Cleaner Waste Systems 2 (xxxx) 100010

Contents lists available at ScienceDirect

Cleaner Waste Systems

journal homepage: www.journals.elsevier.com/cleaner-waste-systems

Diverse sustainable materials for the treatment of petroleum sludge and remediation of contaminated sites: A review

Ahmad Hussaini Jagaba[a,b,*], Shamsul Rahman Mohamed Kutty[a], Ibrahim Mohammed Lawal[b,c], Nasiru Aminu[d], Azmatullah Noor[a], Baker Nasser Saleh Al-dhawi[a], Abdullahi Kilaco Usman[e], Ahmad Batari[b], Sule Abubakar[b], Abdullahi Haruna Birniwa[f], Ibrahim Umaru[b], Aminu Shehu Yakubu[g]

[a] *Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia*
[b] *Department of Civil Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria*
[c] *Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK*
[d] *Nigeria Social Insurance Trust Fund, Regional Office, Kaduna, Nigeria*
[e] *Civil Engineering Department, University of Hafr Al-Batin, Hafr Al-Batin, Saudi Arabia*
[f] *Department of Chemistry, Sule Lamido University, PMB 048, Kafin-Hausa, Nigeria*
[g] *Department of Civil Engineering, Faculty of Engineering Technology, Nigerian Army University, PMB 1500, Biu, Borno State, Nigeria*

ARTICLE INFO

Keywords:
Petroleum sludge
Treatment
Sustainability
Pyrolysis
Resource recovery

ABSTRACT

Activities in the petroleum industry unavoidably generates huge amount of petroleum sludge that contain hazardous constituents. Numerous treatment techniques are proven to reduce toxicity, sludge volume, and extract petroleum products. Their efficiency is determined by the sludge properties. These treatment technologies can lessen the hazardous elements in sludge and alleviate their negative environmental and human health impacts. However, only a few, can strike a compromise between meeting strict environmental regulations and consuming notable quantity of water, energy, and chemicals. Now, there are no waste-free and cost-effective technologies available for petroleum sludge treatment. Therefore, this review was designed to highlight the several waste, plants, and other materials that have been utilized during petroleum sludge or petroleum contaminated site treatment for resource recovery and to ensure environmental safety. The application of various additives to remediate petroleum sludge contaminated areas has been proven to be a practical and environmentally beneficial alternative. The review found that reusing remediated soils for bioremediation activity on soil contaminated with oil sludge was efficient. The review further revealed that phytoremediation by sowing plants in the soil can remarkably boost microorganism's growth and TPH elimination rate. Also, in planted treatments using Zea mays L., *Secale cereale* L., *Festuca arundinacea, Onobrychis viciifolia, Vertiver zizanioide, Cajanus cajan, Medicago sativa, Lolium perenne, Ttrifolium pratense* etc. the most probable number were significantly higher than in unplanted treatments. It was also discovered that there is a commercial potential for the use of plants as sources of biosurfactant for use in accelerated TPHs degradation. Biosurfactant supplementation in the phytoremediation of metals and petroleum hydrocarbons co-contaminated soil was effective. The review suggests the use of composite materials for petroleum sludge treatment.

1. Introduction

1.1. The petroleum industry

Petroleum is a mineral oil extracted from under the earth's surface and then used to make a variety of chemical compounds. With porosities ranging from 10% to 30%, the liquid petroleum is discovered in rock deposits. Water can take up to 50% of the pore space. It could also be described as a complicated blend of non-aqueous and hydrophobic ingredients such a n-alkane, aromatics, asphaltenes, and resins. Since the commencement of the twentieth century, it has been the primary economic driver in the developed world. The word "petroleum"

---

* Corresponding author at: Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia.

E-mail addresses: ahjagaba@gmail.com (AH. Jagaba), shamsulrahman@utp.edu.my (SR.M. Kutty), mlibrahim@atbu.edu.ng (IM. Lawal), nasiruaminu@yahoo.com (N Aminu), azmatullahn@gmail.com (A Noor), baker_18002007@utp.edu.my (BN.S. Al-dhawi), aukilaco@uhb.edu.sa (AK. Usman), ahmadbatari@gmail.com (A Batari), absadiqq@gmail.com (S Abubakar), birniwa01@gmail.com (AH. Birniwa), ibropopoi@yahoo.com (I Umaru), aminushehuy@gmail.com (AS. Yakubu).

https://doi.org/10.1016/j.clwas.2022.100010
Received 24 December 2021; Received in revised form 17 April 2022; Accepted 11 May 2022

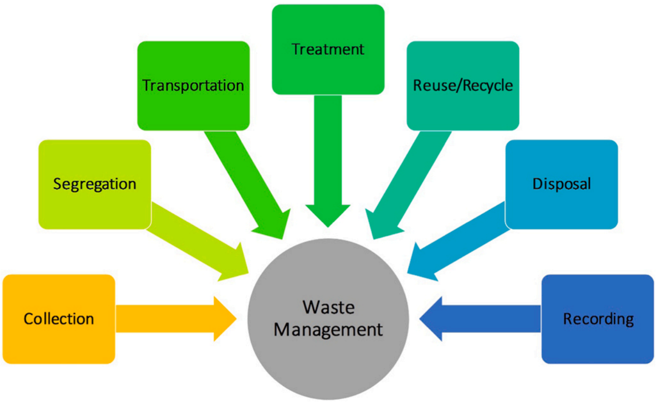

Fig. 1. Waste management process at the petroleum industry.

comes from the Latin terms *petra* (rock) and *oleum* (oil) (Chirwa et al., 2017). In the petroleum industry, there are several processes/steps namely crude oil exploration, cutting, onshore and offshore surveys, production (oil and gas), transportation, storage/handling, and refining from starting the exploration of oil and/or natural gas to their consumption (Borgheipour et al., 2018). Activities in this industry generates a variety of oily and viscous residue called petroleum industry waste which needs to be managed according to Fig. 1.

Petroleum industry waste vary in concentrations of hydrocarbons (40–60%), water (30–90%), and mineral particles (5–40%). They are categorized into hazardous and non-hazardous waste. Any waste that is reactive, inflammable, explosive, combustible, corrosive, or poisonous is classified as hazardous. The hazardous waste can be classified into (i) solid hazardous waste (batteries, catalysts, fluorescent, tubes, sampling bottles, pipes, filters, oil contaminated rags, oily contaminated soils), (ii) liquid hazardous waste (used lubricants, expired chemicals, spent acids), (iii) soil/sludge (oily soil/sludge from oil spills and crude oil storage tanks) (Ng et al., 2021; Jagaba et al., 2021). Non-hazardous waste is any form of industrial waste that does not pose a direct threat to human health or the environment, but still cannot be dumped of in a dumpster or sewage system due to rules. In the petroleum industry, the non-hazardous wastes could arise from general waste (mix garbage), tires (vehicle tires), food waste (from offices and cafeterias), concrete (construction and demolition waste), paper (cardboard, magazines, office waste papers), wood (wooden pellets), glass (soft drinks, lab reagent bottles), plastic (cables, pipes, packaging materials, containers, LDPE & HDPE bottles), and metals (drums, steel pipes, metal scrap, redundant flow lines, aluminum soft drink tins). Specifically, the major petroleum industry waste is petroleum sludge (PS).

1.2. Petroleum sludge (PS)

Petroleum sludge is known to exist in large quantities. They are hazardous in nature and often difficult to process. After petroleum refining, this sludge is the largest waste produced which has now drawn a lot of attention. This waste is generated due to the long period of sedimentary hydrocarbon compounds accumulation in broad fields. Several petroleum refinery activities such as catalytic cracking, industry wastewater treatment and visbreaking have also contributed to the production of petroleum sludge (Martínez et al., 2018). Its main components are petroleum and wax. Some of the characteristics of the oil components particularly viscosity, and particle size distribution could aid in the accumulation of the sludge. It is an extremely stable suspension emulsion system that contains benzene homologues, polycyclic aromatic hydrocarbons with strong toxicity and has also been categorized as a hazardous waste in several countries (Liu et al., 2017). Two factors usually influence the formation of petroleum sludge. They are inorganic residues in the form of (sand, clay, sediments, dust, and scales) and paraffinic wax precipitation formed in pumps, pipelines, storage tanks, etc. The main mechanism is the adsorption of asphaltenes to hydrophilic solid particles at the oil–water interface (Kriipsalu et al., 2008). The several type of sludge that exist in petroleum industry are landing sludge, pond sediment sludge, refining sludge, tank bottom sludge, petroleum wastewater activated sludge, oil drilling sludge, oil-water separator sludge.

1.3. Petroleum sludge generation

The extracted crude from oil well contains crude oil, condensates, and gas fractions. After extraction of gases, the crude is left over with oil content and condensate. Moreover, oil is also separated which led to generation of petroleum sludge (Noor et al., 2021). As reported by (Mahdi et al., 2017) per year production of PS from oil refineries of daily production capacity of 200–500 barrel of oil is about 10,000 m^3. Similarly, another study stated that 50 tons/year oily sludge is generated from petroleum oil refinery of 105,000 barrel/year. Thus, it is expected that 0.3–0.5% of sludge is generated from one ton of crude oil refining. Teng et al., (2021) reported that generation of oily sludge was 0.5% of global annual crude oil production. da Silva et al., (2012) estimated the generation of petroleum sludge ranging between 0.1% and 1.5%, according to refining capacity of petroleum plant. Also, highlighting the consideration of 0.1% of sludge generation of refinery capacity as an optimistic opinion, 0.5% as a realistic approach and 1.5% as a pessimistic view. Petroleum oily sludge contains around 33% of total petroleum hydrocarbons (TPH) and 550 mg/kg of PAHs.

Considering all the past studies it was concluded that approximately 0.1–0.5% of PS is generated from crude oil production annually. Last 5 years data of crude oil production of seven regions across the globe, was extracted from (US EIA). On an average 0.3% of PS generation from crude oil was measured. It is evident that 228.29 Mt/year of PS was generated in 2020 globally. Annual crude oil production of seven regions for last 5 years. Fig. 2 illustrate the PS generation of all seven regions for last 5 years. Thus, it can be concluded that PS is a global issue until we eliminate the usage of fossil fuel from our society.

1.4. Characteristics and environmental effects of petroleum sludge

Petroleum sludge in the form of a black semi-solid cake usually with properties such as structural complexity, hydrophobicity and longer persistency are characterized by low fixed carbon, high moisture, and low volatiles (Noor et al., 2021). It is made up of complex chemical mixtures with varied petrochemical attributes and some toxic substances. It has less sediment content than oil and water. It contains immunotoxicant and potent carcinogen materials (Kankia et al., 2021; Al-mahbashi et al., 2022). Its physicochemical characteristics varies in a wide range from plant to plant, depending on crude oil source, wastewater treatment method, storage, processing approach and technology, reagents and equipment's utilized during oil processing. Several factors such as sampling time and places influence the variation of the sludge properties and composition. Properties such as viscosity, heating value and density could vary to a very large extent because of the heterogenous nature of the chemical compositions in the sludge. According to the American Petroleum Institute, petroleum sludge compositions comprise both organic and heavy metal components with a normal range of concentrations. The main composition of petroleum sludge includes oil and grease, and several toxic metallic and organic compounds such as benzene, toluene, xylenes, phenolic etc with little quantity of non-acid species like ketones, esters, and amides (Kankia et al., 2021; Almahbashi et al., 2021).

