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INNOVATIVE APPROACHES TO SOIL REMEDIATION

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In a world grappling with environmental challenges, the issue of soil contamination and pollution stands as a significant threat to our planet's health. This article delves into the critical topic of soil remediation and explores a spectrum of innovative methods aimed at rejuvenating our soil's vitality. Capitalizing on the latest advancements in environmental science and technology, these approaches offer a promising path toward healing the Earth. This article sheds light on the diverse toolbox available for the restoration of contaminated soils. As we navigate the intricate web of ecological concerns, understanding and harnessing these innovative remediation strategies is crucial for a greener, more sustainable future.
Key words: *soil remediation, polymer, surfactant, co-solvents, porous media, non-Newtonian fluid, nonaqueous phase liquid.*

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ТОПЫРАҚТЫ ҚАЛПЫНА КЕЛТІРУДІҢ ИННОВАЦИЯЛЫҚ ӘДІСТЕРІ

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Экологиялық мәселелермен күресіп жатқан әлемде ластану, оның ішінде топырақтың ластану мәселелері планетамыздың тіршілігіне төнген елеулі қатер болып отыр. Бұл мақалада топырақтың ластануы, оны қалпына келтіру туралы маңызды мәселе көтеріледі және топырақтың тіршілігін жаңартуға бағытталған инновациялық әдістері қарастырылады. Қоршаған ортаны қорғау ғылымы мен технологиясының соңғы жетістіктерін пайдалана отырып, Жердің тіршілігін жаңғыртудың перспективалы жолдары ұсынылады. Бұл мақалада ластанған топырақтарды қалпына келтіруге арналған әртүрлі әдістерге шолу жасалады. Әлемдегі күрделі *экологиялық мәселелердің бірі болып табылатын топырақты қалпына келтірудің инновациялық стратегияларын түсіну және пайдалану болашақта Жер планетасын қалпында және мәңгі жасыл етіп сақтау үшін өте маңызды.*

Түйін сөздер: *топырақты қалпына келтіру, полимер, беттік белсенді заттар, ко-еріткіштер, кеуекті орта, Ньютондық емес сұйықтық, сулы емес фазалық сұйықтық.*

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ИННОВАЦИОННЫЕ ПОДХОДЫ К РЕМЕДИАЦИИ ПОЧВ

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В мире, который борется с экологическими проблемами, проблема загрязнения и загрязнения почвы представляет собой серьезную угрозу здоровью нашей планеты. Эта статья углубляется в важнейшую тему восстановления почвы и исследует спектр инновационных методов, направленных на восстановление жизнеспособности нашей почвы. Опираясь на последние достижения в области науки и технологий об окружающей среде, эти подходы открывают многообещающий путь к исцелению Земли. В данной статье приводится обзор некоторых актуальных методов и подхододов применяемые для восстановления загрязненных почв. Поскольку мы ориентируемся в сложной паутине экологических проблем, понимание и использование этих инновационных стратегий восстановления имеет решающее значение для более зеленого и устойчивого будущего.

Ключевые слова: *ремедиация почв, полимер, поверхностно-активные-вещества, сорастворители, пористая среда, неньютоновская жидкость, неводная фазовая жидкость.*

Introduction. Environmental pollution, notably soil pollution, is one of the urgent problems at present. Soil remediation is the application of proven technologies to reduce and manage the hazards associated with contaminated soils, which can be hazardous to both human health and the environment.

Petroleum hydrocarbons (PHs) are currently among the most dangerous pollutants. When petroleum products are widely used in industry as well as in their transportation, they can lead to accidental leaks and spills. Crude oil and petroleum products contain many chemicals such as gasoline, kerosene, diesel fuel, jet fuel, Stoddard solvent, mineral-based motor oil, hexane, benzene, toluene, xylene, and polycyclic aromatic hydrocarbons [1]. As a result of various accidental spill incidents, PH can penetrate terrestrial and aquifer ecosystem. These fluids are called non-aqueous phase liquids (NAPLs). NAPLs are divided into two types depending on their density. If they exceed the density of water, they are called as DNAPL. However, if the density is less than that of water, then they are called LNAPL.

