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Circular economy potential and contributions of petroleum industry sludge utilization to environmental sustainability through engineered processes - A review

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ABSTRACT

The petroleum industry activities unavoidably generate a large quantity of sludge named Petroleum industry sludge (PIS). The generation rate has been increasing because of the ascending energy demand. It is a potential energy resource. PIS has been shown to contain hazardous constituents that may have negative consequences on the environment and public health. Thus, the treatment and disposal of this waste is a global issue. Numerous treatment methods have been demonstrated to reduce sludge volume and toxicity and recover petroleum components. The sludge qualities affect how effective they are. These treatment strategies can reduce the toxic substances in sludge and reduce their detrimental effects on human health and the environment. However, because of the sludge's tenacious character, only a few technologies can meet strict environmental laws while using a sizable amount of water, electricity, and chemicals. PIS treatment methods that are both waste-free and cost-effective are currently unavailable. In terms of environmental engineering significance, this study adopted the systematic review to discuss the waste to resource potential applications of PIS for reusability in sustainable construction, wastewater treatment applications, and gas generation. PIS application ineffective microorganism biofertilizer production, levan production, rubber tires manufacturing, metal catalysts synthesis, carbon–clay composites for use in sensors and electronic devices were also discussed. That is not enough, this review also found that the adoption of the circular economy that represents a new direction to create value and prosperity by elongating product lifespan and moving the waste from the end of the supply chain to the outset is very important. Thus, the circular economy potential of PIS to achieve self-cycle operation through the concept of "wastes-treat-wastes" in the petroleum industry was extensively discussed.

1. Introduction

The petroleum industry involves several processes/steps from the commencement of crude oil/gas exploration to when it is consumed, including onshore and offshore surveys, cutting, crude oil exploration, production (oil and gas), transportation, storage/handling, and refining (Borgheipour et al., 2018). As a result of its operations, the petroleum sector produces a variety of oily and viscous waste (Jagaba, 2022).

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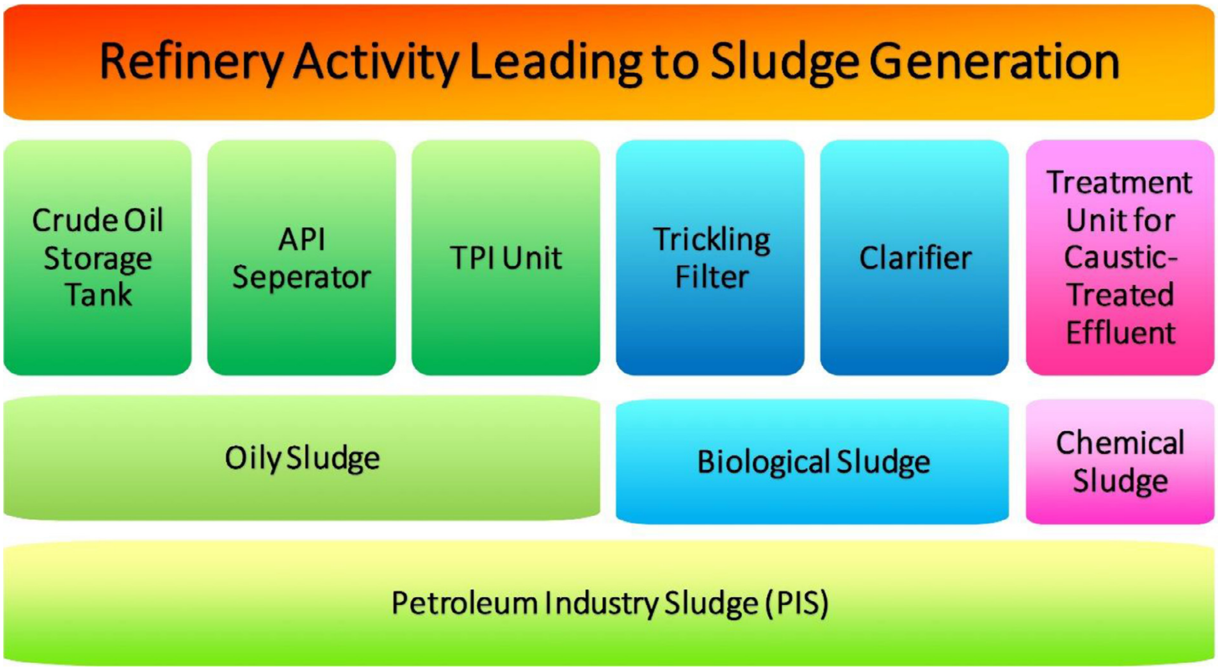

