Oil Recovery Technology: A Multi-Dimensional Solution from Pollution Control to Resource Recovery

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Abstract: This paper conducts a multi-dimensional discussion on petroleum recovery technologies. It first elaborates on the current situation of petroleum pollution, including the leakage risks in various links from exploration to processing, major leakage incidents from 2000 to 2025, their impacts on marine, terrestrial, and freshwater ecosystems, as well as the severe hazards to the environment, human health, and economic development. Then, it analyzes the necessity of petroleum recovery and utilization, involving aspects such as resource scarcity, ecological protection, and policy promotion. Subsequently, it details the principles, effects, influencing factors, advantages, and disadvantages of existing physical, chemical, biological, and combined recovery technologies, and evaluates the removal rates and costs of various technologies. It also points out the bottlenecks faced by current technologies, such as poor environmental adaptability of microorganisms in biological recovery, high energy consumption in physical and chemical recovery, high costs of emerging technologies, as well as issues in policies and standardization. Finally, it prospects that future technologies will develop towards genetically engineered microorganisms, nanomaterials, and intelligent monitoring and restoration, emphasizing the importance of accelerating technological innovation and standardization.

Keywords: Oil Recovery Technology; Pollution Control; Biodegradation

1. Introduction

The risk of leakage exists in all aspects of oil from exploration and extraction to storage, transportation and processing. During extraction, well blowouts may lead to large-scale leakage of crude oil; pipelines often rupture and leak during transportation due to corrosion, third-party damage, or operational errors, etc., and oil tanker collisions or reefs can also lead to oil leakage resulting in oil pollution from marine oil spills; and oil storage facilities may collapse due to structural deterioration or extreme climatic influences[1]. For various reasons, oil spills occur year-round. From 2000 to 2025, several serious spills have occurred, with serious damage to the ecology and economy. In 2002, the Bahamas oil tanker “Prestige” suffered a storm off the coast of Galicia, Spain, spilling about 63,000 tons of heavy oil, polluting 3,000 kilometers of coastline in Spain, France, and Portugal, causing 200,000 sea turtles to die in the sea. It polluted 3,000kilometers of coastline in Spain, France and Portugal, killing 200,000 seabirds and causing billions of euros in damage to the fishing industry. In 2010, the Deepwater Horizon drilling rig exploded and sank in the U.S. Gulf of Mexico. The spill lasted 87 days, releasing about 670,000 tons of crude oil, polluting 1,800kilometers of coastline, causing the deaths of millions of marine organisms, and causing incalculable ecological losses Figure 2. In 2018, the Panamanian oil tanker Sanger collided with a Hong Kong Chinese cargo ship in the East China Sea, leaking about 13,000 tons of condensate and causing widespread marine pollution. In 2020, the diesel fuel storage tanks at the Norilsk thermal power plant in Russia collapsed due to the thawing of permafrost leading to the collapse of the foundations, and about 21,000tons of diesel fuel leaked, polluting the surrounding 350square kilometers of the Arctic region. square kilometers of the Arctic region. Oil pollution is a complex, multi-media environmental problem that affects more than just marine ecosystems, but also terrestrial and freshwater ecosystems. According to statistics, oil spills account for about 45% of marine pollution, 35% of soil pollution and 20% of groundwater pollution Figure 1.

2. Research Status

2.1 The Need for Recycling

The petroleum industry has a great role to play in promoting the improvement of the national economy, which can ensure the smooth development of various industries, and at the same time can provide reliable material energy for people's daily life. However, oil is a non-renewable resource, oil is microorganisms (such as algae, plankton) and a small amount of higher plant residues after death, the remains of the body with the water flow to the bottom, and sediment, minerals together to form organic matter-enriched sediments[2]. The whole process takes hundreds of millions of years, so after oil has been extracted and used by humans, it cannot be replenished naturally in the short term. With the acceleration of global industrialization, oil resources are becoming more and more scarce, and oil recovery technology has come into being, which is of great significance in mitigating oil pollution, protecting the environment and realizing the reuse of resources[3].

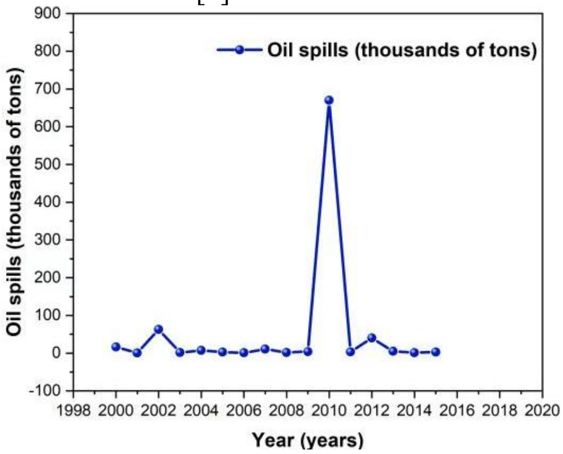

Figure 1. Oil Spill Variability Curve by Year

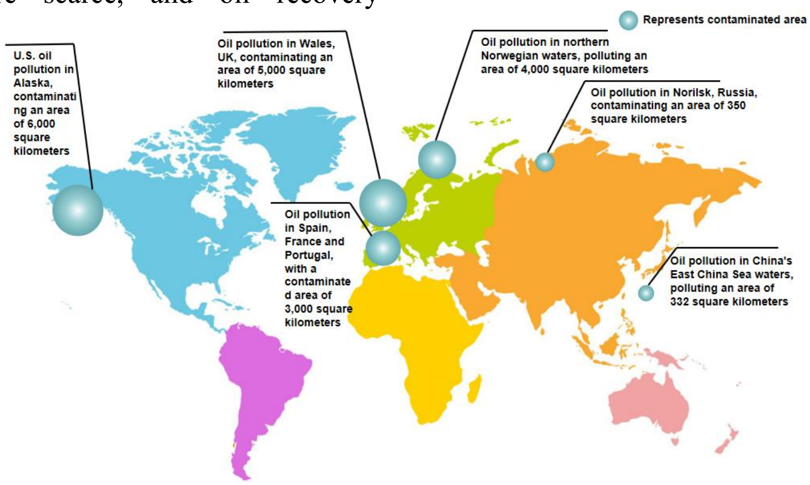

Figure 2. Distribution of Oil Pollution Worldwide

For example, in the field of lubricating oil production, most of the so-called "waste lubricating oil" in fact, not completely lose the use of value, in recent research, through the activated carbon adsorption regeneration of waste lubricating oil technology can make the recovery rate of up to 90% or more, which means that the recycling technology can be used for petroleum products can be re-converted into a usable resource to make the "waste oil" back to life, greatly enhancing the efficiency of resource utilization. This means that the recycling technology can transform used petroleum products into usable resources, giving new life to "waste oil" and greatly improving the efficiency of resource utilization [4]. According to the China Renewable Resources Recycling Association's relevant data show that the production of 1 ton of new lubricants need to consume 7-9 tons of crude oil, in the extraction, transportation, refining the whole process of carbon emissions of about 5-7 tons of CO_2. 1 ton of waste lubricating oil and regeneration of lubricating oil and regeneration of the same quality, only need to consume 0.5 - 1 tons of crude oil equivalent, carbon emissions of about 1-1.5 tons of CO_2.