Since DNAPLs are denser than water, they are located below the groundwater table, while LNAPLs in the contrary, float on top of the water table [2].

There are several soil remediation strategies available today that are based on three major ideas: extraction of contaminants, procedures for degradation or transformation, and sequestration and immobilization of pollutants to contain them [3]. Soil remediation should pay attention to important factors such as (i) the quantity of spill, (ii) the oil's initial physical (surface tension, specific gravity, and viscosity) and chemical characteristics, (iii) existing environmental conditions, and (iv) whether the oil remains at or runs off from the spilled site. When an oil spill occurs, there is a chance that the spilled oil could enter groundwater [4].

The use of polymer for environmental remediation is not well developed because of significant differences in its application contexts (compared to Enhanced Oil Recovery). The application of polymers for environmental remediation was inspired by Enhanced Oil Recovery, where polymers have proven to be excellent residual oil displacement agents. However, in petroleum engineering, the polymer solutions are used at high depths in consolidated rocks at high pressures and temperatures, while in the case of soil remediation, it must be implemented in unconsolidated shallow soils. The polymer injection conditions and formulations should be therefore different for remediation applications. Although the technique appears promising, a better understanding of the mechanisms and their modeling are still necessary before considering its application on a pilot scale. Moreover, a thorough evaluation of its generation and injection conditions is also required.

Research methodology. Soil remediation pertains to the systematic procedure of purifying, reinstating, or enhancing the quality of soil that has undergone contamination or degradation due to various pollutants. There exist two primary methodologies for soil remediation: conventional (also referred to as traditional) and post-conventional. The conventional approach entails the utilization of established and widely recognized methodologies for the remediation of soil that has been contaminated. The post-conventional approach encompasses contemporary methods that are characterized by their novelty, innovation, and heightened focus on environmental sustainability in the context of soil remediation [5].

Injection of surfactant solutions. Surfactant solution is used when conventional methods are no longer sufficiently effective. Surfactants refer to chemical compounds that effectively reduce the surface tension or interfacial tension observed between two distinct phases, namely, a liquid and a gas, a liquid and a solid, or two different liquids. Surfactants can be found in everyday lives, for example it is widely used in pharmaceuticals, food and even detergents. Anionic, cationic and non-ionic, these are the three main types of surfactants. The positively charged head group is present in cationic surfactants [6], therefore cationic surfactant solutions are not recommended for remediation, to avoid adsorption of surfactant, as negatively charged clay minerals may be present in the soil [5]. The concentration of the surfactant solution depends directly on the solubility of the hydrocarbons [7], the solubility of anionic and non-ionic surfactants in solution exhibits a significant increase at the critical concentration where micelle formation occurs [8]. Surfactant solutions have unique features, a polar end (head) and a non-polar end (tail) [9]. Polar or hydrophilic groups consisting of a long chain hydrocarbon and non-polar hydrophobic groups consisting of sulphate or ethylene glycol are called amphiphilic compounds [6]. When contaminants are introduced into the soil, they have the potential to disperse into smaller clusters known as ganglia and subsequently become trapped in surfactant micelles [5], micelles are a geometric shell or more precisely a sphere which formed by surfactant molecules [10].

Hydrocarbon mobilization and solubilization are the main principles of this method. The techniques employed in this study entail the utilization of surfactants, which are chemical compounds capable of modifying the surface tension and interfacial characteristics of liquids. The primary objective is to augment the mobilization and retrieval of hydrocarbons, specifically NAPLs, from polluted environments. The mobilization principle of surfactants involves the reduction of interfacial tension between hydrocarbons, and the adjacent subsurface materials, such as soil or rock. The decrease in tension facilitates the detachment of hydrocarbons from solid surfaces and their subsequent movement through porous media. Surfactants possess molecular structures that encompass both hydrophilic (water-attracting) and hydrophobic (water-repellent) components, thereby facilitating the principle of solubilization. Upon the introduction of surfactants into an environment contaminated with hydrocarbons, the hydrophobic component of the surfactant molecules engages with the hydrocarbons, leading to their encapsulation within micelles or diminutive droplets [11].