Fig. 1. Sources of sludge in refineries (Bhattacharyya & Shekdar, 2003).

Sludge, slurry, liquids, solids, and gases from the petroleum sector are divided into hazardous and non-hazardous waste. Everything that is caustic, explosive, combustible, reactive, or poisonous is considered hazardous waste (Al Qallaf et al., 2016). Specifically, petroleum industry wastes are: treatment unit-derived activated sludge, waste catalysts/spent fluid catalytic cracking, spent engine oil, oil drilling waste, drill cuttings, oil slime, oil-sludge or petroleum residue, hydrocarbon cutting sludge, refinery scale from an old tank; inside the pipe; outside the adapter; an old pipe; burn pits, petroleum refinery sludge; Sludge from refinery exchangers, produced water/oily refinery wastewater, dissolved air flotation unit sourced float, coal water slurry, petroleum coke water slurry, coal sludge slurry, and petroleum coke sludge liquid residue from the thermal treatment of oily sludge

Sludge from the petroleum sector is known to exist in significant amounts (Iacovidou & Zorpas, 2022). It is a highly stable suspension emulsion system with high levels of polycyclic aromatic hydrocarbons (PAHs) and benzene homologs, and it has been designated as hazardous waste in several actions (Liu et al., 2017). They are inherently dangerous and can be difficult to absorb. They are observed to be the largest waste produced after petroleum refining, and it has attracted immense interest. The waste is produced because of the accumulation of hydrocarbon compounds across vast sedimentary fields over a lengthy period. The production of PIS has also been aided by several refinery activities, as shown in Fig. 1 (Martinez et al., 2018)., Industry wastewater treatment, catalytic cracking, and, Vis breaking are some of the other activities. PIS is made up of two basic components: petroleum and wax, both of which are recyclable (Lyu et al., 2018). Some features of the oil components, such as density, viscosity, and particle size distribution, may help the sludge accumulate (Huang et al., 2014). The production of petroleum sludge is mainly influenced by two major variables. These include inorganic residues (clay, sand, sediments, scales, and dust) as well as pipelines, and storage tanks, among other things. The fundamental process is asphaltene adsorption at the oil-water intact (Kriipsalu, Marques & Maastik, 2008). Landing sludge, tank bottom sludge, sludge from oil drilling, refining sludge, petroleum wastewater activated sludge, and oil-water separator sludge are some of the several types of sludge found in the petroleum sector.

Crude oil, gas fractions, and condensates are all present in the crude oil recovered from an oil well. Following the separation of gases, the crude still contains oil and condensate. Furthermore, oil is separated, resulting in the production of sludge in the petroleum sector (PIS). According to (Bhattacharyya & Shekdar, 2003), around 10,000 m^3 of PIS are produced annually from oil refineries with daily output capacities of up to 500 barrels. For example, a different study found that a 105,000 barrels per year oil refinery produces 50 tonnes of oily sludge annually. As a result, it is anticipated that one tonne of crude oil will produce between 0.3 and 0.5 percent of sludge (Jagaba, 2022a). According to a study by (El Mahdi, Aziz & Eqab, 2017), the production of oily sludge represented 0.5% of the world's total yearly crude oil production. According to the petroleum plant's capability for refining, a study by (Teng, Zhang & Yang, 2021) estimated that the generation of PIS ranged from 0.1 to 1.5%. Moreover, highlights the optimistic estimate of 0.1% reasonable estimate of 0.5%, and gloomy estimate of 1.5% of sludge generation of refinery capacity. A review of this previous research determined that crude oil production generates about 0.1 to 0.5% of PIS each year. Data on crude oil output in seven regions throughout the world for the last five years was gathered from (US EIA). PIS generated from crude oil was estimated to be 0.3 percent on average and 228.29 Mt/year globally as of 2020. PIS will therefore continue to be a cause of concern to the environment on a global scale until fossil fuel use is phased out to meet the net zero emission target.