Table 1 depicts that the characteristics of petroleum sludge produced by different countries differs due to the quality and origin of the crude oil changes from one country to another. Based on Tables 2 and 3, it is evident that there is no consensus among authors on the characteristics and metals composition of petroleum sludge especially because of the

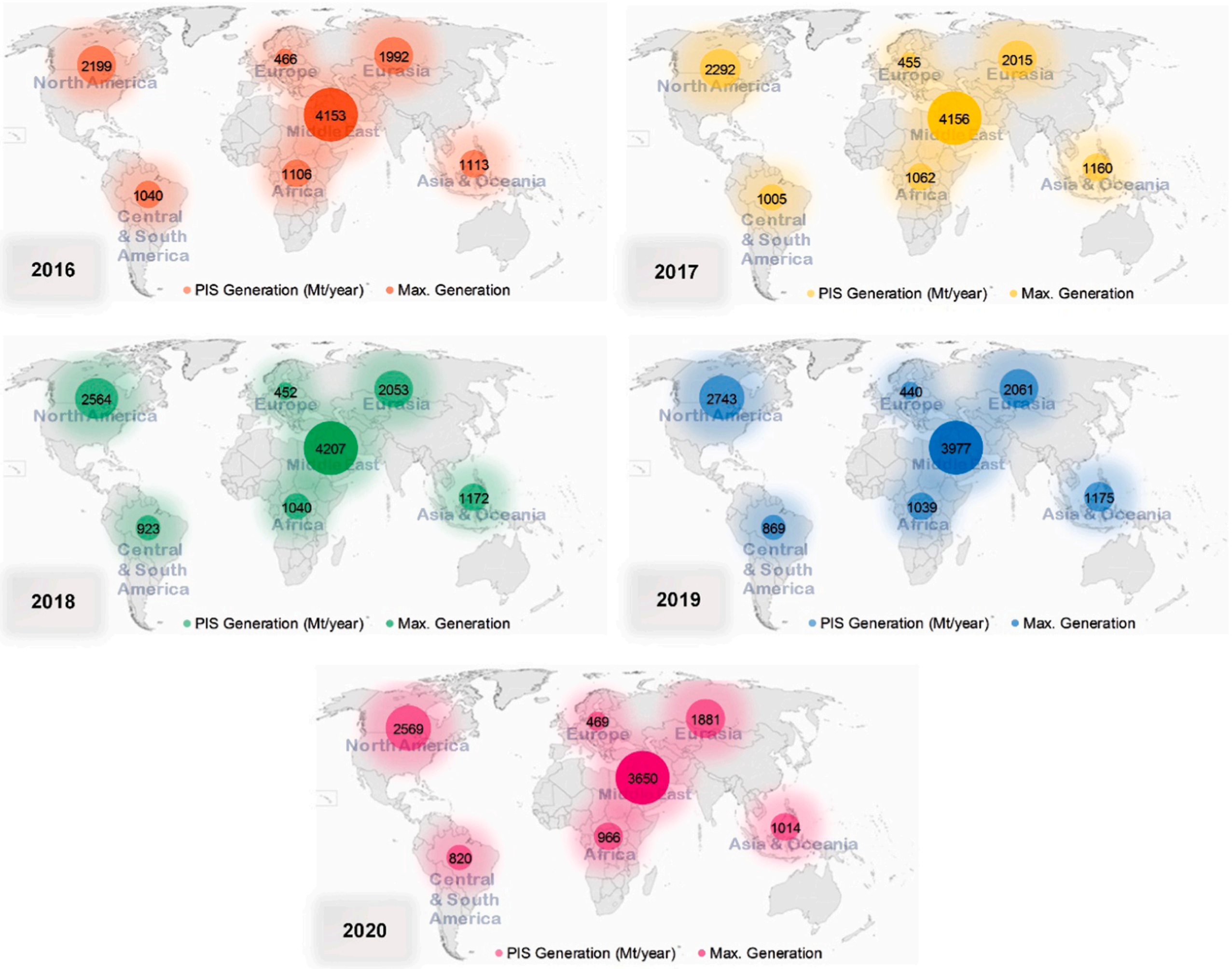

Fig. 2. Amount of petroleum sludge generated for last five years in seven regions across the globe.

uniqueness of each sludge composition (Ramirez et al., 2019). A high number of heavy metals in oily sludge, such as Zn, Cr, Pb, and Cu may travel with the help of various environmental media, posing a threat to human health. The toxicity of heavy metals leached into the environment is an important characteristic to consider when assessing their environmental danger.

Common heavy metals detected in petroleum sludge are Mg, Hg, K, Mn, Zn, Na, Al, Cr, Fe, and Ag (Noor et al., 2021; Jagaba et al., 2022). Their standard for wastewater discharge is 0.20, 0.05, 0.20, 5.00, 0.10, and 0.00003 (mg/L) respectively. In a study by (Qomariyah et al., 2022), with the exception of Hg, all of the components are within the regulatory limit for wastewater disposal. When compared to the regulation limit of 0.00003 mg/L, the concentration of Hg (0.139081 mg/l) is extremely high. According to Indonesian government regulation, Ministry of State for Population and Environment Legal Law No. 23 1997th, the crucial limit for heavy metal level of Cr(VI) in soil is 2.5 mg/L. For Zn(II), the concentration is 7 mg/L, while Fe(III) is 50 mg/L. Permissible limits for evaluating solid waste (SW-846, USEPA) enlisted by USEPA for Cr, Cd, Pb, and Zn are 5, 1, 5 and 25 mg/kg respectively.

Petroleum sludge has been designated as a hazardous waste and a priority environmental pollutant by many countries. It causes unwholesome and environmentally unacceptable pollution effects (see Fig. 3) that may have negative impacts on the environment, thereby affecting human health (Borgheipour et al., 2018). As a result, their discharge into the environment is carefully regulated, and the United States Environmental Protection Agency (USEPA) has designated them as precedence environmental contaminants. It is evident that, some values in Table 3 surpass those of the criterion fixed by World Health Organization (WHO) or USEPA for industrial sludge discharge. This indicates that the sludge has a significant potential for environmental pollution and hence requires treatment before disposal. The proper management of petroleum sludge is necessary because inappropriate methods may result in: (i) negative environmental effects - water and soil pollution, (ii) adverse effect on human health, (iii) huge waste value lost, (iv) non-compliance with laws and standards imposed by the local government authorities, (v) unattractive sight that could harm the company's reputation and (vi) a financial burden on the organization to clean up and restore the area. However, it is necessary to have sufficient information about the sludge characteristics to choose the most suitable treatment and disposal technique (Al Qallaf et al., 2016).

Petroleum sludge that has been dewatered and has an exceptionally low moisture content has the potential to be utilized as a landfill. Nevertheless, landfilling as a final disposal technique for petroleum sludge continues to remain problematic since it may introduce toxic substances into the water and soil environment through leachate. Petroleum hydrocarbons float on top of water, forming thin surface films or slicks, and their weathering process comprises spreading, evaporation, dissolution, dispersion, and emulsification, with the higher molecular fractions sinking to the bottom. Petroleum hydrocarbons found in sludge could have a variety of harmful consequences on human and ecological receptors. Petroleum hydrocarbons can permeate through soil layers and into groundwater, causing deleterious impacts on soil enzymes, microorganisms, and aquatic creatures.

Table 1
Characteristics of petroleum sludge for various countries.

Proximate analysis on dry basis				Ultimate analysis on dry basis					High heating value (MJ/kg)	County	Ref.
Moisture content (wt%)	Ash content (wt%)	Volatile matter (wt%)	Fixed carbon (wt%)	C	H	N	S	O			
9.62	43.18	40.80	7.6	36.26	5.30	1.0	0.74	5.10	31	Russia	(Kadiev et al., 2015)
9.71	1.3	94.8	5.2	73.8	11.3	2	3	12.6		United Arab Emirates	(Mazzoni et al., 2020)
27.8	72.12	15.62	1.86	7.34	1.23	0.41	0.55	18.54		Iran	(Koolivand et al., 2022)
79.34	5.06	5.52	10.51	51.4	7.3	3.3	2.2	35.8	23.60	Brazil	(da Silva et al., 2012)
83.61	28.85	62.90	8.24	36.27	4.37	1.41	1.31	27.78	16.12	China	(Gong et al., 2018)
1.6	60.87	36.02	1.60	83.36	11.87	0.95	2.48	1.34	15.69	Jordan	(Tahhan et al., 2011)
15.72	51.99	93.17	6.83	20.85	2.7	1.4	0.11	6.0	–	Malaysia	(Aeslina and Ali, 2017)
6.3	45.10	49.04	0.31	78.53	10.85	0.64	0.89	9.09	–	Brazil	(Gonzalez et al., 2018)
4.43	25.93	68.93	5.15	68.23	6.02	0.8	0.96	27.99	27.18	China	(Alhadj-Mallah et al., 2015)
37.21	26.10	33.08	4.76	22.65	3.44	0.67	1.28	15.60	–	India	(Singh and Kumar, 2020)
25.53	50.06	39.34	10.60	21.79	2.89	0.39	8.49	16.38	–	Japan	(Cheng et al., 2016)
6.06	71.25	20.02	3.55	14.6	2.06	0.08	0.56	2.36	7.86	Indonesia	(Permadi et al., 2017)
22.53	3.78	63.33	11.84	50.39	7.09	1.66	3.48	37.38	12.42	Algeria	(Bellahcene et al., 2021)

Table 2
Chemical composition of various petroleum industry sludge (wt%).

Sludge type	Chemical compositions														Ref.
	CaO	SiO_2	SO_3	Fe_2O_3	Al_2O_3	MgO	P_2O_5	K_2O	TiO_2	Mn_2O_3	Na_2O	BaO	Cl	LOI	Others	
Petroleum oily sludge	7.76	41.73	–	7.63	10.93	5.87	0.09	0.95	0.52	0.02	0.44	5.03	–	18.74	0.29 SrO	(Pinheiro and Holanda, 2013)
Petroleum waste sludge	2.70	28.62	9.10	0.08	0.20	0.50	–	–	1.10	–	–	39.08	–	14.91	1.70 SrO, 2.01 ZrO	(Khalil et al., 2018)
Dried oily sludge	3.74	7.83	3.41	10.14	4.23	0.58	–	–	–	–	2.41	–	–	66.21	–	(Xiao et al., 2019)
Crude oily sludge	4.46	13.7	–	6.69	2.52	0.42	–	0.95	–	–	2.30	9.97	–	–	33.1 oily content, 25.9 others	(Monteiro et al., 2007)
Petroleum effluent treatment plant sludge	25.04	18.98	–	1.30	48.12	0.56	–	0.39	–	–	1.01	–	–	–	3.21 SO_4^{2-}	(Borthakur and calorimetry, 2005)
Oil sludge ash	8.32	51.06	5.48	9.2	17.3	1.6	–	3.44	1.13	–	1.22	–	0.21		–	(Cheng et al., 2016)
Petroleum sludge ash	13.3	47.28	3.61	6.48	12.2	2.22	1.93	1.93	–	–	7.53	–	–		–	(Pakpahan et al., 2016)
Oily sludge ash	5.41	53.84	7.38	6.48	16.4	2.88	–	2.71	–	–	3.51	–	–	–	–	(Chen et al., 2016)
Petroleum sludge	25.05	5.47	38.41	0.56	1.29	3.47	–	0.27	–	–	3.29	–	–	–	–	(Aeslina and Ali, 2017)
	2.67	6.98	26.25	58.87	2.94	–	–	–	–	–	–	–	–	–	–	(Alhadj-Mallah et al., 2015)
Petroleum refinery sludge	1.03	3.47	11.91	30.99	2.9	0.26	0.13	0.14	0.17	0.21	0.20	0.17	0.05		0.01 Sr, 0.03 Ni, 0.36 ZnO, 0.02 CuO, 0.04 Cr_2O_3	(Zhu et al., 2020)

Table 3
Heavy Metals present in different petroleum sludges.

Metals concentration in the oily sludge (mg/kg)																			Ref.
Cd	Cr	Cu	Fe	Mn	Ni	Pb	Mg	Al	Ba	Co	Ca	Ti	As	Na	Zn	K	V	others	
11.78	49.95	707.36	7167.43	134.43	38.75	77.6	–	1451.98	45.03	5.84	–	49.91	4.99	–	11.08	51.63	28.66	3.85 Sn, 3.42 Mo, 1.58 Li. 0.99 La, 0.42 Be	(Asia et al., 2006)
4.44	119.09	4420.46	4033.58	398.06	56.01	132.7	–	273.02	110.33	3.78	–	0.13	4.96		12,248.7	–	8.28	2269.54 Mo, 1369.36 B, 58.65 Sn, 6.18 Ag, 3.49 Hg, 2.88 Sb, 0.14 Se, 47.92 Li, 43.33 Sr	(Panova et al., 2018)
22.64	70.69	537.09	5923.10	95.90	37.61	122.40	2.79 Mo	1134.55	30.08	15.32		57.81	1.58		15.40	49.22		2.95 Sn, 1.27 La, 4.26 Li	(Ahmad, 2017)
0.16	8.07	–	302.97	–	7.11	4.02	–	–	–	2.39	–	–	1.279	2.23	131	–	2.84	–	(Chandrasekhar and Mohan, 2012)
0.0004	0.0159	0.11	5.16	0.0882	0.05	0.0186	0.4889	3.754	2.583	0.0164	8.758	0.1313	0.0083	1.237	0.1285	1.369		0.4779 Sr, 0.0601, 0.006 Mo	(Kariminezhad and Elektorowicz, 2018)
–	60.34	52.61	–	–	6.22	3.66	–	–	16.77	–	–	–	0.88	–	163.83	–		3.79 Mo, 0.07 Hg, 0.28 Se, 0.10 Sb	(Ling and Isa, 2006)
–	0.6	1.1	300	–	0.8	94.5	19.2	24.4	0.2	–	85.9	1.1	–	59.4	22.3	–	0.8	0.2 Ag, 0.9 Mo, 89.5 Si,	(Alves et al., 2019)
0.6	14	43	–	–	130	40	–	–	–	16	–	–	7.0	–	840	–	74	21 Hg,	(Asadollahi et al., 2016)
42.5	105	35	357.2	4.24	240	198	40	26.40	–	16	100	547	13.5	–	580	3.38	72	–	(Hamed et al., 2010)
–	–	107.46	30,4817	255.69	54	34.41	1460.56	3213	1111.17	–	–	57.17	–	61.94	–	–	5.82	–	(Aziz et al., 2020)
–	0.0036	–	60.82	1.188	0.207	–	–	3.327	–	–	6.84	1.087	–	–	0.788	–		13.80 S, 11.572 Si, 0.336 Sr,	(Atagana, 2008)
5.82	207	223	60,000	277	116	53.39	–	–	–	–	–	–	–	–	8265	1936	29.64	495 P,	(Zhu et al., 2020)
–	162	121	43,000	2594	1311	3609	–	36,000	92,000	–	201,000	2646	–	–	1591	4321	182	106 Si, 33 S, 26 Cl, 3385 P, 877 Sr, 205 Cs, 116 Te,	(Hu et al., 2017)

(*continued on next page*)

Table 3 (*continued*)