In the [12] review, in soil remediation from polynuclear aromatic hydrocarbons (PAHs) has been found that using a surfactant solution with sodium dodecyl sulfate (SDS) gives 73.6-100% efficiency, while the use of water only gives an efficiency of 30–80%. With the same pollutant [13], have achieved close results. The utilization of surfactants as standalone agents in laboratory experiments yields efficiencies ranging from 80% to 85%. Research findings indicate that the efficiency of field soil washing exhibits significant variability, ranging from almost 0 to nearly 100%. This highlights the significance of understanding the characteristics of the domain, such as soil heterogeneity and the nature of contamination, among other factors.

Surfactant has its share of both advantages and disadvantages. Advantages of surfactants are their low cost and relative biodegradability, one of the main disadvantages is the removal of NAPL from heterogeneous soil areas [14]. Therefore, new technologies had to be developed to deliver surfactants by various other means, i.e., by introducing foam or polymers.

Cosolvent "alcohol" flushing. Alcohol flushing have already been studied since the 1990s as a future possible method of soil remediation. The washing technology with Cosolvent as well as the Surfactant solution has been adapted from enhanced oil recovery (EOR). After the primary or secondary methods that have been used in oil production, the same methods can be applied in soil remediation. But it must be noted that EOR and NAPL extraction from soil are different fields, therefore it is necessary to pay attention to different important aspects between these technologies. These aspects are: properties of the porous media, physical and chemical conditions, properties of the contaminating fluids and toxicity with biodegradability of used ingredients. Careful selection of the ingredients is important to reduce costs and achieve efficient NAPL recovery [6].

The potential applications of alcohols in the field of soil remediation have been investigated, particularly in relation to their ability to solubilize and mobilize contaminants. In order to acquire a more profound comprehension of the subject matter, it is crucial to explore the intricate mechanisms that are in operation.

It is crucial to recognize that the effectiveness of solubilization and mobilization mechanisms utilizing alcohols is dependent on several factors. These factors encompass the specific type of alcohol used, the properties of the contaminants, their concentrations, and the soil characteristics. The meticulous evaluation of the suitable alcohol choice and its corresponding application technique is of utmost importance in attaining efficient soil remediation. The determination of the appropriate course of action necessitates a comprehensive evaluation of the distinct pollutants existing within the soil, alongside the prevailing environmental circumstances at the site. By considering these factors, researchers are able to maximize the efficiency of the remediation process and improve its overall effectiveness.

In their study, Jawitz et al., employed a combination of Winsor I-type surfactant and alcohol as an in situ washing agent for the purpose of solubilizing a multi-component NAPL. This process resulted in the formation of a single phase microemulsion (SPME) within a hydraulically isolated test chamber located at Hill Air Force Base (AFB) in Utah. The analysis of soil core data revealed that the SPME flood effectively eliminated around 90-95% of the predominant NAPL constituents present in the cell. An analysis of partitioning tracer data collected before and after the flushing process revealed that approximately 72% of the quantified NAPL volume was effectively eliminated through the use of the SPME flood method. The integration of NAPL constituent breakthrough curves (BTCs) revealed a range of 55-75% removal of the desired NAPL constituents when employing partitioning tracer data to estimate the initial quantity of NAPL present. Additionally, when utilizing soil core data to estimate the initial amount of NAPL present, a removal range of 60-175% was observed for two target constituents. The findings of this study suggest that the SPME flood method was successful in effectively eliminating the NAPL components that were of concern. However, it was observed that an insoluble anthropogenic residue remained after the process [15].