Crude oil, condensates, and gas fractions are all part of the crude that is recovered from the oil well. The crude, which still contains oil and condensate, is left over after gas extraction. Additionally, oil is separated, which resulted in the production of PIS. According to (El Mahdi, Aziz & Eqab, 2017), around 10,000 m^3 of PIS are produced annually from oil refineries with daily output capacities of 200 to 500 barrels of oil. Similar to this, a different study found that a 105,000 barrel per year oil refinery produces 50 tonnes of oily sludge annually. As a result, it is anticipated that one tonne of crude oil will produce between 0.3% and 0.5% of sludge (Jagaba, 2022a). According to Teng, Q. et al. (Teng, Zhang & Yang, 2021), the production of oily sludge represented 0.5% of the world's total yearly crude oil output. According to the capability of the petroleum facility for refining, da Silva, L.J. et al., (da Silva, Alves & de Franca, 2012) estimation of PIS generation ranged

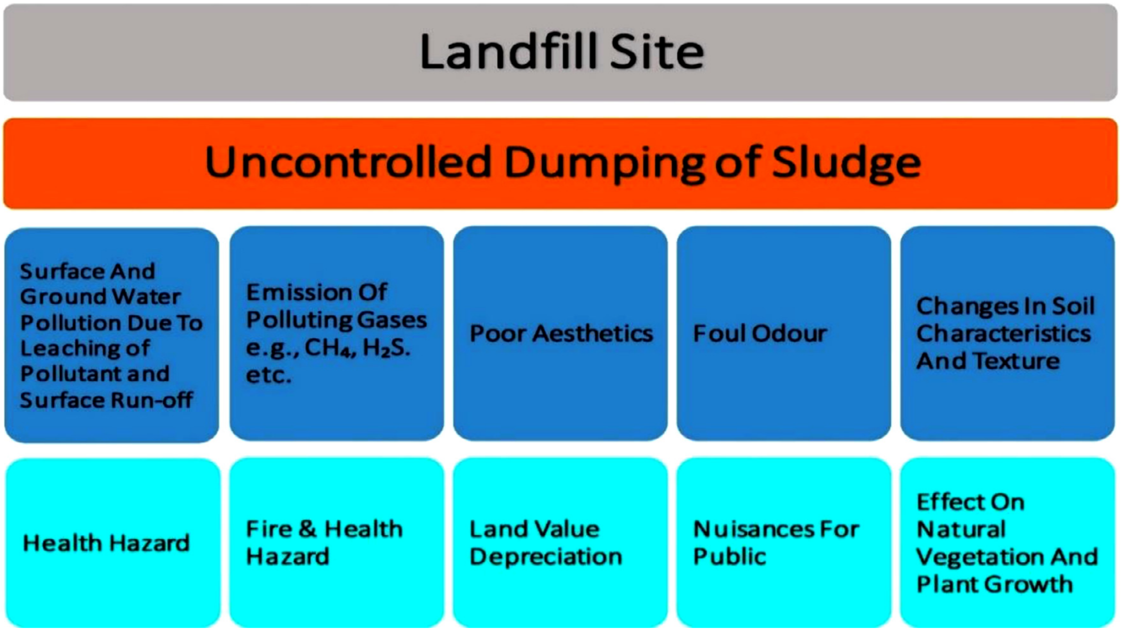

Fig. 2. Primary and secondary impacts of PIS disposal (Bhattacharyya & Shekdar, 2003).

