actively addressing these hurdles through advanced engineering and biotechnological interventions, highlighting a deeper understanding of the practical challenges in scaling up biological processes and the innovative research directions required to translate laboratory successes into real–world, sustainable applications [4].

Enzymatic degradation

Biocatalysis, which utilizes enzymes, offers novel pathways to enhance bioremediation strategies by providing highly specific biological catalysts capable of breaking down complex organic compounds. The use of free enzymes in remediation processes avoids the potential environmental concerns associated with the release of exotic or genetically modified organisms [20].
Research suggests that certain nonaromatic hydrocarbons, such as butane and methane, can be employed to facilitate the breakdown of used motor oil, with a reported ratio of 10 parts hydrocarbon to 1 part used motor oil. While specific enzymes for direct motor oil degradation are still an active area of research, the broader field of biocatalysis is advancing rapidly. The application of molecular tools is expected to significantly improve bioprospecting research, enhance enzyme yield recovery, and increase enzyme specificity, thereby improving cost–benefit ratios for enzymatic remediation approaches. This indicates a future where enzymes could play a more prominent and efficient role in treating complex hydrocarbon mixtures like used engine oil [20].

5. CONCLUSIONS

Treating used engine oil, a complex mixture of hydrocarbons and toxic contaminants, requires innovative and sustainable solutions that surpass traditional methods. Natural and modified agricultural waste–based adsorbents, such as pomelo peel, animal bones and plant residues, show strong potential due to their high adsorption capacity and the added benefit of waste valorization. Their performance is significantly improved through physical and chemical modifications that tailor pore structure, surface properties, and functional groups. More advanced solutions, including cellulose aerogels, chitosan, and nanomaterials, offer high efficiency, selectivity, and reusability, thanks to engineered nanostructures. However, challenges remain in developing scalable, cost–effective, and sustainable production methods. Biochar is a versatile adsorbent whose effectiveness depends on pyrolysis conditions and post–treatment. Its economic appeal is enhanced by its role in carbon offsetting and the potential value of co–products like bio–oil, making it relevant within integrated waste and energy systems.
In addition to adsorption, microbial bioremediation presents a highly effective and eco–friendly method for degrading engine oil, using bacteria and fungi under optimized conditions. Yet, scaling these methods requires innovations such as controlled nutrient release and microbial encapsulation. Enzymatic degradation also holds future potential, especially as molecular technologies evolve to improve enzyme performance.

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Future efforts should focus on developing integrated treatment systems that combine the strengths of different biomaterial approaches, such as adsorption for bulk removal and heavy metal sequestration, followed by microbial bioremediation for complete hydrocarbon mineralization. To advance current remediation strategies, it is imperative to develop innovative methods for the safe and beneficial disposal or reuse of spent biomaterials, potentially through co–processing with other waste streams or conversion into secondary products, to mitigate the environmental burden of accumulated contaminants.

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