Alcohol flushing, a widely employed technique in soil remediation, possesses advantages and disadvantages. One notable advantage lies in its efficacy in the removal of a diverse array of volatile organic compounds from soils that have been contaminated. Alcoholic solvents have the ability to effectively dissolve and mobilize contaminants, thereby facilitating their extraction and subsequent treatment. Nevertheless, a significant drawback of this approach lies in its reliance on the permeability and homogeneity of the soil. In order to achieve optimal alcohol flushing, it is imperative that the cleaning zones possess adequate permeability, thereby facilitating the effective penetration of the solvent into the soil and subsequent contact with the contaminants. Furthermore, it is imperative for the subsurface systems to exhibit homogeneity in order to facilitate the consistent dispersion of the solvent and mitigate the occurrence of channeling or bypassing phenomena, which have the potential to impede the effectiveness of the remediation procedure and result in inadequate purification. Therefore, it is imperative to thoroughly evaluate the specific attributes of a site prior to the implementation of alcohol flushing as a technique for soil remediation.

Application of Non-Newtonian fluids. Non-Newtonian fluids is a fluid that deviates from Newton's viscosity law, or one whose viscosity is variable and based on stress. Stress dependent viscosity, time-dependent viscosity, yield-stress and stress relaxation are characteristic features of non-Newtonian fluids. There are three main groups of non-Newtonian fluids: (i) time-independent fluids are those in which the instantaneous stress at a particular place is the only factor affecting the shear rate at that moment, (ii) fluids that exhibit partial elastic recovery when a deforming load is removed are said to be viscoelastic fluids and these substances combine the characteristics of elastic viscous fluids, (iii) time-dependent fluids are those whose shear rate depends on the intensity, duration, and, conceivably, the interval between successive applications of stress

In this scholarly discourse, we systematically investigate the precise utilities of non-Newtonian fluids in soil remediation:

- Excavation Enhancement: Non-Newtonian fluids, exemplified by bentonite slurries and polymer gels, exhibit the capacity to stabilize soil particles during excavation, thus facilitating the removal of contaminated materials with heightened efficiency.
- Permeability Control: Non-Newtonian fluids, through their propensity to establish impervious barriers, significantly diminish the dispersal of contaminants, effectively containing and reducing their lateral migration.
- Subsurface Transport: These fluids excel in the task of conveying contaminants or remediation agents within the soil structure, guaranteeing precise delivery to designated areas.
- Precision Delivery: The controlled deployment of microorganisms or chemicals to specific zones for in-situ bioremediation or chemical treatment attests to the adaptability of non-Newtonian fluids.

Selecting the most fitting non-Newtonian fluid and application method is contingent upon the unique soil and contaminant attributes, emphasizing the inherent necessity for an integrative approach, wherein non-Newtonian fluids synergize with other established remediation strategies. This scholarly exposition seeks to contribute to the academic discourse surrounding soil remediation, recognizing non-Newtonian fluids as a vital dimension in the ongoing pursuit of sustainable and effective environmental rehabilitation practices [16].

Polymer injection. A polymer is a macromolecule consisting of recurring monomeric units that are linked together through chemical bonds. The process of polymerization involves the sequential bonding of monomers, resulting in the formation of extensive chains or networks, thereby establishing a macromolecular architecture. Polymers exhibit significant diversity in their composition, properties, and applications, which are contingent upon the precise selection of monomers and the subsequent polymerization mechanism employed. These materials exhibit a wide range of characteristics and possess versatile applications within multiple industries. Polymers possess the characteristic of augmenting the viscosity of a fluid. This phenomenon is referred to as front flattening, wherein the velocity of fluids, including those in regions with low permeability, equalizes. This phenomenon indicates that polymers exhibit shear thinning behavior, wherein an increase in shear rate leads to a decrease in fluid viscosity [5].