Metals concentration in the oily sludge (mg/kg)																			Ref.
Cd	Cr	Cu	Fe	Mn	Ni	Pb	Mg	Al	Ba	Co	Ca	Ti	As	Na	Zn	K	V	others	
4.44	69.1	4420	5530	390	56	190	–	2730	–	3.78	–	–	4.96	–	5220	–	8.28	1360 B, 58.6 Sn, 47.9 Li, 3.49 Hg	(Beškoski et al., 2012)
0.06	45.39	12.92	150.47		34.93	2.68	–	–	–	1.34	49.51	–	2.24	3.13	34.70	–		–	(Zhao et al., 2018)
0.16	8.07	2.39	302.97		7.11	4.02	–	–	–	2.39	30.50	–	1.27	2.23	131	–		–	
0.05	48.38	12.89	101.13		38.72	2.62	–	–	–	2.53	78.25	–	2.22	3.56	68.14	–		–	
0.44	0.48	3.43	37.40	25.77	0.34	149.02	–	–	–	–	–	–	–	–	0.20	–		–	(Asgari et al., 2017)
5	5	14	2780	–	23	–	178	144	–	–	860	–	11	410	168	–		572 K,	(Kriipsalu et al., 2007)
–	0.3	12	50	1.5	1.3	2.3	28.4	–	0.7	–	–	–	–	15.4	5.4	–	0.4	–	(Wu et al., 2011)
–	–	155.33	5862	–	21.66	–	–	924.33	–	–	2921.66	–	–	77.66	19.133	524.66	19.57	–	(Wang et al., 2016)
1.1	–	730	33,972	–	152	93	4527	12,615	–	–	36,473	–	–	–	1332	2190	227	0.6 Ag, 15.7 Mo, 495 Sr	(Song and Li, 2010)
0.721	26	75	10,770	184	442	89	1614	43,180	–	23	1272	–	3.0	489	192	368	–	1.0 Hg, 3775 Be,	(Al-Futaisi et al., 2007)

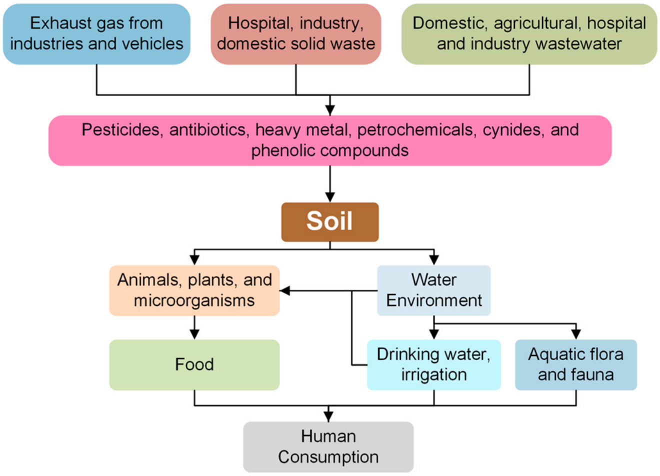

Fig. 3. The formation and diffusion of petroleum sludge and soil pollution.

Organic contaminants emitted from petroleum sludge were explored for their potential to pollute fresh water. To forecast the concentration of total organic contaminants with regard to water contacting time, a diffusion model was suggested. After 12 h of interaction, all freshwater samples were substantially polluted, and total organic pollutants measured by COD were inversely proportional to sludge emulsion stability. After 48 h of interaction, the highest COD value was over 1000 mg/L. Organic pollutant diffusion velocity rose as the water-sludge contact area grew larger. After being contaminated by 2 mL oil for seven days, the total petroleum hydrocarbon concentration of 200 mL ground water from an existing well at Eagle Island in Port Harcourt, Nigeria, was 9304.70 mg/L. As a result, finding fresh water that has been contaminated by petroleum waste is crucial for environmental protection.

1.5. Bioremediation of petroleum sludge

Engineering, geology, soil science, microbiology, and project management are all required for a successful petroleum sludge biodegradation process (Mohammadi and Mirghaffari, 2015). There are several ways for processing oil sludges with the goal of lowering toxicity, reducing sludge volume, and recovering petroleum products. Their efficiency is determined by the macrostructure and chemical composition of the sludge in question. According to literature, various treatment techniques are in practise. Bioremediation techniques (see Fig. 4) involves bioaugmentation, biodegradation, biostimulation, rhizoremediation, landfarming, bioventing, biosparging, and composting (biopiling), surfactant flushing, phytoremediation, and soil/slurry/bioslurry treatment processes (Panova et al., 2018). Additional treatment techniques are natural attenuation, wetlands, chlorination, ozonation, wet air oxidation, gasification, demulsifier systems, solvent extraction, ultrasonic lavage treatment, photo-catalysis, thermochemical conversion, flotation, incineration, pyrolysis, co-pyrolysis, combustion, thermal desorption, coking freezing/thawing, microemulsion systems, centrifugation using cyclotrons, electrokinetic method, microbial fuel cell, stabilization/solidification/encapsulation, advanced oxidation processes (Ahmad, 2017). The use of technologies such as: effective microorganism, microwave radiation, supercritical water oxidation, thermal plasma treatment using a thermal plasma reactor have also been reported (Chandrasekhar and Mohan, 2012). These treatment approaches have been found to minimize harmful elements in petroleum sludge and lessen their negative environmental and human health effects. However, because of the sludge's obstinacy, only a few technologies can strike a compromise between meeting tight environmental rules and consuming a large amount of energy, chemicals, and water. In some instances, even after treatment, there exist stable emulsions including water and hydrocarbons (Ali et al., 2019). Disadvantages

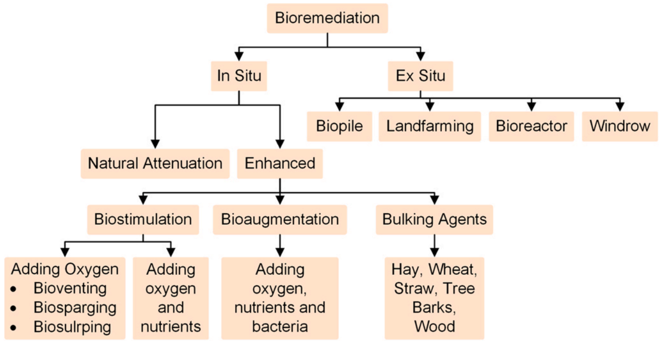

Fig. 4. Various bioremediation techniques.

Table 4
Petroleum sludge valorization methods.

S/N	Petroleum sludge valorization	Ref.
1	Sustainable construction	
	Cement clinker production	(Benlamoudi et al., 2018)
	Mortar production	(Pinheiro and Holanda, 2013)
	Building blocks	(Al-Futaisi et al., 2007)
	Ceramics	(Johnson et al., 2015)
	Brick and tile fabrication	(Pinheiro et al., 2013)
2	Road construction	
	organic binders,	(Li et al., 2015)
	Roadbed material	(Pakpahan et al., 2016)
	paving layer mixes	(Benlamoudi et al., 2018)
	dust suppressor for unpaved road maintenance,	(Roldan et al., 2010)
	bitumen supplementation	(Memon et al., 2020)
	asphalt production	(Karami and Jafari, 2018)
3	Wastewater treatment	
	Adsorbent material (Biochar and activated carbon)	(Wang et al., 2017)
	Bacteria isolates from petroleum sludge for wastewater contaminants degradation	(Silva et al., 2009)
4	Gas generation	
	Anaerobic digestion	(Ghaleb et al., 2020; Ghaleb et al., 2020; Ghaleb et al., 2021)
5	Metal catalyst synthesis	(Castro-León et al., 2020)
6	Carbon clay composite production	(Andrade et al., 2009)
7	Rubber tires manufacturing	(Turebekova et al., 2019)
8	Levan production using biofertilizer produced through effective microorganism (EM) technology	(Kekez et al., 2015)

suffered by these processes are uneconomical, ineffectiveness, greenhouse gas emissions, acidification, generation of secondary air pollution, eutrophication, ozone depletion, ecological toxicity, large space requirement, leakage and leaching of hazardous components to the underground, emission of volatile organic compounds, emission of hazardous gases and low molecular polycyclic aromatic hydrocarbon, non-ecofriendly, pre- and post-treatment requirement, sophisticated instrumentation along with skilled labors (Suganthi et al., 2018). Therefore, when choosing a petroleum sludge treatment design, environmental scientists should pay attention to treatment cost, environmental protection standards, resource recovery, sludge characteristics, treatment of toxic compounds, and social impact.

1.6. Petroleum sludge valorization

Accordng to literature, various methods of valorization of petroleum sludge exist. They have been greatly summarized in Table 4 below:

2. Research methodology

From 2005 through 2021, data was gathered from the Web of Science core collection. 'Topic' conducted the search using the phrase "Petroleum sludge." As the amount of publications increases dramatically, it is clear that petroleum sludge treatment has gotten a lot of attention in the last few decades. This could be due to the environmental impact of petroleum sludge produced by large-scale oil production. The search strategy utilized in this study focuses on four (4) electronic databases to find papers relevant to the topic of the study. The databases were chosen because they are among the most comprehensive and extensive scientific databases with broad data coverage, facilitating the development of credible bibliometric studies. Other sites such as "Researcher" and "ResearchGate" were used to find more records. In terms of search criteria, it's worth noting that this evaluation covered the years 2005–2021, and included the following studies, given that some materials are currently being researched for potential use in petroleum sludge treatment. The data collection was concluded on June 30th, 2021.

The eradication of duplicates was the first step in this study's screening stage. Since four (4) electronic databases were considered, as well as two (2) extra sources, several duplicates were discovered. Records that remained after the duplicates were removed were inspected again for relevant content. Book chapters, conference proceedings, corrigendum, dissertation, editorial papers, no access to full text, retracted articles, just abstract, and others were all removed at this time. The second stage of the literature search was to insert two phases in the document search: TITLE-ABS-KEY "petroleum sludge" AND "treatment" to find petroleum sludge treatment experiments across the scientific community. Since most authors do not use the phrase "remediation" in their article titles, it was not used. Instead, they prefer the term "treatment" because it encompasses a broader range of issues and is their primary focus. The final search was carried out in order to gather the most important articles for use in this evaluation. The study was based on the selection of articles that had clear contributions, legitimate research, and data. The purpose of the inclusion and exclusion method was to find the right research, extract the data, and synthesize it. Many articles were initially obtained for examination from the designated database. The inclusion criteria for articles chosen for the complete review after screening were based on their quality and well-known significance. This assessment considered a total of 42 (127) different sources of information. This demonstrates that students and publishers are beginning to place greater emphasis on the use of various materials in the treatment of petroleum sludge.

3. Waste, plants, soil, and diverse materials utilization during PS treatment for resource recovery

3.1. Waste materials for enhancing PS treatment, gas generation and oil recovery

The rich nutrient content in waste biomass and their economic viability are enabling factors that support their performance in oil-contaminated areas bioremediation. The possibility of using waste materials and transforming them into products of great economic value has been described here. To remediate petroleum sludge contaminated areas, the application of various additives has been proven to be a practical and environmentally beneficial alternative. Co-digestion, inoculum supplementation, and use of extra additives anaerobically and simultaneously with reactor conditions modification are required to arouse the microbial environment and thus increase the total specific landfill gas because petroleum hydrocarbon waste lacks sufficient nutrients to break down and may contain some heavy metals inhibitors. The benefit and challenges during the utilization of various waste materials have been highlighted in this section.

A study investigated the effectiveness of composting for treating oily sludge and the influence of adding sewage sludge on oily sludge biodegradation. Under low temperature conditions, sewage addition resulted in an accelerated biodegradation of oil and grease (65.6%) over 9 weeks for the contaminated soil to sewage sludge ratio of 1:0.5. The leftover 34% was classified as recalcitrant, meaning it was firmly adsorbed onto soil particles and/or retained in soil macro and micro pores, rendering it inaccessible to microorganisms (Ling and Isa, 2006). Because hydrogen can be generated in a two-stage anaerobic digestion, researchers in one study co-digested 60% petroleum hydrocarbon waste with 40% wastewater treatment sludge at 35 °C in a bigger reactor with additional hydration. Specific landfill gas levels were found to be as high as 130 mL/kg (Janajreh et al., 2020).

The effect of adding two organic co-substrates (fish sludge and municipal sewage sludge) for PS treatment by composting was examined. Treatments preserved fish and municipal sewage at thermophilic temperatures for 14 and 8 days, respectively. The addition of fish sludge reduced total petroleum hydrocarbon (TPH) by 39.5%, whereas municipal sludge addition reduced TPH by 23.9%. Using sewage sludge from the fish processing factory as a co-substrate for composting proved to be the most successful treatment for bioremediation of hydrocarbon residues. It offered nutritional circumstances that favored the growth of fungal communities and had the potential to function as a surfactant on the hydrocarbon residue, resulting in a larger TPH decrease. Due to its wide diversity and microbial biomass, municipal sewage sludge offered a bioaugmentation impact, assisting the growth of the composting process, although to a lesser extent than fish sludge (Alves et al., 2019). The possible use of sewage sludge to grow maize on experimental soil was studied. The *Zea mays* L. and sewage sludge additives, enhances plants' root and shoot growth, as well as stimulating soil respiration immediately, which increases over time. Even though the sludge impact on TPH removal was substantially larger than the plants' impact, the combined treatment at the most leading rate reduced more than half of the initial pollution. The findings suggest that sewage sludge can significantly improve the restoration of PS-contaminated soil, particularly when combined with an appropriate plant like maize (Asadollahi et al., 2016).