Oil recovery technology plays a prominent role in ecological protection. Once oil and its products enter the environment, they can cause serious pollution. Take the marine oil spill for example, the oil film will block the gas exchange between seawater and the atmosphere, resulting in the death of marine organisms due to lack of oxygen and asphyxiation, and also destroying the food chain of the marine ecosystem, affecting the sustainable development of fishery resources. After the soil is polluted by oil, its structure and physicochemical properties will be changed, microbial activity will be inhibited, the growth of crops will be hindered, and even groundwater will be polluted through soil infiltration, which will threaten the safety of drinking water for human beings. Efficient oil recovery technology can significantly reduce the degree of harm caused by such pollution incidents. This is because recycling oil reduces the need to extract and process new oil resources, while oil extraction, transportation and refining processes consume large amounts of energy and emit greenhouse gases. Recovery technologies cut energy consumption at the source and reduce carbon emissions.

From the policy dimension, States are increasingly focusing on oil pollution prevention and resource recycling. The international community and many countries have adopted a series of policies and measures to address the challenges of climate change and marine oil pollution. These policies include the signing and implementation of international environmental agreements, such as the Paris Agreement, as well as greenhouse gas emission reduction targets and environmental regulations set by countries. In response to oil spills from ships and ports, in the past five years, the International Maritime Organization (IMO) and other organizations have introduced a number of key regulations to reduce oil spills from ships and ports, mainly centered on the revision of the International Convention for the Prevention of Pollution from Ships (MARPOL), covering various aspects such as emission limitations, data management, and equipment requirements[5]. China's introduction of the Soil Pollution Prevention and Control Law (Draft) clearly stipulates that wastewater, waste gas and solid waste generated in soil pollution risk control and remediation activities should be treated and disposed of in accordance with the provisions of the law to prevent soil pollution. This covers oil contaminated soil treatment and oil recovery related work, providing legal support for the application and promotion of oil recovery technology[6]. The European Union's “Environmental Liability Directive” also requires that the responsible party for environmental pollution incidents such as oil spills must take the necessary measures to repair the polluted environment and promote oil recovery and pollution control. Under the impetus of such policies, oil recovery technology continues to innovate and progress, and the scope of application continues to expand[7].

Oil recovery technology is a powerful means to alleviate the shortage of oil resources, reduce environmental pollution and help cope with climate change. In the context of global sustainable development, increasing investment in research and development of oil recovery technology, improving relevant policies and regulations, and increasing the popularization rate of the technology are inevitable choices to realize a win-win situation between economic development and environmental protection, which is of great significance to the long-term development of human society.

2.2 Existing Technical Means of Treatment

Currently, oil treatment methods are mainly categorized into physical, chemical, and biological methods. Due to the serious harm of oil spills, countries and governments have put forward higher technical requirements for oil treatment[8]. Physical recovery methods are mainly adsorption of oil-absorbing materials and various forms of skimmer recovery[9], for the oil spill on the sea surface and oil pollution in the coastal zone, the physical method is the most effective method compared to the chemical method and biological method, and the adsorption method stands out among these two physical methods, and the aerogel adsorbent made of chitosan has many advantages compared to the other traditional adsorbent with a much higher adsorption capacity[10]. However, in general, although adsorbents can effectively filter the color and odor in the sewage, the adsorbent dosage is difficult to accurately control is easy to cause incomplete decontamination or cause secondary pollution, and the treatment cost is high[11]. Chemical recovery methods mainly include solvent extraction, catalytic cracking, emulsification and dispersant, etc. The biggest problem when using chemical recovery methods is secondary pollution, and the excessive use of chemical reagents will cause re-contamination of the ocean. Bio-recovery methods mainly include plant and animal enrichment and microbial degradation. Among them, activated sludge treatment technology is characterized by low cost. However, the biological method has the disadvantages of slow recovery rate and high cost, whether it is plant and animal enrichment or using microbial degradation, so the method is not applicable to sudden large-scale oil spills[12].

3. Oil Recovery Technology

3.1 Physical Recycling Technology

3.1.1 Absorbent materialng

Oil-absorbing materials can be categorized into natural absorbing materials and synthetic absorbing materials(Table 1). Natural adsorbent materials are generally derived from agricultural by-products, forestry wastes and domestic wastes, such as straw, wood chips, cotton fibers, graphite, etc., which have the characteristics of low price and fast adsorption speed, but their oil adsorption capacity is smaller than that of synthetic adsorbent materials[13-14]. When the stacking density of poplar wadding fiber is 0.002g/cm^3, 1g of fiber can adsorb 50~60g of heavy oil; when the stacking density is 0.005g/cm^3, 1g of fiber can adsorb 182~211g of heavy oil, and it can be reused by extruding[15]. The manufacture of chemically synthesized adsorbent materials by modification and other means can greatly improve the oil adsorption properties of natural materials. Cellulose aerogels composed of poplar floss fibers were used to prepare pressure-sensitive and conductive (PSC) carbon aerogels. The resulting PSC aerogels showed high absorption of oil and organic liquids (80-161g/g)[16]. Nguyen et al. pretreated barley straw with three different pretreatments, alkali, dilute acid and acidified glycerol to obtain fibers, which were subsequently processed and modified to obtain cellulosic aerogels, and the cellulosic aerogels synthesized all possessed up to 30 times of their own weight in oil adsorption capacity and excellent storage capacity Fiber carbon aerogels (CCAs) were prepared from cotton pulp by Wang et al.) The adsorption capacity of the prepared material for different oils and organic solvents could be up to 25-55 times of its own weight[17]. Zhang et al. prepared a kapok/cellulose aerogel for waste oil treatment by simple freeze-drying and surface modification, which was highly efficient and economical. This aerogel exhibited excellent oil absorption (141.9g/g) and retention (97.7%), as well as excellent selective adsorption properties, making it an ideal absorbent for oil spill cleanup[18]. In addition to aerogels, synthetic materials include high oil-absorbing resins and films[13].

