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Research Papers

Comprehensive Analysis of Crude Oil Sludge Management: Advances in Treatment, Sustainable Disposal, and Future Perspectives

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Abstract: A prevalent occurrence of hazardous pollutants generated by the crude oil industry is known as crude oil sludge. Crude oil sludge is a persistent issue that reduces the capacity for storing oil and has corrosive consequences. The cost of removing and disposing of sludge is part of the economic impact; the cost of disposing of ecologically harmful waste is more expensive. Recently, there has been significant difficulty with the handling and disposal of sludge generated from crude oil. This technical study offers information on different procedures utilized in the processing and management of petroleum sludge. A comprehensive exploration of different approaches employed for crude oil sludge treatment and disposal is provided, encompassing processes like biodegradation, oxidation, stabilization/solidification, and cremation. Additionally, various techniques used in order to extract oil from petroleum sludge, many techniques including techniques like surfactant EOR, ultrasonic irradiation, freeze-thaw, centrifugation, froth flotation, solvent extraction, electro-kinetic method, microwave irradiation, and pyrolysis, were thoroughly reviewed and analyzed. The advantages and drawbacks of each method were critically assessed, culminating in recommendations for the economically feasible disposal of this environmentally challenging substance, exploring alternative options.

Keywords: Crude Oil Sludge, Hazardous waste, Sludge disposal, Crude Oil Sludge Treatment

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1. Introduction

Crude oil production and exploration produce a variety of wastes, including drilling mud, wastewater from petroleum processing, sludge from petroleum effluent treatment plants, and sediment from tank bottoms. According to [1], a crude oil refinery that produces 105,000 drums of crude oil per day would produce 50 tons of oily sludge annually. The substances found at the bottom of tanks and other storage facilities are known as sludge. Water, hydrocarbons, inorganic particles, paraffin, asphaltenes, iron oxides, iron sulfides, and sand make up the remaining sludge from each crude oil storage tank. However, petroleum sludge, which is created when the qualities of crude oil are altered by changes in the environment, is primarily made up of hydrocarbons. Crude oil sludge is frequently produced as a result of the formation of emulsions by adding water, light end evaporation, interacting with unfriendly compounds, and cooling below the cloud point [2]. The Resources Conservation and Recovery Act (RCRA) classifies sludge and other hazardous wastes as hazardous wastes [3]. Additionally, lead, sodium, cadmium, magnesium, phosphate, calcium, chromium potassium, iron, and phosphorus are among the elements found in petroleum sludge [4]. Furthermore, a recurring problem that has corrosive consequences is petroleum sludge and it reduces the capacity of oil storage. The cost of sludge disposal and removal is part of the economic impact; the cost of disposing of ecologically harmful waste is more expensive. There are many methods used to process and dispose of petroleum sludge, including chemical, thermal, biological, and mechanical methods. These cannot be sustained economically as a whole. Among these pollutants are petroleum hydrocarbons including polycyclic aromatic hydrocarbons (PAHs) and aliphatic hydrocarbons. Additionally, petroleum oily sludge contains heavy metals as nickel, arsenic, zinc, lead, mercury, chromium, barium, and polychlorinated biphenyls (PCBs) [6–8] in addition to approximately 33%

of the total petroleum hydrocarbons (TPH) and 550 mg/kg of PAHs were found in the petroleum sludge [5]. Every storage tank eventually builds up muck, but petroleum storage tanks are particularly problematic near manufacturing sites. Thus, as a crucial maintenance procedure, the removal of tank sludge should be recognized by petroleum material producers, refiners, and carriers.

2. Petroleum Sludge

Petroleum sludge compositions, according to the American Petroleum Institute (API), include both heavy metals and organic components, with typical concentration ranges [9]. Also reported the concentrations of Fe, Zn, Cr, Ni, Cu, and Pb in the petroleum sludge were reported as 60,200 mg/kg, 1,299 mg/kg, 480 mg/kg, 480 mg/kg, 500 mg/kg, and 565 mg/kg, respectively; had the highest metal concentrations in petroleum sludge from refineries, according to studies done between 2010 and 2013 [10–13]. Furthermore, the incorrect waste petroleum that is released into the environment creates a substantial concern by drastically changing the morphological traits and chemical and physical properties of the adjacent soils [14]. As a result, the recipient soils' plants grew slowly and had nutritional deficiencies [15]. The high viscosity of the sludge causes it to be entrapped within soil pores, creating a continuous layer around the land [16]. Hydraulic conductivity, wetting power, and other soil parameters have all been shown to decline when there is petroleum waste present [16, 17]. Additionally, it has been discovered that high molecular weight components can produce hydrophobic crusts, which reduce water availability and water-air exchange into the soil [18] and have a long-term impact on agricultural land [14]. Petroleum consists of petroleum hydrocarbons (PHCs) and polycyclic aromatic hydrocarbons (PAHs), both of which possess genotoxic properties that can be harmful to both humans and animals, making it a serious health threat when not properly processed and disposed of into the environment [14].