Activated sludge and municipal wastewater serving as inoculum and diluent were both used for refinery sludge biodegradation. In the aerobic batch reactor, municipal wastewater aided in the biodegradation of this harmful contaminant because it has a balanced N:P ratio and chemicals that facilitate hydrocarbon emulsion. In the first 19 days, the original total hydrocarbon concentration of 750 mg/L was decreased to 5 mg/L with a chemical oxygen demand elimination rate of 97%. Hydrocarbon load influenced bacterial dominance. The authors noted that bacterial strains suitable for oily sludge biodegradation were found in municipal wastewater and activated sludge (Hamed et al., 2010). Biochar produced from fruit + vegetable waste and sewage sludge were used to improve the bioremediation of diesel-polluted soil. The additions were shown to greatly increase the rate of hydrocarbon biodegradation, with removal efficiencies above 70%. Biological processes, not adsorption, were blamed for the hydrocarbon decomposition. Bioaugmentation with cow manure boosted the removal effectiveness even more, bringing it to 82%. The prevalence of 27 different bacteria phyla was detected in the treatments with the best levels of elimination efficiency by *Proteobacteria* and *Actinobacteria* being the most abundant (Aziz et al., 2020). Greater than 380,000 mg/kg TPH contaminated soil was bioremediated by composting. Inoculated with sewage sludge, the soil mixed with wood chips in a 1:1 (v/v) ratio was incubated for 19 months. A part of it was then mixed with sewage sludge in a 4:1 ratio. TPH in the sewage sludge compost was lowered by 99% at the end of the incubation period. During the same time span, the concentrations of most of the tested hydrocarbon components dropped by up to 100%. The decrease in soil hydrocarbon concentration was shown to be correlated with microbial activity (Atagana, 2008).

The distribution of products, gas compositions, and evolution behavior were studied in relation to pyrolysis temperature and interactions between PS and sawdust. The findings revealed that high temperatures encouraged gas generation, with a significant increase in gas yield when temperatures above 700 °C. The inclusion of sawdust aided in the development of volatiles, the rise of gas yield, and the production of H_2 and CO. The activation energy required for breakdown was lowered. At 60 wt% sawdust, the gas yield was 39.59 wt%, the H_2 + CO content was 61.34 vol%, and the LHV was 13.39 MJ/Nm^3, indicating the largest accelerative impact on gas yield. It was concluded that sawdust addition was found to be beneficial to syngas production (Zhu et al., 2020). In another related study on the co-pyrolysis of sawdust with refinery sludge, a synergetic influence led to about a 4% increase in the yield of oil obtained from sawdust. The oil and char produced were likewise of greater quality, than the bio-oil produced just through sawdust pyrolysis. The carbon content of the char formed rose as the percentage of sawdust in the feedstock rose. In comparison to sawdust pyrolysis alone, the greater heating value of oil derived from sawdust increased by 5 MJ/kg after co-pyrolysis at a sawdust/oily sludge ratio of 3:1 (Hu et al., 2017).

During a 90-day period, the impacts of sawdust and a mixture of cow and sheep dung on hydrocarbon bioremediation were studied in a test biopile consisting of soil contaminated with petroleum waste. The soil was fluffed by 1.5% sawdust and a biostimulant *autochthonous* microflora was used. TPHs were lowered from 52 to 10.6 g/kg. Gram-positive bacteria from the actinomycete family and autochthonous microorganisms were the most common microorganisms in the soil. At 45 days, they were able to breakdown 1.6 × 10^7 cfu/g hydrocarbons. The authors found that the biopile experiment is a cost-effective, efficient, ecologically friendly, and optimum technique for petroleum hydrocarbon-contaminated soil restoration (Beškoski et al., 2012). A study investigates hydrocarbons reduction in petroleum sludge using wheat straw, pine fruit, walnut shell, almond shell, and sawdust as low-cost adsorbents. The sawdust showed the highest oil and grease reduction for more than 60% mass. The optimum amounts of contact time and adsorbent dose and size for sawdust were found to be 50 min, 60 g/L, and 0.3–0.6 mm. The results demonstrated that sawdust can be a low-cost, widely available, and flammable adsorbent for the reduction of oil pollutants from the storage tank sludge (Mokhtari-Hosseini et al., 2017). Rice husk, apricot shell, sawdust, and walnut shell were used to investigate the co-pyrolysis of oil-containing sludge. Adding biomass within 0–1.0 wt% gradually decreases the water content in the oily sludge. The sludge dewatering ability was highest when apricot shell was used. This was followed by walnut shell, rice husk, and finally sawdust. The increased oil recovery could be related to biomass involvement in the pyrolysis process, which could prevent unequal heat transfer and increase the amount of useful energy for pyrolysis. Rice husk and sawdust were more effective at recovering petroleum hydrocarbons than other materials. The recovery efficiency rose with increasing biomass quantity in the region of 0–0.2 wt%, then gradually decreased as biomass quantity increased from 0.2 to 1.0 wt%. As a result, the optimal quantity of biomass plays a critical role in the recovery rate (Zhao et al., 2018).

Oily sludge from an oil refinery wastewater treatment plant was subjected to aerobic biodegradation for 53.3 weeks treatment period. The sludge was blended with one of the following additions in four 1 m^3 pilot bioreactors with regulated airflow: kitchen waste compost, shredded waste wood, matured oil compost and sand with PAHs reductions as 92%, 88%, 86% and 97% respectively. The TPH decrease based on mass balance were 74%, 49%, 51%, and 62%, respectively (Kriipsalu et al., 2007). The development of the microbial population during the bioaugmentation of petroleum-contaminated soil with *Enterobacter cloacae (E. cloacae)* as an inoculant was studied. *Pseudomonas sp. and Rhodothermus* sp. grew faster after being seeded with *E. cloacae*. The use of wheat straw as a typical lignin waste in combination with bioaugmentation increased *E. cloacae* growth. After 8 weeks of treatment, the total dehydrogenase activity increased from 0.50 to 0.79 μgTPFg^{-1}min^{-1}, microbial content enhanced to about 130% for bacteria and 84% for fungus, and an overall improvement in the degradation ratio from 44% to 56% (Wu et al., 2011).

Using in screen house experiments, the effectiveness of composted municipal organic wastes in degrading TPHs present in soils polluted with petroleum compounds was evaluated. According to the findings, the treatments boosted soil pH and electrical conductivity while lowering TPH. Compost technology resulted in a maximal 76% TPH reductions. Plant growth toxicity decreased to 16.12% (Adekunle, 2011). Landfarming treatment with additional cotton stalks was used for a 39-month field bioremediation of oil sludge polluted environment. TPH, saturated fraction, and aromatic fraction removal efficiency were 69%, 90% and 86%, respectively (Wang et al., 2016). The impact of using hog fuel as a bulking agent for oil-contaminated soil restoration was studied in 5 months period at an average temperature of 11.4 °C. According to the findings, landfarming reduced TPH concentrations by 81%. This implies that hog fuel considerably increased landfarming's treatment potential by boosting soil aeration, increasing porosity, and diluting hydrocarbon pollutants in the soil (Song and Li, 2010). Sludge from the tank bottom can be solidified as an alternative to disposal. Different sets of specified additives, such as regular portland cement, cement by-pass dust, and quarry fines, were used to solidify the mixtures (Al-Futaisi et al., 2007).

Ex-situ bioremediation of crude PS was investigated to determine the function of co-culture and external nutrients addition in an anaerobic microenvironment. The co-culture materials and nutrients utilized are domestic sewage, 4% cow dung, anaerobic sludge from industrial and domestic wastewater treatment plants), 2 g NPK source (DAP) sludge. TPH elimination was highest when biostimulation and bioaugmentation were combined (44%), followed by bioaugmentation alone (34.5%), co-substrate enhanced operations (9.9–23.4%), and control (4.4%). In all the settings tested, the aromatics fraction showed a higher rate of deterioration. Combining biostimulation and bioaugmentation resulted in good degradation of four-ring PAHs, while bioaugmentation alone resulted in excellent degradation of three-ring PAHs. With the use of biostimulation, lower ring PAHs compounds demonstrated good breakdown. PAH-degrading microorganisms during the process were identified as *Bacillus, Pseudomonas, Acidobacteria*, sulphur-reducing bacteria *Firmicutes*, and others. Both the inclusion of co-cultures and the augmentation of nutrients had a substantial impact on the overall deterioration pattern (Devi et al., 2011). The combination of biostimulation, bioaugmentation, and co-substrate inclusion showed efficient deterioration of TPH (38.4%), aliphatics (44.5%), asphaltenes (29.6%), and aromatics (51%) compounds. In a closely related study by the same authors using domestic sewage, cow dung, NPK source (DAP), and distillery wastewater as co-substrates (15%). The breakdown of lower ring compounds was more noticeable than that of higher ring compounds. Individual PAHs showed a similar pattern of breakdown. Distillery waste was shown to be more efficient than domestic sewage (Mohan et al., 2011). The co-pyrolysis of oily sludge and rice husk was conducted to examine the effects of interactions on the products and increase the pyrolysis oil quality. The catalytic actions of ash and alkali metals obtained from biomass are responsible for the synergy. It was reported that, the synergy improved the quality of the oil product by increasing the concentration of saturates and aromatics while lowering heavy fractions. The interaction drastically reduced the quantity of oxygenated molecules by 46–93% and increased the percentage of chain hydrocarbons. The gas output was increased due to the stimulation of secondary reactions, which resulted in the production of additional H_2, CO, and C_1–C_2 hydrocarbons. Sulfur dispersion in oil and gas stages was encouraged. During the co-pyrolysis process, thiophene was degraded and further oxidized (Lin et al., 2018).

The impact of adding biogas slurry and using rice hulls as bulking agents on the composting of petroleum-contaminated soils was studied. As an activator, biogas slurry was introduced to the compost of hydrocarbon-contaminated soil. The results reveal that adding it to composting increased oestrogen levels. However, the products were still at a safe level. It also improved organic matter degradation, composting maturity and humic acid (HA) humification, increased germination index by 18%, and improved TPH degradation by 12.8% compared to the control group (CK). It did, however, lower the amount of phytotoxin in composts via controlling total nitrogen (TN) and HA. The estrone in biogas slurry was eliminated during composting and had no effect on the compost's phytotoxicity (Xi et al., 2020). Green mango peel extracts were used to make zero-valent iron nanoparticles. Green mango peel-nanozero valent iron (GMP-nZVI) activated system was the product's name. TPH was removed from oil sludge-contaminated soil using GMP-nZVI, which resulted in > 90% degradation after one (1) week of treatment. The GMP-nZVI outperforms chemically manufactured nanoparticles in terms of TPH removal efficiency, low production costs, and low environmental issues (Desalegn et al., 2018).

Microwave absorbers (coconut activated carbon (CAC), palm kernel shell activated carbon (PKSAC), and petroleum coke) were investigated to see how they affected the product yield from microwave pyrolysis of oily sludge. In a nitrogen environment, the absorbers were applied to raise the temperature of the pyrolysis reaction. CAC, petroleum coke, and PKSAC addition increased the heating rate by shortening the drying process. In comparison to other absorbers, adding 10% CAC resulted in higher production rate for H_2 (15%) and CO (13.3%), resulting in a lower heating value of 5.57 MJ/m^3. For all moisture content of oily sludge samples, 65 wt% of gas was created. It also reduced the time it took for oily sludge to dry to 30 min. Although the supplemented sample with petroleum coke achieved the highest maximum temperature, the lowest gas product was collected (59%) (Mokhtar et al., 2018). Dry yard waste (CI) and non-recyclable paper (CII) were used as bulking agents in the co-composting of oil sludge polluted soil. Over the course of the 98-days research, the maximal TPH reduction for CI and CII was 55% and 56%, respectively. The nearly identical TPH removal achieved in CI and CII demonstrates the value and effectiveness of adding paper products in composting, which gives cost, processing, and removal advantages (Malakahmad and Jaafar, 2013).

Chemical and physical features of biomass and petroleum industry sludge differ. The features such as ash concentration, volatile matter, and oxygen content can result in a synergetic interaction between them during co-pyrolysis. Dewatering and pyrolysis behavior are expected to improve with the addition of biomass. As a result, waste biomass such as petroleum sludge, sawdust, cow and sheep dung, and others could be employed as supplement during pyrolysis process of another waste to improve energy recovery rate. Biomass addition also aid the synthesis CO and CxHy and regulates the pollutants in exhaust gas emitted. The mixture also efficiently reduces the dangers of hazardous waste to the environment. It was also observed that composted waste could help bioremediate soils that have been contaminated by petroleum and petroleum products (Kriipsalu et al., 2007).

3.2. Phytoremediation for PS contaminated soil

Plant-based restoration is a relatively new, economical, and eco-friendly method that has the capability to remove toxins like hydrocarbons. The use of a plant materials that can grow in the face of high levels of pollutants was one of the most important aspects of successful phytoremediation. Hydrocarbon breakdown is believed to be faster in vegetated soils than in non-vegetated soils, however the influence of these pollutants on plant physiology and antioxidant systems is unknown. Therefore, several authors began to investigate the effect on these plants.