Table 1. Physical Recycling Technology

Categorization	Recycling technology	Principle	Removal effect	Factor	Advantages and disadvantages
Physical recycling technology	Absorbent material	Oil adsorption via natural/synthetic materials.	Natural materials absorb 50-200x weight; synthetics like aerogel up to 80-161g/g.	Material type, structure, modification process, oil type	Pros: Cheap renewable naturals; efficient, selective reusable synthetics. Cons: Low absorption/high regeneration energy.
	Machinery Recycling	Floating oil removal via skimmers, booms, mechanical separation.	80-90% removal in emergency treatment	Equipment type, sea state, oil thickness, operating parameters	Pros: Efficient emergency treatment, no chemicals, no secondary pollution. Cons: High equipment/transport/fuel costs.

Wang Ziru et al. prepared a new type of composite high oil-absorbent resin by graft copolymerization method using ethyl cellulose (EC) made from waste cotton fabric as the matrix, methyl methacrylate (MMA) and butyl acrylate (BA) as the grafting monomers, benzoyl peroxide (BPO) as the initiator, and N, N-methylene bisacrylamide (MBA) as the cross-linking agent. The results showed that the adsorption of trichloromethane, dichloromethane, toluene, and o-xylene by this oil-absorbing resin reached 31.2, 25.2, 15.5, and 17.4g/g, respectively[19]. Wang Xiaohua et al. used octadecyl acrylate as the main monomer, together with wood pulp cellulose, MBA as the cross-linking agent, BPO as the initiator, and poly (vinyl alcohol) (PVA) as the dispersant, and polymerized into a high oil-absorbent resin by suspension polymerization method, and by adjusting the dosage of the initiator and the dispersant etc., it could adsorb 47.993 times of its own oil quantity for carbon tetrachloride, and also 21.373 times of its own oil quantity for gasoline[20].

3.1.2 Machinery Recycling

Skimmer is a mechanical device used to remove oil spills from the water surface, skimmer can be used in offshore platform blowout accidents, when the crude oil leaks to the sea surface, the skimmer can be quickly deployed to the scene, through the oil boom will be the oil spill containment and concentration, and then use the physical separation mechanism to remove the oil layer from the water surface, and then subsequently recycled[21]. The design logic of oil skimmers is mainly based on the density differences and physical separation properties of different liquids. Oil is usually less dense than water (e.g., the density of crude oil is about 0.8-0.9g/cm³, and water is 1g/cm³), and it naturally floats on the surface of the water to form an oil layer. Oil skimmer will separate the floating oil and water through mechanical devices, realizing the recycling of oil and water purification. There is no need to use chemicals in this process, avoiding secondary pollution. There are various types of oil skimmers, which can be categorized into centrifugal skimmers, weir skimmers, tubular skimmers, inclined plate skimmers, etc.[22]. These skimmers are usually composed of skimmer heads and auxiliary equipment, and the recycling performance depends on the structural form of the skimmer head. In order to improve the oil phase content and recovery efficiency of oil spill recovery mixtures, An Wei et al. proposed a concentrated vortex skimmer based on surface vortex and cyclone separation technology, and the recovery efficiency could reach more than 60% through data simulation and actual testing[23]. In addition, it was found that the recovery efficiency showed a linear correlation with the diversion ratio, and with the gradual increase of the diversion ratio, the recovery efficiency would then gradually increase in a linear trend. The device can form a stable vortex and carry out oil spill recovery operations under the conditions of equivalent tertiary sea state waves and small movement of the skimmer itself[23]. Ma Xukai proposed a new type of tubular skimmer for a typical contamination problem that may occur during the operation of rolling mills (metal rolling and processing equipment) - hydraulic oil and lubricating oil leakage mixed into the emulsion and diffused with the circulatory system. When the oil content in the emulsion exceeds a critical value, its lubricating properties will be significantly reduced, which in turn leads to rolling process strip surface due to insufficient lubrication and scratches and other quality defects. Therefore, the skimmer is the key equipment for removing floating oil. This equipment can improve the removal rate of waste oil without chemical contamination, and has considerable economic value[24]. LAMOR LRB skimmer is a kind of high-efficiency oil spill recovery equipment developed by LAMOR Finland, based on the mature LAMOR hard brush wheel technology, combining the high-efficiency skimming function of the brush skimmer with the scraping and digging function of the excavator's bucket, which is mainly designed for the cleanup of pits and pits on land, shore, marshy areas or frozen areas, and is also used for the cleanup of the oil spill in the process of rolling. , marsh areas or frozen waters, but is suitable for almost all types of spills. Currently, there are no manufacturers of this type of equipment in China[21].

3.2 Chemical Recovery Technology

3.2.1 Solvent extraction

Extraction is a technique that utilizes the difference in solubility of substances in different solvents to achieve separation(Table 2). The main components of petroleum are hydrocarbons (such as alkanes, aromatics, etc.). According to the principle of “similar solubility”, the extractant should be selected and petroleum polarity similar organic solvents (such as n-hexane[25], carbon tetrachloride[26], dichloromethane, etc.), or has a specific functional group of surfactant extractant. These extractant molecules and petroleum molecules between the force (such as van der Waals forces) is strong, through contact with the petroleum from the aqueous phase or solid media “extraction” to the extractant phase, so as to realize the separation. Due to the high cost of extractant and most organic solvents have toxicity and volatility (e.g. Carbon tetrachloride is a carcinogen), if not handled properly can easily cause secondary pollution, so solvent extraction is usually applied to the treatment of low-concentration oil contamination, marine oil spill emergency response, laboratory pre-treatment of the three aspects. When the oil phase is a continuous phase (such as a large number of floating oil), the physical method (such as skimmer) is more direct and efficient. For petroleum hydrocarbons in soil, He Guozhong et al. chose acetone-dichloromethane

(1:1) and acetone-hexane (1:1) as the extraction solvents, and set up two different sample concentrations of 46.5 mg/kg and 310 mg/kg, respectively. The experiments found that, for rapid solvent extraction of petroleum hydrocarbons (C_{10}-C_{40}) in soil, acetone-dichloromethane (1:1) was used as the solvent for the extraction efficiency (about 90%) was higher than that of acetone-hexane (1:1) as solvent (about 77%)[25]. For petroleum-based substances in water bodies, carbon tetrachloride is usually used as an extractant. However, due to the volatility and high toxicity of carbon tetrachloride, which is a serious hazard to human health and destructive to the atmospheric ozone layer, the United Nations Environment Programme (UNEP) has stipulated that the production and consumption of carbon tetrachloride should be completely stopped from January 1, 2010 onwards. Therefore, Chengmin Zhang et al. explored whether perchloroethylene can be used as a substitute for carbon tetrachloride extractant and conducted experiments on the extraction efficiency and stability of the two. The study showed that perchloroethylene and carbon tetrachloride have the same extraction effect, the same reproducibility and precision, and perchloroethylene is more stable than carbon tetrachloride under the conditions of sealing, room temperature, and no direct sunlight, which indicates that perchloroethylene can be completely used as a substitute for carbon tetrachloride[26].