3. Properties of Crude Oil Sludge

A stable emulsifying mixture containing metal, petroleum hydrocarbons (PHCs), solids, and water is known as crude oil sludge [15]. The sample sludge has a total petroleum hydrocarbon (TPH) concentration of 15 to 50% (percentage of mass), whereas the water and solid contents are 30 to 85 and 5 to 46%, respectively [16]. The sludge's chemical makeup is highly intricate. Benzene series, anthracene, solid suspended matter, wax, asphaltene, gum, phenols, pyrene, and heavy metal salts, in addition to a sizable amount of crude oil, it frequently contains additional hazardous and dangerous compounds as well [17]. Oily sludge typically has a pH value between 6.5 and 7.5. Aromatics make up 28-33% of the composition, alkanes constitute 40-55%, asphaltene accounts for 8-12%, and resin comprises 10-22.4% of the petroleum sludge (as a percentage of mass) [18].

4. The Environmental Impact of Crude Oil Sludge

If crude oil sludge is not properly handled and disposed of, it can have major detrimental repercussions. The three ways that the negative consequences can show themselves are as follows:

i. The high concentration of total hydrocarbons in the surrounding air will be caused by the volatilization of petroleum elements in petroleum sludge.

ii. Inadequately handled sludge will substantially exceed the threshold for COD and petroleum compounds in the water, polluting both surface and groundwater.

iii. Many poisonous and dangerous organic chemicals, including phenols, hydrocarbons, benzene ring compounds, and anthracene, are present in the crude oil sludge. Some compounds have impacts on the environment that are mutagenic, teratogenic, and carcinogenic [19]. The sludge has been added to the National Hazardous Waste List (NHWL) as a result.

5. Reduction, Recyclable and Harmless Treatment of Crude Oil Sludge

Three strategies employed for the treatment and handling of crude oil sludge are quality reduction, recyclable, and environmentally safe approaches [20].

i. Enhance production technology in the petroleum industry to minimize the generation of oily sludge from the source, resulting in reduced amounts from petroleum and petrochemical enterprises.

ii. Extract and recycle valuable petroleum energy from the current oily sludge, making it reusable.

iii. Implement diverse technologies to manage non-recoverable petroleum sludge residue or the sludge itself, thereby preventing environmental pollution caused by oily sludge [21].

The procedures used to treat crude oil sludge traditionally include pyrolysis, chemical cleansing, and solvent extraction. Supercritical water oxidation (SCWO), ultrasonic treatment, and microwave radiation are some of the most recent advancements in treatment technology.

4.1. Traditional Crude Oil Sludge Treatment Technology

These include;

A. Solvent Extraction Technology

Oily sludge is extracted using organic solvents that have qualities comparable to crude oil in this type of technology, achieving the goal of crude oil recovery. This technology is based on the idea of similar miscibility [22]. The extraction of crude oil from sludge is a standard liquid-solid extraction, which entails selecting the right extraction solution, thoroughly combining it with the sludge, distilling the solvent/oil mixture, and finally separating the oil from the solvent [23]. Thus, after condensation, the solvent can be reused. Common extractants include trichloromethane, propane triethylamine, reforming oil, etc. Oily sludge can be easily separated into recyclable hydrocarbons, smaller solid and semi-solid wastes, and recyclable hydrocarbons using the straightforward and efficient recyclable treatment method known as solvent extraction. The solvent extraction process has the ability to handle a lot of crude oil sludge. The use of organic extractants is currently one of the main barriers to the widespread application of the crude oil sludge treatment method, and a substantial volume of employed organic solvents can easily result in secondary pollution [24]. The supercritical fluid extraction approach, however, can significantly cut the amount of extractants needed and accelerate the extraction process. However, due to its difficult operating conditions, it is not appropriate for large-scale use [25].

B. Chemical Cleaning Technology

The basic goal of chemical cleaning technique is to achieve three-phase separation of the liquids oil, sludge, and water. The procedure is as follows: add the correct amount of hot water and chemical reagents to the oily sludge. Then, using the roll-up, emulsification, dissolution, and solubilization functions of the chemical reagents, alter the characteristics of the oil-liquid phase and oil mud interface in the oily sludge. As a result, crude oil is removed from the sludge's surface and its viscosity is decreased. The subsequent settling and swirling procedures allow oil, sludge, and water to be separated [26].

The simplicity, low cost, great reliability, and high oil recovery rate of chemical cleaning are its benefits. However, the chemical cleaning agent has significant specificity and is simple to generate secondary pollution. Chemical cleaning methods' separation effectiveness is influenced by reagent type and dosage, washing temperature, liquid-solid ratio, stirring intensity, stirring time, and pH level [27].