Maize seedlings have been transplanted into spiked soils to investigate their behavior during oily sludge contaminated soil remediation. It was revealed that only a certain content of crude oil (2147 mg/kg) in the soil might boost maize shoot biomass output. Remarkably, a higher quantity (6373 mg/kg) did not have negative impact on the germination of maize plant (Liao et al., 2015). PAHs with very less molecular weight were found in maize tissues, but the number of PAHs in the plant did not rise when the amount of crude oil in the soil increased. During sixty (60) days treatment period, TPH in planted soil was reduced by up to 73%, while that of the matching controls was only 34%. The adaptation of maize to crude oil pollution stress was shown to be good. Plant-growth-promoting rhizobacteria (PGPR) strains were utilized by (Huang et al., 2005) to boost plant resistance and accelerate their development in severely polluted soils.

A polyglycerol polyricinoleate (PGPR) consortium made up of *Bacillus altitudinis, Comamonas* and *Bacillus cereus*, from the *Comamonadacea* and *Stenotrophomonasmaltophilia* family was blended with fertilizer and utilized to assess the physiology of maize (*Zea mays L.*) growing in a PS polluted area. At day 3 period, TPH degradation in a combined treatment was 59% higher in maize (Zea mays L.) treated plant than in an untreated one. Once inoculated with the PGPR consortium, maize can be regarded a resistant plant species for remediating oily sludge contaminated soils, as it thrives better under 30% of oily sludge. It can improve the physiology of maize by enhancing hydrocarbon decomposition. It does, however, react to oxidative and osmotic stress (Shahzad et al., 2016). In a related study using same bacterial consortium with alfalfa (*Medicago sativa* L.) plant in combination with fertilizer to remediate an oily sludge: soil mixture 30:70 ratio, 63% TPHs were degraded with significant degradation (80%) of n-alkanes (nC13 to nC29) witnessed at day 3. Thus, the mixture has been proven to be efficient in hydrocarbon remediation (Shahzad et al., 2020). Winter rye (*Secale cereale* L.) was used as the main phyto-remediating plant, while nitrogen fertilizer, alfalfa (*Medicago sativa L.*), and PGPR strain (*Azospirillum brasilense* SR80) were used as extra components, either independently or in numerous combinations, to stimulate phytoremediation of oil sludge contaminated soil in vegetative experiments. The results demonstrated that alfalfa is crucial for phytoremediation of hydrocarbon-contaminated soil. More specifically, the use of several multicomponent treatments led to a 70% reduction in pollutant content in soil (Muratova et al., 2010). Peat replaced fertilizer in a highly petroleum hydrocarbons (~3.5% by weight) contaminated aged soil to evaluate the phytoremediation potential of tall fescue (*Festuca arundinacea*) and *Zea mays L.* Although, the maximum removal (96%) was obtained in tall fescue, findings revealed that the examined plant species are promising and efficient in TPHs degradation (Zand et al., 2010). Still on peat, a study also utilizes it (0%, 1.3%, 7.4% and 12.2%) in a batch pot experiment to enhance oily sludge contaminated soil restoration. Tall fescue, cotton, and ryegrass were found to have excellent saline-alkaline resistance and decomposed petroleum hydrocarbons promptly in contaminated soils. After 24.3 weeks of treatment, TPH elimination ranged from 30% to 40% (Wang et al., 2016).

Petroleum sludge contaminated soil remediation by phytoremediation were studies over a 3-months incubation period with ryegrass, natural attenuation, wheat straw-derived biochar amendment, and a hybrid mixture of ryegrass and biochar. The outcomes revealed that sowing ryegrass in the soil can remarkably boost microorganism's growth and TPH elimination rate. The removal rate of total nalkanes (46%) was higher than that of PAHs (30%) within TPHs. Biochar supplement did not cause notable adverse impacts on soil microflora. It, however, subdued ryegrass maturity and development with no significant improvement in TPH removal (Han et al., 2016). To assess the application *Ludwigia octovalvis* for phytoremediation of crude oil sludge in contaminated site, its phytotoxic effects on tropical native plants were investigated. Findings reported the high TPH removal at 42-day exposure as 67%, 42% and 46% in sand spiked with crude oil sludge at 10%, 50% and 100% respectively. Thus, it is evident that L. *octovalvis* can diminish hydrocarbons in crude oil sludge (Alanbary et al., 2019). The abilities of leguminous *Onobrychis viciifolia* species to form a vegetative cover on contaminated soil with 2.86% TPH and to assess the degradation efficiency from the rhizosphere was evaluated. The fertilization of contaminated soil with 50 t/ha fertilizer agent, municipal sludge anaerobically bio-stabilized, combined with indigenous volcanic tuff (5 t/ha), determined the vegetation of *Onobrychis viciifolia,* resistant to prolonged drought. *Onobrychis viciifolia,* has demonstrated the ability to biodegrade TPH. The results obtained on the experimental variants supplimented with sewage sludge in the presence of indigenous volcanic tuff showed 55–70% degradation and an increased level of crop germination after an 8-week vegetative cycle. The quantity of dry biomass produced under conditions of mixed fertilization with addition of indigenous volcanic tuff was like that harvested on the experimental variants of unpolluted soil (Masu et al., 2013). Another leguminous plant *Cajanus cajan* was assessed as a phyto remediating substitute for petroleum oily sludge (POS) contaminated soil. Compared to other treatments, results here demonstrate that for oily sludge concentrations of 1–3%, an increase in microbial counts from 0 to 3 months was found in the polluted rhizosphere. TPH degradation rates were 92%, 90%, 89%, 68%, and 47% with 1%, 2%, 3%, 4%, and 5% (w/w) of POS, showing removal hindrance at higher POS concentrations. *C. cajan* proved to have a lot of potentials when it comes to restoring POS-contaminated soil (Allamin et al., 2020).

A 90-day pot culture experiment for TPH degradation of oil sludge contaminated soil was carried out. *Vertiver zizanioide* bio-augmentation treatment with a bulking agent (wheat husk) was examined. It was clear that 85% oil decreased in the system. TPH reduction and aromatic fraction degradation were observed to be 89% and 92% respectively. The multipotential rhizosphereic consequence confirmed to be prosperous in eliminating most aromatic and insoluble asphaltene content of TPH (Dhote et al., 2017). Same authors in another study (Nanekar et al., 2015), using same amendments and time as earlier reported but under controlled conditions, found 28-fold rise in dehydrogenase activity and total PAHs mineralization. Furthermore, in bulked treatments with plant, nutrients, and consortium, 73% TPH degradation was found. The phytoremediation activity of *Vetiveria zizanioides* (L.) Nash (vetiver) in a fresh and aged contamination with 3500 mg/kg and 700 mg/kg aliphatic petroleum hydrocarbon (APH), respectively were studied. The APH level was reduced by 89% in both contaminated soils where vetiver was grown for 64.3 weeks, and the vetiver vegetation improved hydrocarbon bioavailability, consequently increasing the degree of biodegradation hydrocarbons in the soil. In both vegetated soils, the carbon availability index increased by (~1). In soils under vetiver vegetation, the mRNA level of the *nosZ* gene risen considerably, and this was linked to the buildup of APH in the soil solution (Rajaei and Seyedi, 2018). When the capacity of Australian red ash (*Alphitonia excelsa*) extract biosurfactant was assessed for bioremediation of PS-contaminated soil, the findings confirmed that the extracted biosurfactant was appreciably effective in terms of total 16 USEPA key focus on PAHs (79%) and TPH (93%) degradation (Blyth et al., 2015).

Rhamnolipid biosurfactant supplementation in the phytoremediation of metals and petroleum hydrocarbons co-contaminated soil through sunflower (*Helianthus annuus L.*) cultivation was monitored for 90 days. The outcome of the remediation tests reveals that sunflower plants grown with 4 mg/kg rhamnolipid yielded the best contaminant degradation. Under these conditions, TPH, PAH, Ni, Cr, Pb, and Zn concentrations were reduced by 58%, 48%, 41%, 30%, 29%, and 20% respectively. Sunflower planting and biosurfactant reinforcement is a practical and efficient approach for treating soils polluted with metals and petroleum hydrocarbons, with no impact on the structure of the soil's prevalent bacterial community. The potentials of *Cyperus brevifolius* (Rottb.) Hassk and *Cyperus rotundus* (Linn.) native sedge species to degrade TPH from PS contaminated soil were examined during one (1) year operation. In the fertilized soil, findings revealed that, 345.5 g and 250.6 g were discovered as the average biomass production for *C. rotundus* and *C. brevifolius* respectively with 75% and 64% TPH degradation for *C. rotundus* and *C. brevifolius* respectively. The TPH accumulated in the roots and shoots (Basumatary et al., 2013). The potential of petroleum sludge treatment by composting, phytoremediation, and composting + phytoremediation experiments using elephant grass (*Penninsetum purpureum*) were examined. The compost consisting of N-P-K fertilizer aiming at plant growth enhancement was used for the bio-stimulation of indigenous microbes. The composting, phytoremediation, and composting + phytoremediation over 12-weeks treatment period showed 47%, 69%, and 29% reduction respectively (Ayotamuno et al., 2010). With 71–121 g/kg d.m. TPH, a combination

Table 5
Efficiency of environmental microbes from petroleum industry sludge for contaminated soil amendment.

Strain type	Specific environmental microbe used	Source	Process	Removal efficiency (%)	Duration (days)	Ref.
Bacterial	*Pseudomonas putida, Flavobacterium* sp., *and Pseudomonas aeruginosa*	Refinery sludge	multi-process phytoremediation system	90 TPH removal	240	(Huang et al., 2005)
Bacterial	*Bacillus cereus*	bottom of crude oil storage tanks	filter membrane processS	81.7 TPH	15	(Said et al., 2006)
Fungal	*Paecilomyces variotii*;			74 TPH	10	
Bacterial	*Pseudomonas aeruginosa ZS1(Zhou-Shan isolate 1).*	loading dock of oil tanks		50 crude oil	12	(Cheng et al., 2017)
Bacterial	*Pseudomonas spp. (4M12) and Pseudomonas xanthomarina (4M14),*	Oil Refinery	slurry phase bioremediation protocol	96–97 TPH	90	(Mansur et al., 2016)
Bacterial	*Rhodococcus ruber AKSH-84*	Petroleum Refinery Unit		63 yield of bioconversion	120	(Kamal et al., 2011)
Bacterial	*Pseudomonas aeruginosa PSA5*	oil refinery	Biodegradation	88 benzo(a)pyrene degradation	–	(Mishra et al., 2014)
Bacterial	*Sphingomonas olei strain* KA1 and *Acinetobacter radioresistens* strain KA2	oil refinery plant	Composting and bioaugmentation	60.14–91.24 TPH	90	(Koolivand et al., 2019)
Bacterial	*Enterobacter hormaechei* strain KA3 and *Staphylococcus equorum* strain KA4	oil refinery plant	two-step inoculation composting process	89.35 TPH	120	(Parhamfar et al., 2020)
Bacterial	*Pseudomonas, Achromobacter, Bacillus* and *Micromonospora*	Oil Refinery	Biodegradation	82–88 TPH	90	(Gojgic-Cvijovic et al., 2012)
Bacterial	*Pseudomonas aeruginosa* NCIM 5514	oil fields	Bioaugmentation + Biostimulation	92.97 decrease in oily sludge	56	(Varjani et al., 2020)
Bacterial	*Acinetobacter radioresistens strain KA2, Enterobacter hormaecheistrain KA3*	oil refinery plants	vermicomposting	85–91 TPH	90	(Koolivand et al., 2020)
Bacterial	*Acinetobacter* sp. *SCYY-5*	–	Biodegradation	69.17–79.94 TPH	10	(Cai et al., 2021)
Bacterial	*Klebsiella pneumoniae* (Kp) *and Pseudomonas aeruginosa* (Pa)	activated sludge of a petroleum refinery	Biodegradation			(You et al., 2018)
Bacterial	*Bacillus pumilus* MVSV3	open-to the-air storage tanks of refinery		97 TPH	122	(Varma et al., 2017)
Bacterial	*Bacillus aerius* B2, *Psuedomonas stutzeri* B3, *Ochrobactrum interme-dium* B4, *Micrococcus lylae* B5, and *Acinetobacter calcoaceticus* B9	oil field	natural attenuation	88 TPH	14	(Iyobosa et al., 2021)
Bacterial	*Franconibacter pulveris* strain DJ34	oil fields				(Pal et al., 2017)
Fungal	*Trichoderma atroviride, Aspergillus nidulans* and *Aspergillus sydowii*	oil spilled site		27.7–36.8 TPH	30	(Khandelwal et al., 2021)
Bacterial	(*Acinetobacter radioresistens* strain KA2	oil refinery plant	Bioaugmentation and composting	67.64–89.56 TPH	120	(Poorsoleiman et al., 2020)
Bacterial	*Bacillus subtilis, Bacillus megaterium, Achromobacter xylosoxidans, Pseudomonas fluorescens, Candida tropicalis* and *Rhodotorula dairenensis*	petroleum-contaminated soil	bioremediation	80.6 TPH		(He et al., 2014)

of grassland species *Ttrifolium pratense, Lolium perenne, Medicago sativa*, and *Festuca arundinaeasca*, were utilized during an in-situ phytoremediation of oil tainted soil. Włóka et al. (2019) investigation revealed that the better outcomes for PAHs percentage removal and biomass yield were obtained when energy crops *Brassica napus L.* (*B. Napus L.*) and *Phalaris arundinacea L.* (P. arundinacea L.) and were coupled with compost fertilization and assisted by nano-SiO_2 addition.