Table 2. Chemical Recovery Technology

Chemical Recovery Technology	Solvent extraction	Solvent/surfactant extraction via similar solubility.	Removal rate 77%-90%	Temperature, pressure, solvent type, oil phase concentration	Pros: Fits low-concentration oil, lab pretreatment. Cons: Toxic, costly solvents, secondary pollution risk.
	Catalytic cracking	Catalytic conversion/cleanup of heavy/residual oils.	Degrades large hydrocarbons but forms coke/harmful gases.	Catalyst type, process parameters, feedstock composition	Pros: Better oil utilization, higher conversion efficiency. Cons: Catalyst loss risks acidification; coke/side reactions/energy issues.
	oil condensate	Oil condensed via cross-linking with booms/skimmers.	Promotes aggregation for recovery; sole effect depends on oil properties.	Oil type, temperature, pH, type of oil condensate	Pros: Rapid oil immobilization in emergencies, reduces spreading. Cons: Ecosystem impact, toxic condensates.

The recovery efficiency of petroleum by extraction method is affected by the conditions of temperature and pressure, Yang Li et al. explored the effect of temperature and pressure on the extraction solvent, and used n-hexane-dichloromethane mixture with volume ratio of 1:1 as the extractant, and experimented the effect of different extraction pressures (8.27, 10.34, 12.41, and 13.79MPa) on the mass concentration of the oil at extraction temperature of 100°C, respectively, as follows The extraction effects of different extraction pressures (8.27, 10.34, 12.41 and 13.79MPa) on petroleum hydrocarbons (C_{10}~C_{40}) in solid waste spiked samples with mass concentrations of 31.0, 155 and 248 mg/L were investigated, and it was found that the recoveries of petroleum hydrocarbons did not increase significantly with the increase of extraction pressure; whereas, the extractions of petroleum hydrocarbons in solid waste spiked samples with mass concentration of 31.0, 155, 248 mg/L were investigated at extraction pressures of 10.34 MPa and with different extraction temperatures (80°C, 100°C and 120°C), 155 and 248 mg/L of petroleum hydrocarbons (C_{10}~C_{40}) in solid waste spiked samples, and it was found that the recoveries of petroleum hydrocarbons (C_{10}~C_{40}) ranged from 67.7% to 74.1%, from 80.6% to 89.5%, and from 74.1% to 89.9%, respectively, when the extraction temperatures were 80°C, 100°C, and 120°C[27]. 3.2.2 Catalytic cracking

Deep chemical conversion of primary process products (e.g. heavy oils, residual oils) requires secondary process catalysts, which are generally classified as catalytic cracking catalysts, catalytic hydrogenation catalysts, catalytic reforming catalysts and alkylation catalysts. At present, the most researched catalysts are catalytic cracking catalysts and catalytic hydrogenation catalysts. FCC catalysts are used to convert heavy oils (e.g., reduced-pressure distillates, residual oils) into light products such as gasoline, diesel, and liquefied petroleum gas (LPG). The catalytic hydrogenation catalyst acts to crack large molecules into small molecules of hydrocarbons and remove harmful substances such as sulfur, nitrogen, and heavy metals from heavy oils[28]. Optimization measures for catalytic cracking technology mainly include four aspects: preferred catalyst system, strict control of process parameters, coordination of process flow and enhancement of environmental protection and energy saving in the application of process technology[29]. For different types of oil, we need to flexibly select different catalysts and adjust them according to the actual situation. For example, when the catalytic cracking process technology is mainly used for the production of light hydrocarbon products, acid catalysts need to be selected in order to increase the yield of these products. If more side reactions are found on the acid catalyst during the process, an alkaline catalyst can be introduced in appropriate amount to reduce the occurrence of side reactions and improve the selectivity of the whole catalyst system to the target product reactants. Hydrocracking catalyst consists of main catalyst, carrier and co-catalyst. In order to improve the hydrotreating catalytic technology, the following requirements are placed on the carriers: the ability to provide a good acidic heating environment at the same time, the effective improvement of thermal stability and heat strength, the ability to provide effective molecular pore sizes and structures suitable for the surface and temperature at the same time, the proper interactions with the active metal components, the prevention of fusion of the metal crystals and other carrier interactions, and the favor of the active metal dispersion[30]. Aluminum hydroxide and non-aluminum hydroxide carriers are currently the two most widely used, longest lasting and most studied compounds of catalyst reaction carriers for hydrocracking aluminum. Catalytic cracking can degrade large petroleum hydrocarbons, but it may produce coke and harmful gases. Jian Wang et al. researched this problem and pointed out that the composition of raw materials, catalyst properties and operating conditions have an important influence on the formation of coke, and analyzed the important role of catalyst property regulation in controlling coke accumulation, and proposed that the catalyst acid properties and carrier pore structure could be regulated and optimized; meanwhile, it was also pointed out that unsaturated hydrocarbon radicals in the raw materials are the main reason for the accumulation of coke, and it is possible to control coke accumulation by rationally controlling the properties of raw materials and controlling the reaction temperature. It is also pointed out that the unsaturated hydrocarbon radicals in the feedstock are the main cause of carbon accumulation, and the reasonable control of the feedstock properties, as well as the control of the reaction temperature, pressure and other working conditions, will help to inhibit the formation of carbon accumulation[31].