from 0.1% to 1.5%. In addition, it should be noted that 0.1% of refinery capacity for sludge creation represents an optimistic view, 0.5% represents a realistic estimate, and 1.5% represents a pessimistic one. It was determined after taking into account all the previous studies that the production of crude oil accounts for between 0.1 and 0.5% of PIS annually. Seven regions' last five years' worth of crude oil output data were taken from (US EIA). The average PIS generation from crude oil was measured to be 0.3%. It is certain that 228.29 Mt/year of PIS was produced globally in 2020.

2. Characteristics and environmental effects of petroleum industry sludge

High moisture, low volatiles, and Low fixed carbon describe petroleum industrial sludge with traits encompassing hydrophobicity, complex structure, and extended persistency (Ali et al., 2019). It is composed of complicated chemical mixes with a variety of petrochemical properties as well as certain dangerous compounds. It has less sediment than water and oil do. It has chemicals that are cancer-causing and immune-toxic (Asgari et al., 2017, Okai-Mensah, Howard & Okai-Mensah, 2022). Its physicochemical characteristics differ significantly depending on the supply of crude oil, the method used to treat wastewater, storage conditions, the processing plant, and oil processing technology. The variability of sludge characteristics and composition is influenced by several factors such as sample time, location, and so on (Jagaba et al., 2022). Because of the heterogeneous nature of sludge compositions, viscosity, heating value, and density may vary significantly (Al-dhawi et al., 2022). Oil and grease, as well as a variety of poisonous metals and organic compounds like toluene, benzene, phenolic acids, xylenes, and a small amount of non-acid species like esters, ketones, and amides, make up the majority of petroleum industry sludge (Birniwa et al., 2022). Given the variety of sludge compositions, it is evident that writers cannot agree on the composition of PIS oxides. This directly affects the results obtained for their proximate and ultimate analysis (see Table 1). It could also be observed in Fig. 3 that, among all the chemical components present in the various sludge types, Fe_2O_3 is the most abundant metal oxide found in petroleum sludge (51wt%), dried oily sludge (10.14wt%), and petroleum refinery sludge (30.99wt%). This made the materials inhibit low volatility, and low water absorption properties thus being used as roadbed material and for syngas production. It is significant to note that the Fe_2O_3 content in PIS could be reduced to FeO and Fe by carbon with the generation of CO and CO_2. SiO_2 is the highest oxide present in crude oily sludge, oily sludge ash, petroleum sludge ash, and petroleum oily sludge. This made it possible for authors (Abdullahi, 2022, Chen et al., 2016, Pakpahan et al., 2016) to utilize the materials as solid heat carriers during the g pyrolysis process of oil sludge, cement replacement, and for tile/brick manufacturing. Surprisingly, petroleum waste sludge used for ceramics production had 39.08 wt% of BaO. This is higher than the 28.62 wt% obtained for SiO_2. Al_2O_3 and Fe_2O_3 have very fewer percentages of 0.20 and 0.08 respectively. Therefore, to cover up for their deficiency, it is required to supplement PIS with another biomass material.

It is general knowledge that the actions of oil-producing firms have an impact on the environment and the health of the people who live nearby. The PIS is a dangerous contaminant, and the most significant waste by weight in the oil sector. Because of the rising energy demand, the PIS' generating quantity has been expanding. The refining process, which produces valuable items, causes a slew of issues. The process provides the potential for the release of poisonous, mutagenic, and carcinogenic chemicals by accident regularly (Cheng et al., 2016). Wax deposit, sludge deposit, limited oil recovery, emulsion formation, asphaltene deposit, water, and land pollution are experienced as consequences of spilled oil residue during the process (Pinheiro & Holanda, 2013). PIS is categorized by many governments as a hazardous and a high-priority contaminant. It is an unhealthy and environmentally unacceptable pollutant (see Fig. 2), which may have adverse environmental effects and hence harm human health (Borgheipour et al., 2018).