C. Pyrolysis Technology

To achieve the goal of resource utilization, pyrolysis technology involves heating crude oil sludge under micro-positive pressure without oxygen in order to separate out oil and organic matter and separate oily sludge into pyrolysis residue, pyrolysis liquid, and pyrolysis gas [28]. The thermal transformation of oily sludge in this procedure can be separated into two steps, namely:

i. The initial phase is known as "term evaporation," and it takes place at temperatures below 350℃. During this stage, low-boiling-point light hydrocarbons will evaporate from the oily sludge.

ii. The second stage refers to parallel-sequential reaction. This occurs when the pyrolysis reaction on the heavy oil possesses a temperature that exceeds 350℃, and hydrocarbons will generate free radicals due to thermal activation at about 400℃ [29]. At the same time, a series of free radical reactions will occur. On the one hand, they are directed towards the pyrolysis process of generating small molecular hydrocarbons, and on the other hand, they are directed towards the condensation process of coking carbon generation [30]. Finally, oil, water, non-condensable gas and hard coke are produced. Nevertheless, the proportion of things varies slightly when the reaction conditions changed. Compared with the incineration technology, the NOx and SOx discharged by the oily sludge pyrolysis process are far lower than the incineration process [31]. Heavy metals and other pollutants in petroleum sludge can be enriched and fixed in solid residue, which greatly reduces the environmental pollution degree. The liquid product produced by the pyrolysis process has a good capacity reduction effect and is convenient for storage and transportation. Thus, the recovered oil can be directly applied to diesel engines; the carbon-containing solid residue can also be reused as adsorbent, flocculent, soil improver and so on. Consequently, the pyrolysis technique really realizes "turning waste into treasure" and recovers and utilizes the resources effectively [32]. Nevertheless, petroleum sludge usually contains a large amount of water and the cost of the dehydration process before pyrolysis is high. In addition, the temperature of the pyrolysis reaction and the energy consumption are high, and the requirements for equipment are strict.

4.2. Newly Developed Crude Oil Sludge Treatment Technology

These include;

A. Supercritical Water Oxidation (SCWO) Technology

In order to achieve the goal of making oily sludge harmless, the supercritical water oxidation (SCWO) method begins a free radical reaction that uses supercritical water as the reaction medium and oxygen, hydrogen peroxide, and air as catalysts at high temperatures and pressure. It is useful to use supercritical water oxidation in that it is both quick and effective. Thorough pollution degradation is possible, and environmental influence is reduced. However, this technology has some drawbacks, including a high cost of operating and the inability to completely eradicate the harm that heavy metals cause. Reaction temperature, pressure, time, ratio of real hydrogen peroxide dose to predicted demand, concentration of alkali, and solution pH are all elements that impact how effective supercritical water oxidation technique is [33].

B. Ultrasound Treatment Technology

The mechanical, thermal, and acoustic cavitation effects of the sound field are all factors in ultrasound treatment technology [34]. Under the ultrasonic irradiation used in this technology, the viscosity decreases as The temperature within the oily sludge emulsification system experiences an increase, which considerably weakens the stability of the emulsification system. This method encourages waste oil to desorb from the surface of solid particles [35]. Acoustic cavitation can produce micro-jets with velocities of up to 400 km/h. Tiny particles within the emulsion system of oil-bearing sludge travel faster and collide more frequently as they descend through these shock waves. These facilitate droplet condensation and coalescence, facilitating the division of the oil and water phases [36]. Mild acoustic cavitation settings are more effective than severe acoustic cavitation levels for removing oil from greasy sludge. Investigations into the effects of numerous variables on the oil removal effectiveness in ultrasonic treatment technology revealed that treatment time, ultrasonic frequency, ultrasonic power, and treatment temperature all had a significant impact [34]. Ultrasonic treatment technology offers numerous advantages, including high efficiency, rapid processing speed, and no secondary pollution. It is considered an environmentally friendly technique capable of treating oily sludge in a short period. On the other hand, using equipment that emits ultrasonic radiation for oily sludge treatment is mostly confined to the experimental stage [33]. There is limited information on large-scale applications in the oilfield. Future research should focus on studying specific oily sludge systems, optimizing equipment, and enhancing reactor structures to advance the field.

C. Microwave Radiation Technology

The effects of microwave radiation are thermal, electrical, magnetic, and chemical [26]. The oil-water interface's Zeta potential in oily sludge can be destroyed by microwave radiation. Additionally, non-polar oil molecules can be magnetized by the magnetic field created by a microwave, and oily sludge can be demulsified and dehydrated [30]. Microwave heating exploits the movement and friction of polar molecules present in materials to generate heat. This efficient and selective process enables the demulsification and separation of oil-water emulsions within the sludge. Additionally, microwave heating proves useful for drying and dewatering the sludge due to its rapid, uniform, and sensitive nature.