3.2.3 Emulsifying and dispersing agent, oil condensate

Emulsifying and dispersing agent (also known as oil eliminator) is a kind of chemical agent widely used in the treatment of oil spill at sea, oil emulsifying and dispersing agent is mostly surfactant, relying on the unique molecular structure to realize the dispersing function. Its molecular lipophilic groups inserted into the oil or oil particles inside the hydrophilic groups toward the water phase, in the oil-water interface or particles on the surface of the directional adsorption, greatly reducing the interfacial tension, so that the oil is dispersed into tiny particles. At the same time, the dispersant forms a single molecule adsorption layer, rigid interfacial membrane or hydration layer, which prevents the particles from agglomerating and settling and enhances the stability of the system through charge repulsion and spatial site resistance effects. In addition, the dispersant can also penetrate into the petroleum colloid or solid particles, weakening its interaction force, breaking up the aggregate structure. Its effect is affected by the molecular structure of the dispersant (such as HLB value, chain length), system pH, temperature, electrolyte concentration and oil phase composition and other factors, widely used in oil extraction, transportation and pollution control and other fields. When applying degreaser, not only the degreasing effect and its own toxicity should be considered, but also the toxicity of the oil spill emulsion must be considered; and when considering the toxicity scale, not only the effect on a certain organism should be understood, but also the effect of degreaser on the food chain and the whole ecosystem should be considered. At present, ester-type surfactants are generally used, which not only have good emulsification and dispersion, but also have low toxicity to marine organisms[32]. Condensates, on the other hand, condense oil through chemical reactions. For example, some oil condensate agents can cross-link with the components in the oil to form a three-dimensional mesh structure, in which the oil is immobilized. Others change the surface tension or viscosity of the oil, making it easier to coagulate. The performance of the oil condensate is affected by a variety of factors, such as the type of oil, temperature, pH value, and so on. Condensate has important application value in the fields of oil spill emergency response, oil storage and transportation. Oil condensate is often used in combination with physical booms and skimmers. At present, the main condensate agents used are amino acid derivatives, polymers, waxes and so on.

3.3 Bio-recycling Technology

3.3.1 Phytochemical enrichment

Plants suitable for the enrichment of petroleum-based pollutants need to be characterized by high tolerance, large biomass, and well-developed root systems, and at the same time, they can absorb, transport, or collaborate with microorganisms to degrade petroleum components through the root system(Table 3). For soil petroleum contamination, Zhang et al. analyzed the situation of soil petroleum contamination in different oil mining areas of the Loess Plateau in northern Shaanxi, and compared the uptake of petroleum contaminants by major plants in the study area, and concluded that iceplant, Artemisia ferruginea, sea buckthorn, and wolfsbane have a strong ability to transfer and enrich total petroleum hydrocarbons, and they are the advantageous and tolerant plants for remediation of petroleum-contaminated soils in the local area[33]. For marine oil pollution, the main role is played by algae, algae adsorption of oil is based on the principle of its cell structure, surface chemical properties and biological metabolic activities, through the synergistic effect of physical adsorption and biodegradation to achieve the capture and removal of petroleum pollutants. Algae cells (e.g. microalgae, macroalgae) have a huge specific surface area and complex porous structure (e.g. cell wall cellulose, polysaccharide lattice)[34], which can adsorb petroleum through surface adhesion and pore filling in two ways, and the rough surface of the algal cell wall can directly retain petroleum particles or oil droplets, especially for emulsified oil or suspended petroleum pollutants with significant effect. The cell wall micropores (pore size is usually nanometer to micron level) can adsorb small molecules of petroleum components (e.g., benzene, short-chain alkanes), forming physical retention. Some algae can actively absorb petroleum pollutants through metabolic activities and convert them into low-toxicity substances. Small molecule petroleum hydrocarbons (e.g., C_6-C_{12} alkanes) can diffuse into the cell through the lipid bilayer of the cell membrane and be catalyzed by intracellular enzymes (e.g., dehydrogenases) for degradation to CO_2 and water. Liang Yizhi et al. pointed out that Chlorella and Halophyceae can utilize petroleum hydrocarbons to enrich oils and fats. In the petroleum concentration of 1.5-10.0 μg/ml of culture solution, Chlorella and Halophyceae were able to effectively degrade hydrocarbons with conjugated double bonds, with degradation rates ranging from 25.3% to 35.5% and from 17.9% to 24.0%, and aromatic hydrocarbons with degradation rates ranging from 22.1% to 30.2% and from 18.7% to 26.2%, respectively; at the concentration of 3.5μg/ml of petroleum, the degradation of hydrocarbons with conjugated double bonds was also effective. At an oil concentration of 3.5μg/ml, both microalgae had the greatest degradation efficiency for hydrocarbons with conjugated double bonds and aromatic hydrocarbons, and the degradation ability of Chlorella was slightly better than that of Salix salina[35].

3.3.2 Animal enrichment

When oil enters the ocean, tiny plankton bear the brunt. These basic producers of marine ecosystems incorporate toxic components of oil, such as polycyclic aromatic hydrocarbons (PAHs), into their bodies. Zooplankton, represented by copepods, although tiny, continuously absorb oil pollutants dissolved in seawater during filter feeding. When small fish, such as herring and sardines, consume these zooplankton, the petroleum contaminants enter their digestive system along with their food. These small fish in turn become prey for large predatory fish, seabirds, and marine mammals, and oil contaminants accumulate in organisms at higher trophic levels[36-37]. In the case of killer whales, which are at the top of the food chain, high concentrations of petroleum contaminants have been detected in their fatty tissues. These substances not only affect the physiological functions of animals, disrupt the endocrine system, and damage the immune system, but may also lead to reduced reproductive capacity, malformation of larvae, and threaten the continuation of the species. More seriously, human beings, as consumers of marine fishery resources, may also indirectly ingest petroleum pollutants through consumption of contaminated seafood, jeopardizing their own health. For the petroleum pollution in soil, Huang Panpan et al. found that earthworms have selective enrichment of polycyclic aromatic hydrocarbons (PAHs) in soil. Under the same concentration of petroleum hydrocarbon pollution exposure, earthworms' enrichment of PAHs in the 2-ring, 3-ring, and 4-ring was significantly ($P<0.05$) greater than that of the 5-ring and 6-ring, and the larger the concentration of petroleum hydrocarbons was, the more obvious the characteristics of this selective enrichment were. Moreover, with the increase of petroleum hydrocarbon concentration, the BCF of earthworms on total PAHs and PAHs showed a tendency of increasing and then decreasing[38].

Table 3. Bio-Recycling Technology

Bio-recycling technology	Phytochemical enrichment	Oil-tolerant plants/algae absorb/degrade oil contaminants.	Plants enrich hydrocarbons; algae degrade 35.5% at 3.5μg/ml.	Plant tolerance, environmental conditions, oil concentration	Pros: Low-cost, eco-friendly, improves soil structure. Cons: Long cycle, poor high-pollution adaptability, food chain transfer risk.
	Animal enrichment	Oil accumulates in organisms via food chain ingestion.	Enriches contaminants, no removal, risks biotoxicity.	Animal species, contaminant toxicity, exposure time	Pros: Ecological monitoring indicator. Cons: Harms organisms, risks human health via food chain.
	Microbial degradation	Microbial enzymes degrade oil into CO_2/water or low-toxins.	Single strain: 30%-60%; combined: over 80%.	Environmental parameters, microbial species, nutrients	Pros: Eco-friendly, low energy, handles deep pollution. Cons: Poor extreme adaptability; toxic intermediates, long cycles.