PIS contains various malodorous, toxic, and hazardous elements. These include bacteria, sulphur compounds, nitrogen compounds, wax, asphaltene, colloid, PHCs, heavy metals (see Table 2), and organic pollutants such as PAHs (Huang et al., 2014). PIS contains hydrocarbon molecules acquired from petroleum oil hydrocarbons. Oily sludge, on the other hand, passes through several aging and weathering processes that result in a greater mean molecular weight and alterations in TPH fractions (Tahhan et al., 2011).

The constituents in PIS are capable of causing respiratory, renal, and central nervous system disorders (Jasmine & Mukherji, 2015). Therefore, some of the consequences of not treating could be soil, water, and air pollution, and occupying a lot of valuable fertile land. PIS has also been reported to decrease the storage capacity of a tank and at the same

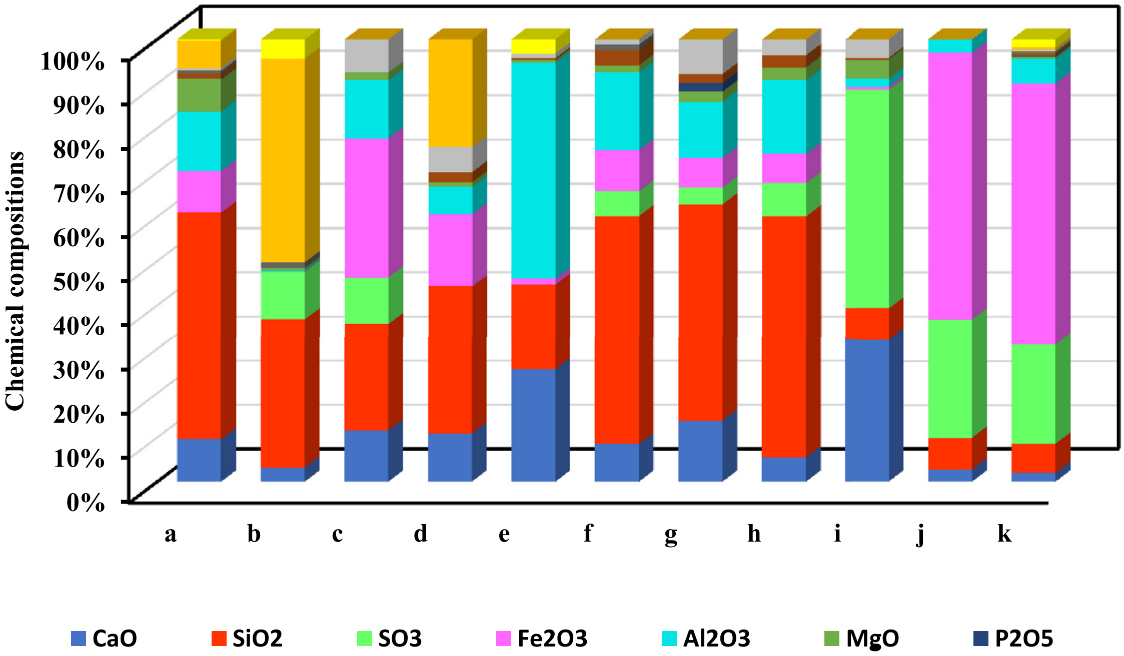

Fig. 3. Chemical composition in (wt.%) for (a) Petroleum sludge (Alhadj-Mallah et al., 2015), (b) Petroleum effluent treatment plant sludge (Jagaba, 2022), (c) Petroleum refinery sludge (Zhu et al., 2020), (d) Crude oily sludge (Abdullahi, 2022), (e) Dried oily sludge (Xiao, Yao & Zhang, 2019), (f) Petroleum oily sludge (Pinheiro & Holanda, 2013), (g) Oil sludge ash (Cheng et al., 2016), (h) Petroleum sludge ash (Pakpahan et al., 2016), (i) Petroleum waste sludge (Khalil, Algamal & Saleem, 2018) (j), Tank oil sludge (Chen et al., 2016) (k) Petrochemical sludge (Wang et al., 2012)