4.3 Petroleum Sludge Disposal Approaches

After extracting all usable oil and hydrocarbons from petroleum sludge, various disposal techniques are employed. Some of these processes include biodegradation, solidification/stabilization (S/S), incineration, and oxidation, among others.

A. Incineration

Incinerators play a crucial role in the complete combustion of petroleum industry waste sludge in the presence of abundant air and auxiliary fuel. Fluidized beds and rotary kilns are the two most common types of incinerators. Fluidized bed incinerators typically operate at combustion temperatures that range from 730 to 760°C, and a residence time expressed in days. On the other hand, rotary kiln incinerators operate at higher combustion temperatures, ranging from 980 to 1,200°C, and have a shorter residence time of around 30 minutes. The fluidized bed incinerator is preferred for sludge with lower quality as a result of its high combustion efficiency, low pollutant emissions, excellent mixing efficiency, and fuel flexibility.

B. Stabilization/Solidification

The main goal of this approach of encasing/sealing waste with a binder is to stop the waste from leaking into the environment, whether physically or chemically, and enable the conversion of the products in the landfill for disposal or into green building materials or non-hazardous waste. Three main steps are involved in the stabilization or solidification of hazardous waste by cement:

i. Removing chemical contaminants by modifying the direct chemical reactions between the pollutants and the cement's hydration products.
ii. Physically absorbing impurities from the hydrated cement products' surfaces; and
iii. Encapsulating contaminated waste or soil (due to the hardened pastes' low permeability).

Other ingredients are added to the mixture in an effort to improve stabilization/solidification's failure to totally immobilize the dangerous pollutants.

4.4 Bio Pile/Composting

The bio pile/composting treatment method involves the transformation of petroleum wastes into piles, allowing degradation by indigenous or invading microorganisms, referred to as Bio pile. This approach has the potential to replace land treatment, which demands significant land areas. When organic materials are added to enhance its effectiveness, this technology is referred to as composting [17]. Oily sludge in the piles is composted with the help of straw and crude manure resulting in a 46-53% reduction in TPH content within 56 days, while control piles exhibited a 31% reduction rate [37]. In terms of reducing TPH in oily sludge, kitchen waste compost was found to be the most useful organic substance in comparison to sand amendment, mature oil compost, and finely chopped waste wood, as reported in [38]. Comparing biopile/composting treatment to land farming, the former uses less land and is more environmentally benign. Nevertheless, it still necessitates a considerable land area and longer processing time.

4.5 Bio-slurry Treatment

The treatment technique involves mixing sludge-associated solids and water in a proportion of 5-50% w/v. This mixture allows the impurities to disperse into the aqueous phase, which is where solubilized impurities are acquired in significant amounts. Breakdown of these contaminants by microbes then reduces their toxicity or converts them into carbon dioxide and water. According to [39], bio-slurry treatment has proven to be a highly effective and time-efficient approach for reducing total petroleum hydrocarbons (TPH) in oily sludge. Within a span of two weeks, this method can achieve a TPH reduction ranging from 40.7% to 53.2%, and within six weeks, the reduction rate increases to an impressive 63.7% to 85.5%. Furthermore, the addition of a bio-surfactant, as indicated by [40], can significantly enhance the TPH reduction, leading to a remarkable 80-99% reduction within just 10-20 days of oily sludge biodegradation. Although bio-slurry treatment offers numerous benefits, including its effectiveness and minimal land requirement, it is important to note that it comes with a relatively higher cost compared to other disposal technologies. Nonetheless, its ability to rapidly and efficiently treat oily sludge makes it a favorable option for addressing the challenges posed by this hazardous waste.

5. Conclusions

Because of its danger, the production of crude oil sludge in the petroleum sector cannot be avoided, which presents a significant global problem in its management and treatment. Although many methods, include biodegradation, solidification/stabilization (S/S), incineration, ultrasonic treatment, land farming, solvent extraction, chemical treatment, pyrolysis, and photocatalysis, have been developed to efficiently manage petroleum sludge. Among these techniques, some have proven to be particularly efficient in regaining crude oil from the sludge but come with high operating costs, restricting their use on a large scale. More specifically, the petroleum industry can use solvent extraction, pyrolysis, chemical cleaning and microwave radiation technologies since they have a good effect on treating crude oil sludge. However, based on the characteristics of various disposal techniques, petrochemical firms should choose complete crude oil sludge disposal techniques that take into account their own geographic location, types of crude oil, process characteristics, sludge characteristics, and enterprise demand in the practical application of crude oil sludge disposal projects.

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