3.3.3 Microbial degradation

Biosurfactants have unique properties relative to chemical surfactants such as biodegradability, foaming, non-toxicity, high efficiency, biocompatibility, and high selectivity for pH, temperature and mineralization[39]. Typically bioemulsifiers are composed of proteins, polysaccharides, lipoproteins, lipopolysaccharides, and their complexes[40-41] Biosurfactants can be obtained by three methods: microbial fermentation, enzyme synthesis, and extraction from plant and animal materials. The main means of obtaining biosurfactants is by using microbial fermentation. Different surface activator strains produce different surface activators[42-43]. For marine environments, Pseudomonas nitroreductus[44], Actinobacillus baileyi[44], Bacillus thermophilus adiposeus[45], and Pseudomonas aeruginosa[46] can be used. For soil environments, Bacillus subtilis[47], Rhizobium tropicalis[48], and Streptomyces[49] can be used. Bacteria are mainly used to degrade petroleum hydrocarbons in marine environments, and fungi are used to degrade petroleum hydrocarbons in freshwater or terrestrial environments[50] The degradation of petroleum contaminants using microorganisms requires the combined action of multiple enzymes, and it is a relatively complex degradation process. Typically, the biodegradation of petroleum compounds consists of three processes: in the first step, petroleum-based pollutants are adsorbed onto the surface of microorganisms; in the second step, the adsorbed petroleum-based pollutants are transferred to the microbial cell membranes; and in the third step, the petroleum-based pollutants are ultimately degraded in the microbial cells into a variety of small molecules[51]. Since microorganisms are not easy to grow and reproduce under extreme conditions such as low temperature and high salt, the isolation and screening of salt-tolerant and salinophilic microorganisms for degrading PAHs has received extensive attention worldwide. Currently, the salinophilic microorganisms that can degrade alkanes have been isolated and screened out, including Saltomonas, Saltboxyla, Haemobacterium, Alkanophilus, Actinobacillus polysporus, Salinobacillus, Pseudomonas aeruginosa, etc.; salinophilic microorganisms that can degrade PAHs include Haemocyclosporium, Desmodium, Micrococcus, Pseudomonas, Alkaloidobacterium, Saltboxyla, etc.; salinophilic microorganisms that can degrade BTEX are Actinobacteria, Bacteriodesium, etc.; salinophilic microorganisms that can degrade BTEX are Actinomyces, Bacteriodesium, etc, Penicillium flavum-producing bacteria, etc.; able to degrade phenolics, benzoate salt of the salinophilic bacteria are Pseudomonas tropicalis, Chromobacterium spp. and so on[52].

3.4 Combined Recycling Technology

3.4.1 Combined physical-microbiological

The combination of physical methods as pre-treatment and biological methods for in-depth purification can significantly improve remediation efficiency (Table 4). Mechanical screening and oil-absorbing treatment of contaminated water or soil can remove large impurities and floating oil, and reduce the concentration of pollutants to a tolerable range for biological methods. For example, centrifugal separation technology is utilized to treat oil-containing sludge, and the separated oil is initially purified by adsorbents (e.g., activated charcoal) and then degraded by the addition of salinophilic bacteria. Biochar was put into oil-polluted water bodies to enrich the oil pollution through adsorption, after which microorganisms were used to degrade the pollutants[53]. Wenfang et al. found that the degradation of petroleum hydrocarbons (C_{10} to C_{40}) by the combined biochar-microbial technology was superior to that of biochar and microbial technology alone, and that the best promotion of microbial degradation of crude oil was achieved at a biochar addition of 2.5%, with a maximum degradation rate of 46.7%. The degradation rate was enhanced by 6 times and more compared to the degradation rate of bacterial agents or biochar alone[54].

3.4.2 Joint chemical-microbiological

The principle of photocatalytic degradation of petroleum is mainly based on the redox reaction generated by semiconductor photocatalysts under light radiation, which decomposes organic pollutants in petroleum into harmless carbon dioxide, water, and small molecules through the generation of highly active free radicals. These small molecules can then be degraded by microorganisms. Commonly used photocatalysts include titanium dioxide TiO_2, zinc oxide ZnO, cadmium sulfide CdS and so on. Wu Yun et al. used magnetic carbonyl iron particles as the carrier, loaded nano TiO_2 to make composite photocatalysts, and hydrophobic and lipophilic modification of the surface of the composite catalysts, to prepare loaded nano TiO_2 composite photocatalysts with hydrophobic and lipophilic characteristics, and experimentally found that the new catalytic material has better degradation efficiency for petroleum hydrocarbon pollutants in water, and the photolysis of conventional TiO_2 zeolite catalysts effect had a maximum removal rate of about 75% for the pollutants, while the maximum removal rate of TiO_2-modified carbonyl iron could reach 95% and the degradation rate was faster, and the degradation effect was improved with the increase of the catalyst concentration, but the degradation effect was decreased when the concentration was further increased to 4g/L[55]. In addition to TiO_2, ZnO is considered a promising material for purifying and disinfecting water and air as well as remediating hazardous wastes due to its high activity, environmental friendly properties and lower cost[56]. Dongdong Hu et al. prepared pure nano-ZnO by ultrasonic chemical precipitation and co-precipitation, and then modified the homemade nano-ZnO in terms of reducing the photogenerated electron-hole pair complexation and decreasing the forbidden band width of the catalysts, respectively, and the photocatalytic degradation rate could reach more than 84% under the optimal reaction conditions[57].

3.4.3 Plant-microbe association

The plant root system is utilized to absorb and adsorb petroleum pollutants, while the microbial community around the root system can further degrade the pollutants. Shen Yanbin et al. screened two plants, ryegrass and alfalfa, with good remediation ability for oil-contaminated soil based on the tolerance of plant seeds to oil-contaminated soil, the morpho-physiological indexes of the plants, and the degradation of petroleum hydrocarbons in the soil. A microbial agent ZD with high efficiency remediation capacity for petroleum-contaminated soil was screened from the inter-root soil of the plants. Using ryegrass and alfalfa in combination with the composite microbial agent ZD for remediation of petroleum-contaminated soil, it was found that when the inoculum amount of the microbial agent ZD was 1.25%, the combined plant-microbial remediation of petroleum-contaminated soil obtained a better effect (78.28%)[58].