time contaminate the stored oil products (da Silva & Silva, 2022). Its disposal at landfills is no longer a good alternative because it is costly, inhibit methane fermentation, and contains the hazardous compound. Due to high crude oil generation, PIS disposal makes landfill reach their full capacity earliest (Pinheiro & Holanda, 2013, Choromanski, Karwowska & Lebkowska, 2016). To avert this, composting was proposed and experimented with as one of the most powerful measures for PIS treatment. However, it results in huge oily compost leachate generation. PIS is mostly exposed to biological and abiotic processes over time, resulting in different degrees of pollution (Sayed et al., 2021). It can accelerate corrosion, reduce oil storage capacity and disrupt production and processing operations (Huang et al., 2014). The presence of sulphur compounds is undesirable, as they ruin expensive catalysts and release sulphur oxides into the atmosphere when burned, thereby creating environmental problems (Al Majidi, 2019). The hydrocarbon content in PIS could penetrate lagoons, lakes, rivers, and groundwater. However, when the oil concentration of water surpasses the environmental limit of rivers or lakes, fish eggs will be severely hampered, leading to a reduction in aquatic biodiversity. It could also create problems of odour and fire hazards (Bhattacharyya & Shekdar, 2003).

Plants develop slowly in PIS because large-molecular hydrocarbons clog pores on the surface, thereby reducing dissolved oxygen and making it harder to transmit water and energy to them, which can result to plant roots rotting and death (Teng, Zhang & Yang, 2021). PIS effect on seed growth, shoot and root length, and plant susceptibility revealed a drastic drop in the length, vigour index, and weight of the seedlings examined. It also induces oxidative stress in plants (Marti et al., 2009). The high oil content was discovered to have been the cause of alteration to the osmotic association between seed and water and consequently decrease absorbed water quantity. This proves that the nutrients and oil concentrations in the treated sludge were toxic to plants (Sangeetha & Thangadurai, 2014). Oil sludge handling is difficult and time-consuming. It, however, causes a huge loss of oil resources if not processed (Sayed et al., 2022). PIS encroachment in soil could lead to changes in physical, chemical, and nutrient properties. The hydrocarbons present can decrease water hydraulic conductivity, soil enzymes and microorganisms' activity, soil permeability, and water-retaining capacity. The consequences of this could be a reduction in soil fertility, hindrance to seed germination, crop growth limitation, and imbalance in the microbial flora of soil (Varjani, Pandey & Upasani, 2020).

PIS discharge into the environment is strictly controlled because of all the effects, and the US Environmental Protection Agency has identified them as a priority environmental contaminant. Some of the values in Table 2, exceed those set by the World Health Organization (WHO) or the United States Environmental Protection Agency (USEPA) for industrial sludge discharge. As a result, the sludge must be treated before disposal because it poses a significant danger of damaging the environment (Asia, Enweani & Eguavoen, 2006). Sludge from the petroleum sector needs to be managed properly because incorrect techniques could cause: (i) Water and soil contamination are detrimental environmental repercussions, (ii) negatively affecting human health, (iii) huge waste value loss, (iv) disregard for local government regulations and legislation, (v) a repulsive sight that can ruin the reputation of the business, and (vi) an additional cost for the organisation to maintain and clean up the area. However, to select the most appropriate treatment and disposal procedure, adequate and critical information about the sludge's characteristics is required (Al Qallaf et al., 2016).