This review found that the most probable number in planted treatments was remarkably greater than in unplanted ones. Therefore, these plants are fit for phytoremediation of PS polluted environments. It also discovered that there is a commercial potential for the use of some or most of these plants as sources of biosurfactant for use in accelerated TPHs degradation. In addition, the concoction of different additives in the sequence; plant-microbe-bulking agent-soil system otherwise referred to as rhizodegradation helps in soil restoration and can be utilized as a powerful mechanism for PS contaminated area remediation. This because, bioaugmentation enhances microbial degradation, nutrients addition stimulates native and expanded consortium while bulking agents increase porosity and aeration.

3.3. *Soil for petroleum sludge treatment*

In a slurry phase reactor, aerobic biodegradation of petroleum sludge was investigated using varied natural soil concentrations. TPH and PAHs were found to be successful at removing them, however this was discovered to be dependent on the soil content. In the PAHs profile, efficient aromatic compound removal was observed, with lower ring compounds demonstrating greater removal efficiency than higher ring compounds. Proteobacteria were discovered to be dominating, accounting for 50% of the overall population (25% of γ-proteobacteria; 16.6% of β-*proteobacteria*; 8.3% of α -*proteobacteria*), with uncultured bacteria accounting for 33.3% and *firmicutes* accounting for 16.6% (Reddy et al., 2011). On soil contaminated with oil sludge, the possibility of reusing remediated soils for bioremediation activity for 84 days was investigated. In naturally attenuated microcosms, TPH decrease was considerable ($> 80\%$). This revealed that the observed TPH decrease could be linked to the soil's intrinsic hydrocarbon-degrading capacity. Hydrocarbon-degrading genera like *Scedosporium* and *Alcanivorax* were found to be dominant. As a result, the study concludes that remediated soils have a higher hydrocarbon degrading capacity. The tendency to re-harness this capability is appealing since it lowers operational expenses by eliminating the need for extra bioremediation procedures. It could also prolong the life of a landfill because soils can be reused before being disposed of. The efficiency of a biosurfactant-producing and oil-sludge-degrading bacterial strain (*Ochrobactrum* stain CN3) obtained from the soil of a wood treatment factory was examined. The isolate was able to thrive on PS as a source of carbon and energy, and when complemented with the biosurfactant it created, it demonstrated improved degradation. The isolate deteriorated up to 40% of the hydrophobic long chain aliphatic and PAHs, while the biosurfactant-added microcosm demonstrated up to 70% degradation of the PS most hydrophobic components in 21-days. The isolate had a great level of thermal stability, was resistant to high salinity, and had a good effect on raising pH (Bezza et al., 2015).

3.4. *Diverse materials for petroleum sludge treatment*

Microporous and mesoporous zeolites are thought to be potential catalysts for digesting petroleum wastes produced during refining. Milato et al. Milato et al., (2020) in their study investigated the use of mesoporous zeolites in combination with various polyolefins for co-pyrolysis of petroleum sludge to produce a paraffin-rich oily product. When polyolefins were present in oil sludge, pyrolysis produced oily products with different yields and compositions, which were directly connected to the polymeric structure. In PS pyrolysis, studies employing linear structure chain polyolefins, the zeolites CBV720 catalyst enabled the production of paraffinic products while reducing aromatic and cyclic chemicals. Only when utilizing the linear chain polyolefin did significant results emerge. Oil sludge was pyrolyzed in the presence of mesoporous zeolite catalysts (CBV 780). The values derived in the addition of mesoporous zeolites had a higher selectivity for light hydrocarbon conversion and a lower proportion of aromatic compounds. In catalytic pyrolysis, the CBV 780's homogenous porosity spread was the deciding factor. The application of this catalyst resulted in a 56% oil fraction with the best light hydrocarbon output (96%. Therefore, pyrolysis with mesoporous zeolite could be used to treat the residue(Milato et al., 2021). During the degradation of petroleum sludge, the use of an upgraded thermogravimetry device a protonic acid form of zeolite (HY) to obtain light gases and distillate fuels was evaluated. The zeolite microporous material (NaY) was synthesized. The crystalline structure of the faujasite zeolite was established according to the samples' characterization. When this microporous material in its protonic acid form (HY) was used to catalyse petroleum sludge degradation, the cracking impact was noticeable. This resulted in a faster transformation of materials due to temperature and a decrease in the needed activation energy. The outcomes revealed that the presence of HY zeolite increases residue decomposition. The most likely model for sludge degradation is diffusion, followed by thermal and catalytic degradation. This is in accordance to activation energy results in the range of 10–14 kJ/mol (Silva et al., 2019).

Microalgae residue (MR) supplement was employed in the pyrolysis of oily sludge to give a green and effective technique for oily sludge processing. This increased the pyrolysis oil's quality and encouraged the transformation of heavy hydrocarbons, leading to a high light hydrocarbon concentration. With a 5% and 30% MR inclusion ratio, the quantity of light oil grew to 38% and 45% respectively. CO and CO_2 content increased as the MR blending ratio was increased, whereas H_2 and C_xH_y content dropped (Gong et al., 2018). The use of filters excludes cross-contamination because only microorganisms under consideration appeared on agar plates. However, cultivating microorganisms on filters has significant drawbacks, since the filter may act as a barrier between certain hydrocarbons and the microbes, limiting the bioavailability of substrate components to the microorganisms (Huang et al., 2005). The sensitivity and growth level of microorganisms on petroleum oily sludges were evaluated using a concept based on cultivating microorganisms on 0.22 m filter membranes spread over oily sludge deposited in metallic cups. The protocol was tested using *Paecilomyces variotii*; *Bacillus cereus*; and a combination of both strains. The strains were identified as oil degraders after being isolated from the oily sludge utilized in the investigation. The drop in petroleum hydrocarbon concentration in the oily sludge as shown in Table 5 was confirmed and corroborated by the findings of the solvent extraction method (Said et al., 2006).

Oil was extracted from oily sludge using a mixture of tertiary amines (TA) and protonated tertiary amines (PTA). It was discovered that 3–5 wt% PTA addition/supplementation improved the oil recovery. Furthermore, the incorporation of positively charged ions of PTA on the sludge boosted the wettability, and the contact between heavy alkanes of crude oil and PTA facilitated the detachment of crude oil from the sludge surface, hence increasing the sludge hydrophilicity (Dai et al., 2020). The mechanics of potassium persulfate oxidation and its feasibility have been investigated. The oil degradation rate was found to be 38%, with visible morphological changes in the sludge before and after degradation. This suggests that oil can be deteriorated in sludge by persulfate, which is based on the production of sulphate radicals and hydroxyl groups during oxidation. The use of toluene and Fe_2O_3 nanoparticles in solvent extraction to salvage and upgrade oily sludge was investigated. The sludge recovery was 37% at ideal circumstances (55 °C, 17 min of mixing time, and a solvent to sludge ratio of 6.4/4.2), which is the highest possible with toluene. During the sludge pyrolysis process, Fe_2O_3 nanoparticles reduced the temperature and time required to obtain maximal conversion to 200 °C and 1200 °C, respectively. This is less than the temperature at which pure sludge is pyrolyzed (Nezhadbahadori et al., 2019).

Biosurfactant (Rhamnolipid) was refined using zerovalent iron nanoparticles to improve oil recovery and promote viscosity reduction of oily sludge. Under the influence of an external magnetic field, contaminants were attached to nanoparticles and easily removed from the biosurfactant solution. In comparison to unpurified rhamnolipid, the combination of nanoparticles with rhamnolipid that results in pure rhamnolipid has a stronger ability to lower viscosity and enhance oil fluidity. Surface tension and critical micelle concentrations (CMC) calculated using equation 2 revealed an increase in rhamnolipid purity from 48% to 83% under ideal conditions. The interfacial tension of n-decane/water (1/1) was reduced by the purified biosurfactant from 27 to 1.2 mN/m, while the unpurified rhamnolipid was reduced from 27 to 6.7 mN/m. Purified biosurfactant reduces the viscosity of oily sludge by 27.2% more than unpurified biosurfactant (Sahebnazar et al., 2018). The level of purity was assessed qualitatively by comparing purified rhamnolipid CMC to standard rhamnolipid CMC. Ethoxylated sugar fatty ester surfactant was prepared by the reaction of glucose with adipic acid to produce a glucose ester which was then ethoxylated by 4000 mol/L molecular weight polyethylene glycols. The prepared surfactant was put to test as demulsifier for petroleum sludge. After 6 h of application, the generated surfactant separated around 90% of the water from the sludge. Low molecular weight hydrocarbons are abundant in the oil phase isolated from the sludge after treatment with the produced surfactants, which may signify their efficiency as demulsifiers for petroleum sludge (Abdul-Raheim et al., 2013).

4. Conclusion

Petroleum industry sludge generation rate has been increasing because of the ascending energy demand. The sludge has shown to contain hazardous constituents that may have negative consequences on the environment and public health. Therefore, their release to the environment needs to be strictly controlled. Different treatment and disposal methods targeting petroleum products extraction, toxicity and sludge volume reduction have been explored. But due to the recalcitrant nature of the sludge, barely a few technologies can strike a compromise between meeting strict environmental regulations while consuming a notable quantity of water, energy, and chemicals. Now, there are no waste-free and cost-effective technologies available for PS treatment. Therefore, this review was designed to highlights the several waste, plants, and other materials utilized during petroleum sludge or petroleum contaminated site treatment to ensure environmental safety and for possible resource recovery. The waste materials include fish, activated sewage and anaerobic sludge; almond, walnut, apricot, and palm kernel shell; green mango peel extracts; wheat straw; rice husk and hull; cow and sheep dung; wood chips; distillery and municipal wastewater etc. The review found that in planted treatments using Zea mays L., *Secale cereale* L., *Festuca arundinacea, Onobrychis viciifolia, Vertiver zizanioide, Cajanus cajan, Medicago sativa, Lolium perenne, Ttrifolium pratense* etc. the most probable number were significantly higher than in unplanted treatments. Therefore, there is a commercial potential for the use of some or most of these for phytoremediation of PS contaminated fields. Finally, the fundamental knowledge contained in this review would inspire researchers to find research gaps that will aid the controlled and sustainable management of PS. It could also serve as a wake-up call for researchers and motivate them to produce new products using PS as a raw material thereby utilizing them appropriately for greater environmental benefits associated with public health safety.

Acknowledgments

The authors would like to express their gratitude to Universiti Teknologi PETRONAS (UTP) for supporting the research.

Declaration of interest

The authors declare that they have no conflict of interest.

References

Abdul-Raheim, M.A., et al., 2013. Some sugar fatty ester ethoxylates as demulsifiers for petroleum sludge. J. Surf. Deterg. 16 (3), 377–387.

Adekunle, I.M.J.B.J., 2011. Bioremediation of soils contaminated with Nigerian petroleum products using composted municipal wastes. Bioremed. J. 15 (4), 230–241.

Aeslina, A., Ali, B., *Petroleum sludge treatment and reuse for cement production as setting retarder*. in IOP Conference Series: Materials Science and Engineering 2017 IOP Publishing.

Ahmad, J.J.P.S., Technology, Bioremediation of petroleum sludge using effective microorganism (EM) technology. 35 14 2017 1515 1522.

Al Qallaf, Y. et al., Analysis and improvement possibilities of waste management at Kuwait Oil Company (KOC) 202 2016 73 84.

Alanbary, S.R.N., et al. Phytotoxicity of contaminated sand containing crude oil sludge on Ludwigia octovalvis 20 2019 11.

Al-Futaisi, A., Jamrah, A., Yaghi, B., Taha, R., 2007. Assessment of alternative management techniques of tank bottom petroleum sludge in Oman. J. Hazard. Mater. 141 (3), 557–564.

Al-Futaisi, A., Jamrah, A., Yaghi, B. Taha, R., Assessment of alternative management techniques of tank bottom petroleum sludge in Oman 141 3 2007 557 564.

Alhadj-Mallah, M.-M. et al., The leaching behavior of toxic metals in petroleum sludge after thermal treatment 33 1 2015 118 126.

Ali, A.M. et al., Analysis of solid residue and flue gas from thermal plasma treatment of petroleum sludge 7 4 2019 103207.

Allamin, I.A. et al. Rhizodegradation of petroleum oily sludge-contaminated soil using Cajanus cajan increases the diversity of soil microbial community 10 1 2020 1 11.

Almahbashi, N.M.Y., Kutty, S.R.M., Ayoub, M., Noor, A., Salihi, I.U., Al-Nini, A., Jagaba, A.H., Aldhawi, B.N.S., Ghaleb, A.A.S., 2021. Optimization of preparation conditions of sewage sludge based activated carbon. Ain Shams Eng. J. 12 (2), 1175–1182.

Al-mahbashi, N., Kutty, S.R.M., Jagaba, A.H., Al-Nini, A., Ali, M., Saeed, A.A.H., Ghaleb, A.A.S., Rathnayake, U., 2022. Column study for adsorption of copper and cadmium using activated carbon derived from sewage sludge. Adv. Civil Eng. 2022, 1–11.