Table 4. Combined Recycling Technology

Combined recycling technology	Combined physical-microbiological	Physical pretreatment + microbial deep degradation of oil.	Combined tech: 6x higher; 46.7% with 2.5% biochar.	Compatibility of physical materials with microorganisms, degree of pretreatment	Pros: Physical-biological synergy boosts efficiency. Cons: High cost, complex process, parameter coordination.
	Joint chemical-microbiological	Photocatalysis + microorganisms degrade oil pollutants.	Photocatalysis 75%-95%; combined degrades thoroughly.	Light conditions, catalyst type, microbial activity	Pros: High efficiency, handles recalcitrant pollutants; complements biology. Cons: High catalyst cost, complex maintenance, UV limitations.
	Plant-microbe association	Plant roots absorb, secretions boost microbial degradation.	Synergy boosts efficiency beyond single plant/microbe.	Plant species and microbial match, soil conditions	Pros: Eco-friendly, soil improvement, microbial degradation, sustainability. Cons: Long cycle, climate/plant growth dependent.

4. Technical Performance Evaluation

4.1 Removal Rate Range

Different types of oil recovery technologies show significant differences in core performance indicators such as removal rate and cost. In terms of removal rate, skimmers in the physical method are outstanding in emergency response scenarios, reaching 80%-90%, such as in marine oil spills where large quantities of floating oil can be recovered quickly and efficiently. In the chemical method, the removal rate of solvent extraction is in the range of 77%-90%, while photocatalytic degradation is in the range of 75%-95%, which has a better decomposition effect on specific components of oil pollutants. Biological methods are relatively complex, the degradation rate of a single strain of bacteria is usually in the range of 30%-60%, while the degradation rate can be increased to more than 80% when combined technologies are applied, such as the “plant-microbe joint remediation” model, which utilizes organic acids secreted by plant roots to stimulate the activity of microorganisms in the inter-root zone, thus realizing highly efficient degradation of petroleum pollutants(Table 5).

Table 5. Comparison of Removal Rates for Various Recovery Technologies

Categorization	Recycling technology	Removal rate range
Physical recycling technology	Absorbent material	Natural materials absorb 50-200x weight; synthetics 80-161g/g oil..
	Machinery Recycling	80-90% removal in emergency treatment
Chemical Recovery Technology	Solvent extraction	Removal rate 77%-90%
	Catalytic cracking	Degrades large petroleum hydrocarbons, but may produce coke and harmful gases

	oil condensate	Promotes oil aggregation for recovery; solo effect depends on oil properties.
Bio-recycling technology	Phytochemical enrichment	Algae degraded 35.5% of conjugated double bond hydrocarbons at a petroleum concentration of 3.5μg/ml.
	Animal enrichment	Some enrichment of contaminants, but no active removal, may lead to biotoxicity.
	Microbial degradation	Single strain degrades 30-60%; combined tech boosts to over 80%.
Combined recycling technology	Combined physical-microbiological	6x higher than single tech; 2.5% biochar gives max 46.7% degradation.
	Joint chemical-microbiological	Photocatalytic degradation rate of 75%-95%, combined with microorganisms to degrade more thoroughly
	Plant-microbe association	Combined plant-microbe remediation rate of about 78%

4.2 Cost Analysis

Physical methods are characterized by high investment in equipment, such as LAMOR skimmers, and the cost of purchase puts a large financial pressure on the companies concerned, although the operating costs are moderate[21]. Physical methods as a whole are complex, difficult and time-consuming[59]. The solvent cost of chemical methods remains high, for example, traditional extractants such as carbon tetrachloride are effective, but toxic and expensive alternatives; the maintenance of photocatalytic equipment is complicated, which further increases the overall cost. Biological methods have low energy consumption, but the remediation cycle is long, resulting in a medium-high overall cost, and the long-term investment in manpower and monitoring cannot be ignored in the remediation of large oil-contaminated sites.

5. Technical Bottlenecks and Challenges

5.1 Bio-Recycling Technology

Microorganisms are sensitive to environmental parameters (temperature, salinity, pH, etc.) and have difficulty functioning effectively under extreme conditions. Therefore, extreme microorganisms such as cryophiles, salinophiles, heavy metal tolerant bacteria, heavy oil tolerant bacteria, etc. need to be considered when using biorecovery. Cryophilic bacteria must live in low temperature conditions and their maximum growth temperature does not exceed 20°C, optimal growth temperature is 5°C, and they can grow and reproduce at 0°C; cryotolerant bacteria have a maximum growth temperature higher than 20°C, an optimal temperature higher than 15°C, and they can grow and reproduce at 0-5°C[60]. Huang Lei et al. (2007) screened a strain of cryotolerant bacteria T7-2 (Rhodococcus spp.) capable of degrading diesel fuel from the seabed mud in the area of oil tanker spill in the Bohai Sea, and initially identified it as Rhodococcus erythropolis Red Flat[61]. In high-salt environments, microbial cells are at risk of osmotic pressure imbalance in marine oil spills or oilfield hypersaline wastewater (salinity >10%). Traditional degrading bacteria (e.g., Escherichia coli) will die due to dehydration at salinity >5%, and halophilic microorganisms are microorganisms that grow with an optimal salt concentration greater than 0.2mol/L Halophilic bacteria (e.g., Saltomonas) survive, but their degradation rate as well as enzyme activity are affected. In addition to the poor adaptability of microorganisms to the environment, microbial metabolism of petroleum hydrocarbons may produce more toxic intermediates, forming a“secondary pollution potential”. For example, microbial degradation of PAHs may generate strong carcinogens such as epoxides, which are 2-3 times more acutely toxic than the parent compound. Aldehydes and ketones produced during the degradation of alkanes are toxic, and some intermediate products (e.g., acrolein) are more water-soluble than the parent hydrocarbons, so they are more likely to diffuse into the groundwater system and pollute the groundwater.

5.2 Physico-Chemical Recycling Technology

Mechanical skimmers (e.g. LAMOR LRB skimmers) are dependent on the ship's power system, with a fuel consumption of 50-100 liters per hour and high transportation costs due to the weight of the equipment. The regeneration of oil-absorbing materials (e.g., high-temperature desorption) consumes 2000-3000kJ/kg, and synthetic resins (e.g., high oil-absorbent resins) degrade in performance by 30% after regeneration, and may ultimately become solid waste. For the chemical method, the use of perchloroethylene for solvent extraction replaces carbon tetrachloride but still forms precursors for photochemical smog after evaporation; the coke from carbonization of heavy oil components in the catalytic cracking process contains PAHs, which requires additional treatment, and the loss of acidic catalysts (e.g., aluminium silicate) can lead to acidification of the soil, which is a challenge when treating oil.