2.1. *Standard regulations for PIS management and disposal*

PIS management has become a most complex area of law. The character of PIS has become even more diverse where some are simple inert materials and some of this material has economic worth in that it can be reused or even recycled. In fact, despite any future potential, it may have toxic elements, which need careful handling. Thus, policies about the reduction, recycling, and reuse of PIS are necessary. The Conservative Government's White Paper *in the UK*. The government's priority is to reduce waste at its source to a minimum. Additionally, the developed countries believe that an effective PIS minimization program should include, as suitable, each of the elements such as specified targets for PIS minimization, top management support, PIS minimization as a company policy, employee training, a technology transfer program,

Table 1

Proximate, ultimate, and heating value analysis results for various petroleum industry sludge

Sludge type	**Proximate analysis on dry basis**				**Ultimate analysis on dry basis**					**High heating value(MJ/kg)**	**Low heating value(MJ/kg)**	**Ref.**
	Moisture content (wt.%)	**Ash content (wt.%)**	**Volatile matter (wt.%)**	**Fixed carbon (wt.%)**	**C**	**H**	**N**	**S**	**O**			
Petroleum sludge	78.91	5.06	5.52	10.51	51.4	7.3	3.3	2.2	35.8	23.60	-	(Ali et al., 2019)
Oily sludge	16.95	51.99	93.17	6.83	20.85	2.7	1.4	0.11	6.0	-	8.530	(Zhou, Jiang & Liu, 2009)
Petrochemical industrial sludge	3.59	25.93	68.93	5.15	68.23	6.02	0.8	0.96	27.99	27.18	26.30	(Ayol & Yurdakos, 2019)
Petrochemical sludge	27.87	50.06	39.34	10.60	21.79	2.89	0.39	8.49	16.38	-	-	(Zhu et al., 2020)
Oily sludge	59.86	8.61	88.09	3.3	33.16	7.18	0.45	0.68	-	17.73	-	(Xu et al., 2014)
Oily sludge	75.30	28.2	60.6	8.1	45	6.6	7.0	1.7	39.7	20.5	-	(Mokhtar, Ethaib & Omar, 2018)
Petrochemical sludge	7.09	36.91	49.95	6.05	31.29	3.77	2.76	-	-	11.89	-	(Ma, Duan & Liu, 2013)
Oil sludge ash	5.18	71.25	20.02	3.55	14.6	2.06	0.08	0.56	2.36	7.86	-	(Cheng et al., 2016)
Petroleum sludge	9.0	1.8	89.2	-	77.8	12.1	-	-	8.2	30.2	-	(Bellahcene et al., 2021)
Oily sludge	30.55	37.27	29.47	2.71	29.52	6.25	1.84	1.31	7.53	-	8.55	(Chu et al., 2021)
Oily sludge	20.0	9.0	16.9	54.1	89.3	6.9		1.4	2.4	39.9	38.5	(Gonzalez et al., 2018)
Petroleum sludge	21.41	3.78	63.33	11.84	50.39	7.09	1.66	3.48	37.38	12.42	-	(Singh, Singh & Kumar, 2021)
Petroleum sludge	6.2	10.3	76.5	16.3	47.0	5.8	0.01		47.2	17.5	-	(Hu et al., 2017)
Oily sludge	5.5	45.10	49.04	0.31	78.53	10.85	0.64	0.89	9.09	-	-	(Nie et al., 2020)
Refinery oil sludge	68.6	12.7	17.5	1.2	64.44	8.39	0.36	1.7	10.47	-	-	(Zhao et al., 2021)
Petroleum sludge	3.6	67.4	26.5	2.5	55.69	4.31	1.18	9.41	29.41	8.64	7.6	(Mazzoni et al., 2020)
Oily sludge	28.12	39.03	29.61	3.24	54.34	12.46	0.56	0.33	32.31	-	-	(Hu et al., 2020)
Petroleum refinery sludge	23.31	2.43	65.10	9.16	53.63	6.52	1.76	3.16	34.93	12.42	-	(Singh & Kumar, 2020)
Crude oily sludge	9.8	1.3	94.8	5.2	73.8	11.3	2	3	12.6			(Prashanth et al., 2021)
Refinery waste sludge	0.2	9.8	22.9	67.1	78.3	4.6	0.8	6.5	9.8			(Senneca et al., 2020)
Oily sludge	36.06	26.10	33.08	4.76	22.65	3.44	0.67	1.28	15.60	-	-	(Chen et al., 2020)
Oil shale sludge	8.42	43.18	40.80	7.6	36.26	5.30	1.0	0.74	5.10			(Qin et al., 2015)
Tank oil sludge	46.99	22.70	51.74	2.88	23.45	3.01	0.22	1.19	2.44	-	11.97	(Gong et al., 2018)
Oily sludge	26.55	42.27	51.19	2.17	16.38	4.25	0.32	2.34	8.91	-	8.536	(Jagaba et al., 2022)
Oily sludge	1.51	60.87	36.02	1.60	83.36	11.87	0.95	2.48	1.34	15.69	-	(Chen et al., 2016)
Oily sludge	-	11.25	21.13	67.62	79.22	6.15	-	1.25	2.13	39.93	38.49	(Gonzalez, Lora & Palacio, 2019)
Petrochemical sludge	84.65	28.85	62.90	8.24	36.27	4.37	1.41	1.31	27.78	16.12	-	(Wang et al., 2012)