Alves, D., Villar, I., Joem Mato, S.J., Thermophilic composting of hydrocarbon residue with sewage sludge and fish sludge as cosubstrates: Microbial changes and TPH reduction 239 2019 30 37.

Andrade, P.F., Azevedo, T.F., Gimenez, I.F., Souza Filho, A.G., Barreto, L.S., 2009. Conductive carbon–clay nanocomposites from petroleum oily sludge. J. Hazard. Mater. 167 (1–3), 879–884.

Asadollahi, A. et al., Using maize (Zea mays L.) and sewage sludge to remediate a petroleum-contaminated calcareous soil 25 1 2016 26 37.

Asgari, S., Bagheri, H., Es-Haghi, A. AminiTabrizi, R., An imprinted interpenetrating polymer network for microextraction in packed syringe of carbamazepine 15 1 2017 1 9.

Asia, I., Enweani I., J.A.Jo.B. Eguavoen Characterization and treatment of sludge from the petroleum industry 5 5 2006 461 466.

Atagana, H.I.J.A.Jo.B., Compost bioremediation of hydrocarbon-contaminated soil inoculated with organic manure. 7 2008 10.

Ayotamuno, et al., Composting and phytoremediation treatment of petroleum sludge 19 6 2010 686 695.

Aziz, S. et al., Enhanced bioremediation of diesel range hydrocarbons in soil using biochar made from organic wastes 192 9 2020 1 14.

Basumatary, B., Saikia, R., Das, H.C., Bordoloi, S., Field note: phytoremediation of petroleum sludge contaminated field using sedge species, Cyperus rotundus (Linn.) and Cyperus brevifolius (Rottb.) Hassk 15 9 2013 877 888.

Bellahcene, A., Hachemi, M., Largeau, J.F., Tarabet, L., Burnens, G., Khiari, K., Tazerout, M., 2021. Experimental investigation on petroleum sludge valorization into fuel via pyrolysis process. Waste Biomass Valoriz. 12 (4), 2131–2143.

Benlamoudi, A. et al. Analysis of the cement clinker produced with incorporation of petroleum sludge Journal of Physics: Conference Series 2018 IOP Publishing.

Beškoski, V. et al., Bioremediation of soil polluted with crude oil and its derivatives: microorganisms, degradation pathways, technologies 66 2 2012 275 289.

Bezza, F.A., Beukes, M., Chirwa, E.M.N.J.P.B., Application of biosurfactant produced by Ochrobactrum intermedium CN3 for enhancing petroleum sludge bioremediation 50 11 2015 1911 1922.

Blyth, W., Shahsavari, E., Morrison, P.D., Ball, A.S., Biosurfactant from red ash trees enhances the bioremediation of PAH contaminated soil at a former gasworks site 162 2015 30 36.

Borgheipour, H. et al., Application of DEA technique in SWOT analysis of oily sludge management using fuzzy data 4 2 2018 183 194.

Cai, Y., Wang, P., Wu, B. Yan, L., Hu, L. Park, S., Ryu, M. Zhou, X., Bioremediation of petroleum hydrocarbons using acinetobacter sp. SCYY-5 isolated from contaminated oil sludge: strategy and effectiveness study 18 2 2021 819.

Castro-León, G., Baquero-Quinteros, E., Loor, B.G., Alvear, J., Montesdeoca Espín, D.E., De La Rosa, A., Montero-Calderón, C., 2020. Waste to catalyst: synthesis of catalysts from sewage sludge of the mining, steel, and petroleum industries. Sustainability 12 (23), 9849.

Chandrasekhar, K., Mohan, S.V.J.B.T., Bio-electrochemical remediation of real field petroleum sludge as an electron donor with simultaneous power generation facilitates biotransformation of PAH: effect of substrate concentration 110 2012 517 525.

Chen, L. et al., Study on the fast pyrolysis of oil sludge and its product distribution by PY-

GC/MS 30 12 2016 10222 10227.

Cheng, S. et al., Evaluation of oil sludge ash as a solid heat carrier in the pyrolysis process of oil sludge for oil production 30 7 2016 5970 5979.

Cheng, T. et al., A novel rhamnolipid-producing Pseudomonas aeruginosa ZS1 isolate derived from petroleum sludge suitable for bioremediation 7 1 2017 1 14.

Chirwa, E.M.N. et al., Biosurfactant assisted recovery of the C5-C11 hydrocarbon fraction from oily sludge using biosurfactant producing consortium culture of bacteria 196 2017 261 269.

Dai, S. et al., Hybrid Extraction of Oily Sludge by Tertiary Amines and Protonated Tertiary Amines 43 11 2020 2160 2166.

Desalegn, B. et al., Green mango peel-nanozerovalent iron activated persulfate oxidation of petroleum hydrocarbons in oil sludge contaminated soil 11 2018 142 152.

Devi, M.P. et al., Effect of Co-culture and nutrients supplementation on bioremediation of crude petroleum sludge. 39 10 2011 900 907.

Dhote, et al., Assessment of hydrocarbon degradation potentials in a plant–microbe interaction system with oil sludge contamination: A sustainable solution 19 12 2017 1085 1092.

Ghaleb, A.A.S., Kutty, S.R.M., Ho, Y.C., Jagaba, A.H., Noor, A., Al-Sabaeei, A.M., Almahbashi, N.M.Y., 2020. Response surface methodology to optimize methane production from mesophilic anaerobic co-digestion of oily-biological sludge and sugarcane bagasse. Sustainability 12 (5), 2116.

Ghaleb, A.A.S., Kutty, S.R.M., Salih, G.H.A., Jagaba, A.H., Noor, A., Kumar, V., Almahbashi, N.M.Y., Saeed, A.A.H., Saleh Al-dhawi, B.N., 2021. Sugarcane bagasse as a co-substrate with oil-refinery biological sludge for biogas production using batch mesophilic anaerobic co-digestion technology: effect of carbon/nitrogen ratio. Water 13 (5), 590.

Ghaleb, A. et al., Anaerobic co-digestion for oily-biological sludge with sugarcane bagasse for biogas production under mesophilic condition IOP Conference Series: Materials Science and Engineering 2020 IOP Publishing.

Gojgic-Cvijovic, G.D., Milic, J.S., Solevic, T.M., Beskoski, V.P., Ilic, M.V., Djokic, L.S., Narancic, T.M., Vrvic, M.M. Biodegradation of petroleum sludge and petroleum polluted soil by a bacterial consortium: a laboratory study 23 1 2012 1 14.

Gong, Z. et al., Study on pyrolysis of oil sludge with microalgae residue additive 96 9 2018 1919 1925.

Hamed, S.B. et al., Efficiency of refinery sludge biodegradation using municipal wastewater and activated sludge and effect of hydrocarbon concentration on culturable bacteria community 60 4 2010 747 755.

Han, T., Zhao, Z., Bartlam, M., Wang, Y., Combination of biochar amendment and phytoremediation for hydrocarbon removal in petroleum-contaminated soil 23 21 2016 21219 21228.

He, Y.M. et al., Enhanced bioremediation of oily sludge using co-culture of specific bacterial and yeast strains. 89 11 2014 1785 1792.

Hu, G. et al., Investigation of waste biomass co-pyrolysis with petroleum sludge using a response surface methodology 192 2017 234 242.

Huang, X.-D. et al., A multi-process phytoremediation system for decontamination of persistent total petroleum hydrocarbons (TPHs) from soils 81 1 2005 139 147.

Iyobosa, E., et al., DEVELOPMENT OF A ROBUST BACTERIAL CONSORTIUM FOR PETROLEUM HYDROCARBON DEGRADATION. 2021..

Jagaba, A.H., et al., 2022. Kinetics of pulp and paper wastewater treatment by high sludge retention time activated sludge process. J. Hunan Univ. Nat. Sci. 49, 2.

Jagaba, A.H., et al. Effect of Hydraulic Retention Time on the Treatment of Pulp and Paper Industry Wastewater by Extended Aeration Activated Sludge System. in 2021 Third International Sustainability and Resilience Conference: Climate Change. 2021. IEEE.

Janajreh, I., Alshehi, A., Jijohe Elagroudy, S. Anaerobic co-digestion of petroleum hydrocarbon waste and wastewater treatment sludge 45 20 2020 11538 11549.

Johnson, O.A., Madzlan, N., Kamaruddin, I., 2015. Encapsulation of petroleum sludge in building blocks. Const. Build. Mater. 78, 281–288.

Jota Borthakur, P.J., calorimetry Thermogravimetric combustion kinetics of petroleum effluent treatment plant sludge 79 3 2005 653 662.

Kadiev, K.M., Gyulmaliev, A.M., Batov, A.E., Kadieva, M.K., Oknina, N.V., Dandaev, A.U., 2015. Structural characteristics of petroleum sludge. Coke Chem. 58 (11), 448–450.

Kamal, A., Kumar, M.S., Kumar, C.G., Shaik, T., Bioconversion of acrylonitrile to acrylic acid by rhodococcus ruber strain AKSH-84 21 1 2011 37 42.

Kankia, M.U., Baloo, L., Danlami, N., Mohammed, B.S., Haruna, S., Abubakar, M., Jagaba, A.H., Sayed, K., Abdulkadir, I., Salihi, I.U., 2021. Performance of Fly Ash-Based Inorganic Polymer Mortar with Petroleum Sludge Ash. Polymers 13 (23), 4143.

Kankia, M.U., Baloo, L., Danlami, N., Samahani, W.N., Mohammed, B.S., Haruna, S., Jagaba, A.H., Abubakar, M., Ishak, E.A., Sayed, K., Amila Bt Wan Zawawi, N., 2021. Optimization of Cement-Based Mortar Containing Oily Sludge Ash by Response Surface Methodology. Materials 14 (21), 6308.

Karami, E., Jafari, T., 2018. Behbahani, *Upgrading Iranian petroleum sludge using polymers.*. J. Petrol. Expl. Prod. Technol. 8 (4), 1319–1324.

Kariminezhad, E., Johm Elektorowicz, M.J., Comparison of constant, pulsed, incremental and decremental direct current applications on solid-liquid phase separation in oil sediments Comparison of constant, pulsed, incremental and decremental direct current applications on solid-liquid phase separation in oil sediments 358 2018 475 483.

Kekez, B.D., Gojgic-Cvijovic, G.D., Jakovljevic, D.M., Stefanovic Kojic, J.R., Markovic, M.D., Beskoski, V.P., Vrvic, M.M., 2015. High levan production by Bacillus licheniformis NS032 using ammonium chloride as the sole nitrogen source. Appl. Biochem. Biotechnol. 175 (6), 3068–3083.

Khalil, N., Algamal, Y., Saleem, Q.M.J.C.I., Exploitation of petroleum waste sludge with local bauxite raw material for producing high-quality refractory ceramics 44 15 2018 18516 18527.

Khandelwal, A. et al., Effect of surfactant on degradation of Aspergillus sp. and Trichoderma sp. mediated crude oil 2021 1 14.

Koolivand, A., et al., 2022. The effect of petroleum hydrocarbons concentration on competition between oil-degrading bacteria and indigenous compost microorganisms in petroleum sludge bioremediation. Environ. Technol. Innov., 102319.

Koolivand, A., Abtahi, H., Parhamfar, M., Didehdar, M., Saeedi , R., Fahimirad, S., Biodegradation of high concentrations of petroleum compounds by using indigenous bacteria isolated from petroleum hydrocarbons-rich sludge: Effective scale-up from liquid medium to composting process 248 2019 109228.

Koolivand, A., Saeedi, R., Coulon, F., Kumar, V., Villaseñor, J., Asghari, F., Hesampoor, F., Bioremediation of petroleum hydrocarbons by vermicomposting process bioaugmentated with indigenous bacterial consortium isolated from petroleum oily sludge 198 2020 110645.

Kriipsalu, M. et al., Bio-treatment of oily sludge: The contribution of amendment material to the content of target contaminants, and the biodegradation dynamics 148 3 2007 616 622.

Kriipsalu, M., et al. Characterization of oily sludge from a wastewater treatment plant flocculation-flotation unit in a petroleum refinery and its treatment implications 10 1 2008 79 86.

Li, G., Guo, S., Ye, H., 2015. Thermal treatment of heavy oily sludge: resource recovery and potential utilization of residual asphalt-like emulsion as a stabilization/solidification material. RSC Adv. 5 (127), 105299–105306.

Liao, C., Xu, W., Lu, G., Liang, X., Guo, C., Yang, C., Dang, Z., Accumulation of hydrocarbons by maize (Zea mays L.) in remediation of soils contaminated with crude oil Accumulation of hydrocarbons by maize (Zea mays L.) in remediation of soils contaminated with crude oil 17 7 2015 693 700.

Lin, B., Huang, Q., Chi, Y.J.F.P.T., Co-pyrolysis of oily sludge and rice husk for improving pyrolysis oil quality 177 2018 275 282.

Ling, C.C. and M.H. Isa, Bioremediation of oil sludge contaminated soil by co-composting with sewage sludge. 2006.48. Alves, D., I. Villar, and S.J.J.o.e.m. Mato, Thermophilic composting of hydrocarbon residue with sewage sludge and fish sludge as cosubstrates: Microbial changes and TPH reduction. 2019. **239**: p. 30-37.

Liu, T. et al., Contamination of fresh water by petroleum sludge 35 4 2017 413 418.