5.3 Emerging Technology

The adsorption capacity of MNP for petroleum hydrocarbons reaches 200-300mg/g, but the preparation cost is 10 times higher than that of traditional activated carbon, and the high price limits the large-scale application. Graphene aerogel has an oil adsorption rate of 900-1200g/g, but its production process requires the consumption of large amounts of strong acids (e.g., concentrated sulfuric acid), generating 3-liters of wastewater per kilogram of product, and increasing the cost of treatment by 20%-30%. TiO_2 nanoparticles may enter the food chain through the biofilm barrier, causing oxidative damage to the liver of aquatic organisms (e.g., zebrafish). Genetically engineered bacteria (e.g., Pseudomonas aeruginosa DN1 high rhamnolipid-producing genetically engineered strain[62]) can degrade 81% of PAHs under laboratory conditions, but the survival rate may be compromised in actual soils due to competition from indigenous flora. For the photocatalytic method, the degradation efficiency is affected by light conditions as well as water quality conditions. Ultraviolet (UV)-driven TiO_2 catalysts can only utilize 3%-5% of the solar spectrum, and the penetration depth is <2cm, which makes it difficult to treat deep soil contamination[63].

5.4 Policy and Standardization

Differences in domestic and international standards for oil recovery are mainly reflected in pollution assessment methods, indicators of remediation effects, and specifications for technology application, etc. These differences not only reflect the environmental governance needs of different regions, but also pose a challenge to the transnational application of technologies and synergistic development of industries. China's soil petroleum pollution assessment is dominated by chemical indicators, for example, the Soil Environmental Quality Risk Control Standards for Soil Pollution on Construction Land (Trial) stipulates the screening and control values for petroleum hydrocarbons (C_{10}-C_{40}), and the EU Soil Protection Framework Directive adopts a risk-oriented assessment, which, in addition to the total amount of petroleum hydrocarbons, requires the detection of toxic components such as PAHs and BTEX and the assessment of the pollutants to the groundwater, food chain. Domestic and international standards vary, for example, the Netherlands has set the intervention value for benzo[a] pyrene in soil at 0.5mg/kg, which is much lower than the control value for construction land in China (15mg/kg), reflecting the strict control of carcinogens. For water bodies, China's standards for oil pollution in water bodies, as exemplified by the Seawater Quality Standards, divide the sea into four categories, with the petroleum-based concentration limit for the first category of seawater at 0.05mg/L, and for the fourth category at 0.5mg/L, without distinguishing between the types of oils (e.g., crude oil, refined products), whereas the U.S. National Oceanic and Atmospheric Administration (NOAA) divides oil spills according to the toxicity of the oils into low-toxicity (e.g., diesel oil), poisonous (e.g., crude oil), and highly toxic (e.g. condensate), with different categories implementing different emergency response thresholds. For example, in the case of condensate spills, the thickness of the oil film on the surface of seawater is >0.1mm, which triggers the first level of response, while crude oil needs to be >0.5mm.

6. Prospect

With the development of science and technology, the future oil recovery treatment technology is going to develop towards genetically engineered microorganisms, nano-materials, intelligent monitoring and remediation. The breakthrough of gene editing technology opens up a brand new path for the bioremediation of oil recovery. Through directional modification of microbial genes, it can be given a stronger degradation ability: on the one hand, optimize the metabolic pathway, so that microorganisms can decompose a variety of petroleum hydrocarbons at the same time, Chang Xiaoning through genetic engineering technology, so that the new genome has a number of genes related to petroleum hydrocarbons degradation, including two medium-chained alkane-degrading genes, two long-chained alkane-degrading genes, genes and four aromatics degradation genes, such as in the n-XXXVIII degradation experiment, compared with the wild-type degradation gene, and the wild-type degradation gene. In the experiment, compared with the wild-type strain, the degradation rate of C_{28} by the engineered strain was increased by 6.72% and 6.89% at 7d and 14d, respectively[64]. On the other hand, the environmental adaptability was enhanced, and with the help of gene editing, the microorganisms were able to stabilize their metabolisms in the extreme conditions of high salt, low temperature, high acid and alkali, and the activity of microorganisms in the remediation of Arctic permafrost contamination was greatly improved after the introduction of extremophilic genes, which expanded the application scenarios of the biological This has expanded the application scenarios of the biological method. In the field of nanomaterials, nanomaterials have become the key to upgrading oil recovery technology by virtue of their unique physicochemical properties. In the field of catalysis, the research and development of TiO_2-modified and precious metal nano-catalysts can significantly improve the degradation efficiency; precisely regulate the size, morphology and surface properties of nano-materials to build a highly efficient photocatalytic system, accelerating the photocatalytic degradation of petroleum pollutants; and develop low-cost and high-performance nano-catalytic materials to replace the expensive noble metals and reduce the cost of technology application. Due to the development of science and technology and Internet big data, the Internet, drones and sensors are fused[65], real-time monitoring, drones equipped with sensors and image recognition systems, rapid scanning of the polluted area, combined with the ground sensor network, accurate access to the distribution of petroleum pollutants, concentration and degradation dynamics, to provide real-time data for the adjustment of restoration programs, to achieve intelligent, refined, and significantly improve the governance efficiency and It realizes intelligence and refinement, greatly improves the efficiency and effect of treatment, and promotes the oil recovery technology to advance towards intelligent ecology.

7. Conclusion

The threat of oil spills to ecology, health and economy is becoming more and more serious, and it is urgent to accelerate the technological innovation and standardization of oil recovery. Existing technologies include physical methods such as oil-absorbing materials and skimmers, which are costly and prone to secondary pollution; chemical methods such as solvent extraction and catalytic cracking, which have toxicity and secondary pollution; and biological methods such as plant enrichment and microbial degradation, which have a long remediation period and poor adaptability to extreme environments, all of which are in contradiction between efficiency and environmental risks. In the future, combined treatment technologies such as physical-microbial, chemical-photocatalytic joint application of the most extensive prospects, can enhance the degradation efficiency of 3-6 times, the initial investment in equipment is higher, but the long-term operating costs are lower than a single technology. Problems faced at this stage are mainly low activity of microorganisms in extreme environments, high cost of nanomaterials, and non-uniformity of policy standards, which constrain the development of existing technologies. In the future, we will focus on the enhanced degradation of genetically engineered bacteria, the development of low-cost nanomaterials, the integration of intelligent monitoring systems, and cross-regional policy synergy and mutual recognition of standards.

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