To the best of current understanding, only two scientific investigations have been conducted to examine the recovery of LNAPL through the utilization of polymers. The primary aim of the laboratory study conducted by Martel et al., is to identify and evaluate polymers that exhibit desirable properties for the purpose of aquifer restoration. The conducted experiments demonstrated that the rheology of xanthan gum solution was investigated to determine the impact of shear rates, xanthan gum concentrations, salinity, and temperature on the viscosity of the solution. The subsequent series of experiments were conducted using a sand box specifically engineered to replicate a rudimentary heterogeneous medium comprising stratified layers of sand exhibiting varying permeability. The conducted experiments demonstrated the capacity of the xanthan gum solution to enhance the sweep efficiency of the surfactant solution and mitigate the occurrence of viscous fingering. The experimental results have demonstrated that: (i) the introduction of a xanthan solution subsequent to a surfactant solution slug leads to a reduction in fluid velocity within layers possessing high permeability, while conversely enhancing fluid velocity within layers characterized by low permeability. Consequently, this approach effectively enhances the sweep efficiency; (ii) xanthan solutions effectively mitigate the occurrence of viscous fingering at the interface between the polymer and surfactant solutions; (iii) it is advantageous to employ a xanthan solution as a preflush in order to restrict the mobility of the surfactant solution and prevent its adsorption onto solid surfaces; (iv) appropriate injection strategies should be implemented, considering the heterogeneity of the site, to prevent displacement of the low-density surfactant solution by higher-density fluids [17].

The study performed by Robert et al., investigated the efficacy of utilizing a micellar-polymer solution in conjunction with multiphase vacuum extraction (MVE) to enhance the recovery of LNAPLs. This investigation was carried out using a medium-scale physical model that accurately replicated a five-point injection/extraction scheme. The presence of LNAPL in its free phase was observed at the groundwater table, while the saturation of LNAPL in the saturated zone exhibited a decreasing trend with increasing depth. The MVE technique was employed to extract approximately 50% of the LNAPL. However, the implementation of the flushing solution did not yield a substantial enhancement in the recovery of oil. The presence of LNAPL residue within the saturated zone has resulted in a decrease in the relative permeability of water. Consequently, the flushing solution is compelled to flow beneath the zone with the highest degree of contamination [18].

The utilization of polymer injection in soil remediation presents a range of advantages and disadvantages. From a favorable perspective, it has been observed that this particular phenomenon greatly enhances the composition of soil, thereby imparting it with enhanced stability and heightened resistance against erosion. Furthermore, the utilization of polymer injection has demonstrated efficacy in the process of immobilizing various contaminants, specifically heavy metals and specific organic pollutants. The utilization of this approach frequently demonstrates cost-effectiveness in comparison to conventional excavation and disposal methods, while also resulting in minimal environmental disturbance and land use interference. The selection of a polymer necessitates meticulous consideration due to the environmental implications associated with this decision. The presence of technical proficiency and specialized equipment is a fundamental requirement, potentially impeding smaller-scale undertakings or initiatives situated in less-developed regions. Finally, the acquisition of regulatory approvals can present a multifaceted and time-intensive undertaking, thereby presenting obstacles to the execution of a particular endeavor. Therefore, it is imperative to emphasize that the utilization of polymer injection as a method for soil remediation holds considerable potential. However, it is crucial to underscore the significance of meticulous strategic planning and the incorporation of site-specific factors in order to optimize the advantages of this approach while mitigating any associated disadvantages. As mentioned earlier about the main disadvantage of surfactant solution, researchers [19] showed a new idea of their development, which is the use of SDS performance with a biopolymer.

Discussion. In this study, to propose a novel approach to soil remediation, employing a biopolymer-based remediation method enriched with a selection of additives. The aim was to develop a more effective and sustainable technique to mitigate soil contamination, building on proven methods while harnessing the potential of biopolymers.

The research built upon the well-established effectiveness of biopolymer-based soil remediation. Biopolymers have shown promise in their ability to immobilize and degrade various contaminants in soil. They are eco-friendly and biodegradable, making them an attractive option for sustainable soil remediation.

To enhance the performance of the biopolymer, introduced a range of additives that were selected based on their potential to augment the remediation process. These additives served various functions, including: surfactants and co-solvents.

In conclusion, a novel approach to soil remediation, combining biopolymers with a range of additives, has the potential to offer a sustainable, customizable, and efficient solution to soil contamination. By carefully selecting and optimizing these additives, aim to create a versatile method that can be tailored to the unique needs of contaminated sites, ultimately contributing to a cleaner and healthier environment.

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