Mahdi, A.M.E., H.A. Aziz, and E.S. Eqab. Review on innovative techniques in oil sludge bioremediation. in AIP Conference Proceedings. 2017. AIP Publishing LLC.

Malakahmad, A. and N. Jaafar. Oil sludge contaminated soil bioremediation via composting using refinery treatment plant sludge and different bulking agents. in 2013 IEEE Business Engineering and Industrial Applications Colloquium (BEIAC). 2013. IEEE..

Mansur, A.A. et al., An effective soil slurry bioremediation protocol for the treatment of Libyan soil contaminated with crude oil tank bottom sludge 115 2016 179 185.

Martínez González, A., Silva Lora, E.E., Escobar Palacio, J.C., Almazán del Olmo, O.A., 2018. Hydrogen production from oil sludge gasification/biomass mixtures and potential use in hydrotreatment processes. Int. J. Hyd. Energy 43 (16), 7808–7822.

Martínez, J.D., et al. Ceramic light-weight aggregates production from petrochemical wastes and carbonates (NaHCO3 and CaCO3) as expansion agents 180 2018 124 133.

Masu, S., N. Dragomir, and M. Popa, Variation of oil products in contaminated soil cultivated with leguminous species. 2013..

Mazzoni, L., Janajreh, I., Elagroudy, S., Ghenai, C., 2020. Modeling of plasma and entrained flow co-gasification of MSW and petroleum sludge. Energy 196, 117001.

Memon, A.M., Hartadi Sutanto, M., Napiah, M., Khan, M.I., Rafiq, W., 2020. Modeling and optimization of mixing conditions for petroleum sludge modified bitumen using response surface methodology. Const. Build. Mater. 264, 120701.

Milato, J.V., Franca, R.J., Calderari, M.R.M. Co-pyrolysis of oil sludge with polyolefins: Evaluation of different Y zeolites to obtain paraffinic products 8 3 2020 103805.

Milato, J.V., França, R.J., Marques, M.R.J., Pyrolysis of oil sludge from the offshore petroleum industry: influence of different mesoporous zeolites catalysts to obtain paraffinic products 42 7 2021 1013 1022.

Mishra, S., Singh, S.N., Technology Biodegradation of benzo (a) pyrene mediated by catabolic enzymes of bacteria 11 6 2014 1571 1580.

Mohammadi, S., Mirghaffari , N.J.N.C.M., Root and Root Canal Morphology of Human Third Molar Teeth A preliminary study of the preparation of porous carbon from oil sludge for water treatment by simple pyrolysis or KOH activation 30 4 2015 310 318.

Mohan, S.R.V. et al., Bioremediation of petroleum sludge under anaerobic microenvironment: Influence of biostimulation and bioaugmentation 10 11 2011 1609 1616.

Mokhtar, N., Ethaib, S., Omar, R.J.J.E.S.T., Effects of microwave absorbers on the products of microwave pyrolysis of oily sludge 13 10 2018 3313 3330.

Mokhtari-Hosseini, Z.B. et al., The reduction of oil pollutants of petroleum products storage-tanks sludge using low-cost adsorbents 23 2 2017 237 244.

Monteiro, S. et al., Red ceramic industrial products incorporated with oily wastes 21 2007 11.

Muratova, A.Y. et al., Use of integrated phytoremediation for cleaning-up of oil-sludge-contaminated soil 46 8 2010 789 794.

Nanekar, S. et al., Microbe assisted phytoremediation of oil sludge and role of amendments: a mesocosm study 12 1 2015 193 202.

Nezhadbahadori, F., Abdoli, M., Baghdadi, M.J.P., Evaluation of Applying Solvent Extraction and Iron Nanoparticles for Oily Sludge Recovery and Upgrading Based on Sludge Specifications 5 3 2019 449 461.

Ng, J., et al. Organic and nutrient removal for domestic wastewater treatment using bench-scale sequencing batch reactor. in AIP Conference Proceedings. 2021. AIP Publishing LLC.

Noor, A., et al., 2021. Integrated Submerged Media Extended Aeration Activated Sludge (ISmEAAS) Reactor Start-Up and Biomass Acclimatization. J. Hunan Univ. Nat. Sci. 48, 9.

Noor, A., et al., 2021. Bio-kinetics of organic removal in EAAS reactor for co-treatment of refinery wastewater with municipal wastewater. IOP Conference Series: Materials Science and Engineering. IOP Publishing.

Noor, A., et al. Kinetic modelling of nutrient removal of petroleum industry wastewater remediation. in 2021 Third International Sustainability and Resilience Conference: Climate Change. 2021. IEEE..

Pakpahan, E., et al. Petroleum sludge thermal treatment and use in cement replacement–A solution towards sustainability. in Engineering Challenges for Sustainable Future: Proceedings of the 3rd International Conference on Civil, Offshore and Environmental Engineering (ICCOEE 2016, Malaysia, 15-17 Aug 2016). 2016. CRC Press.

Pakpahan, E., et al. Petroleum sludge thermal treatment and use in cement replacement—A solution towards sustainability. in Engineering Challenges for Sustainable Future—Proceedings of the 3rd International Conference on Civil, Offshore and Environmental Engineering, ICCOEE. 2016.

Pal , S. et al., Genome analysis of crude oil degrading Franconibacter pulveris strain DJ34 revealed its genetic basis for hydrocarbon degradation and survival in oil contaminated environment 109 5–6 2017 374 382.

Panova, Y., et al. Analysis of oil sludge and selection of solvents for the extraction method of petroleum products recovery 92 2018 75 80.

Parhamfar, M. et al., Biodegradation of heavy oily sludge by a two-step inoculation composting process using synergistic effect of indigenous isolated bacteria 91 2020 223 230.

Pérez Silva, R.M., Ábalos Rodríguez, A., Gómez Montes De Oca, J.M., Cantero Moreno, D., 2009. Biosorption of chromium, copper, manganese and zinc by Pseudomonas aeruginosa AT18 isolated from a site contaminated with petroleum. Bioresour. Technol. 100 (4), 1533–1538.

Permadi, P., Fitria, R., Hambali, E., 2017. Palm oil based surfactant products for petroleum industry. IOP Conference Series: Earth and Environmental Science. IOP Publishing.

Pinheiro, B., Holanda, J., 2013. Obtainment of porcelain floor tiles added with petroleum oily sludge. Ceramics Int. 39 (1), 57–63.

Pinheiro, B., Faria, R., Holanda, J., 2013. Thermal transformations of floor tile pastes containing petroleum waste. J. Ther. Anal. Calorim. 111 (1), 527–533.

Pinheiro, B., Holanda, J.N.F., Reuse of solid petroleum waste in the manufacture of porcelain stoneware tile 118 2013 205 210.

Poorsoleiman, M.S. et al., Effect of two-step bioaugmentation of an indigenous bacterial strain isolated from oily waste sludge on petroleum hydrocarbons biodegradation: scaling-up from a liquid mineral medium to a two-stage composting process 17 2020 100558.

Qomariyah, L., et al., 2022. Bioremediation of heavy metals in petroleum sludge through bacterial mixtures. Mater. Today: Proc.

Rajaei , S., Seyedi, S.M., Air, Water, Phytoremediation of Petroleum-Contaminated Soils by Vetiveria zizanioides (L.) Nash. 46 8 2018 1800244.

Ramirez, D. et al., Characterisation of oil sludges from different sources before treatment: high-field nuclear magnetic resonance (NMR) in the determination of oil and water content 174 2019 729 737.

Reddy, M.V., Devi, M.P., Chandrasekhar, K., Goud, R.K., Mohan, S.V., Aerobic remediation of petroleum sludge through soil supplementation: microbial community analysis Aerobic remediation of petroleum sludge through soil supplementation: microbial community analysis 197 2011 80 87.

Roldan, F., Maldonado, C., Guevara, C., Cubillos, A.M., 2010. Natural attenuation of oily sludge used for the maintenance of an unpaved road in Arauca (Colombia). Bioremed. J. 14 (2), 81–91.

Sahebnazar, Z. et al., Zero-valent iron nanoparticles assisted purification of rhamnolipid for oil recovery improvement from oily sludge 6 1 2018 917 922.

Said, M., Elektorowicz, M., Ahmad, D., Chifrina, R., A new rapid technique for screening the potential of implanted microorganisms to tolerate and grow on petroleum oily sludges A new rapid technique for screening the potential of implanted microorganisms to tolerate and grow on petroleum oily sludges 27 10 2006 1115 1123.

Shahzad, A., Saddiqui, S., Bano, A.J., The response of maize (Zea mays L.) plant assisted with bacterial consortium and fertilizer under oily sludge The response of maize (Zea mays L.) plant assisted with bacterial consortium and fertilizer under oily sludge 18 5 2016 521 526.

Shahzad, et al., Hydrocarbon degradation in oily sludge by bacterial consortium assisted with alfalfa (Medicago sativa L.) and maize (Zea mays L.) 13 17 2020 1 12.

da Silva, L.J., Alves, F.C., de França, F.P., 2012. A review of the technological solutions for the treatment of oily sludges from petroleum refineries. Waste Manag. Res. 30 (10), 1016–1030.

Silva, J.M. et al., Improved thermogravimetric system for processing of oil sludge using HY zeolite catalyst 136 4 2019 1861 1868.

Singh, B., Kumar, P., 2020. Physicochemical characteristics of hazardous sludge from effluent treatment plant of petroleum refinery as feedstock for thermochemical processes. J. Environ. Chem. Eng. 8 (4), 103817.

Song, X. and J. Li. Application of Hog Fuel for the Bioremediation of Oil Contaminated Soils. in 2010 4th International Conference on Bioinformatics and Biomedical Engineering. 2010. IEEE.

Suganthi, S.H. Murshid, S. Sriram. S. Ramani, K., Enhanced biodegradation of hydrocarbons in petroleum tank bottom oil sludge and characterization of biocatalysts and biosurfactants Enhanced biodegradation of hydrocarbons in petroleum tank bottom oil sludge and characterization of biocatalysts and biosurfactants 220 2018 87 95.

Tahhan, R.A., et al., 2011. Enhancing the biodegradation of total petroleum hydrocarbons in oily sludge by a modified bioaugmentation strategy. Int. Biodeterior. Biodegradation 65 (1), 130–134.

Teng, Q., Zhang, D., Yang, C., 2021. A review of the application of different treatment processes for oily sludge. Environ. Sci. Poll. Res. 28 (1), 121–132.

Turebekova, G.Z., Shapalov Sh.K., T., Alpamysova, G.B., Issayev, G.I., Bitemirova, A., Lyubchyk, S., Yergubekova, Zh.S., Pusurmanova, G.Zh, 2019. Recycling of wastes of petroleum refining industry by using them in the manufacture of tire rubbers. Известия НАН РК. Серия химических наук 1, 16–20.

Varjani, S., Upasani, V.N., Pandey Bioremediation of oily sludge polluted soil employing a novel strain of Pseudomonas aeruginosa and phytotoxicity of petroleum hydrocarbons for seed germination Bioremediation of oily sludge polluted soil employing a novel strain of Pseudomonas aeruginosa and phytotoxicity of petroleum hydrocarbons for seed germination 737 2020 139766.

Varma, S.S., Lakshm, M.B., Rajagopal, i P., Velan , M., Degradation of Total Petroleum Hydrocarbon (TPH) in Contaminated Soil Using Bacillus pumilus MVSV3 22 1 2017 17 23.

Wang, J., Liu, T.L., Huang, Q.X., Ma, Z.Y., Chi, Y., Yan, J.H., 2017. Production and characterization of high quality activated carbon from oily sludge. Fuel Process. Technol. 162, 13–19.

Wang, S. et al., Bioremediation of oil sludge contaminated soil by landfarming with added cotton stalks 106 2016 150 156.

Wang, S. et al., Screening of herbaceous plants for peat-enhanced rehabilitation of contaminated soil with oily sludge 18 1 2016 62 68.

Włóka, D., Placek , A., Smol, M., Rorat, A., Hutchison, D., Kacprzak, M., The efficiency and economic aspects of phytoremediation technology using Phalaris arundinacea L. and Brassica napus L. combined with compost and nano SiO2 fertilization for the removal of PAH's from soil 234 2019 311 319.

Wu, Z. et al., Enriched microbial community in bioaugmentation of petroleum-contaminated soil in the presence of wheat straw 164 7 2011 1071 1082.

Xi, B., Dang, Q., Wei , Y., Li, Y., Zheng, X., Zhao, X., Biogas slurry as an activator for the remediation of petroleum contaminated soils through composting mediated by humic acid 730 2020 139117.

Xiao, W., Yao, X., Zhang, F.J., Recycling of oily sludge as a roadbed material utilizing phosphogypsum-based cementitious materials 19 2019 297.

You, Z. et al., Comparison of petroleum hydrocarbons degradation by Klebsiella pneumoniae and Pseudomonas aeruginosa 8 12 2018 2551.

Zand, A.D. et al., Phytoremediation of total petroleum hydrocarbons (TPHs) using plant species in Iran 34 5 2010 429 438.

Zhao, S. et al., Dewatering and low-temperature pyrolysis of oily sludge in the presence of various agricultural biomasses 39 21 2018 2715 2723.

Zhu, J. et al., Co-pyrolysis of petrochemical sludge and sawdust for syngas production by TG-MS and fixed bed reactor 45 55 2020 30232 30243.