Table 2
Heavy metals concentration (mg/kg) in the PIS

Metal conc. (mg/kg)	Sludge type						
	Oily sludge	Petroleum sludge	Petrochemical sludge	Bottom Sludge	Acidic oily refinery sludge	Refinery oil sludge	Waste disposal pit sludge
Cd	0.0004-100	0.4-42.5	-	11.78-22.64	0-4.44	0.16-0.721	0.05-5
Cr	0.0159-207	0.012-105	60.34	49.95-70.69	69.1-119.1	0.0036-8.07	8.07-48.38
Cu	0.11-730	0.52-35	52.61	537.09-707.36	0-4420.46	43-75	2.39-14
Fe	5.16-304817	0.131-357.2	-	5923.10-7167.43	4033.6-5530	60.82-10770	101.13-2780
Mn	0.0882-542	0.003-25.77	-	95.90-134.43	390-398.06	1.188-184	-
Ni	0.05-152	0.34-240	6.22	37.61-38.75	0-56.01	0.207-442	7.11-38.72
Pb	0.0186-565	1.45-198	3.66	77.6-122.40	132.7-190	4.02-89	2.62-4.02
Mg	0.4889	0.174-56	-	-	-	432-1614	0-178
Al	3.754-12615	0-26.40	-	1134.55-1451.98	273.02-2730	3.327-43180	0-144
Ba	0.2-1111.17	-	16.77	30.08-45.03	0-110.33	0-2136	-
Co	0.0164-100	1.2-16	-	5.84-15.32	0-3.78	2.39-23	1.34-2.53
Ca	8.758-36473	80.41-100	-	-	-	6.84-1272	30.50-860
Ti	0.1313-57.17	0-547	-	49.91-57.81	0-0.13	0-1.087	-
As	0.0083-7.0	13.5-24.5	0.88	1.58-4.99	0-4.96	1.279-3.0	1.27-11
Na	1.237-77.66	-	-	-	-	2.23-489	2.23-410
Zn	0.1285-8265	0.005-580	163.83	11.08-15.40	5220-12249	0.788-209	34.70-168
K	1.369-2190	0-3.38	-	49.22-51.63	-	368-423	-
V	0.8-227	2.1-72		28.66	0-8.28	0-2.84	-
Ref.	(Zhou, Jiang & Liu, 2009, Bellahcene et al., 2021, Nie et al., 2020, Mohammadi & Mirghaffari, 2015, Sangeetha & Thangadurai, 2014)	(Ali et al., 2019, Singh, Singh & Kumar, 2021, Aeslina & Ali, 2017)	(Ayol & Yurdakos, 2019)	(Koolivand et al., 2017)	(Asgari et al., 2017)	(Zhao et al., 2021, Behera et al., 2020)	(Nejad et al., 2020)

program evaluation, etc. Thus, Relevant statutes and Regulations should be strengthened especially to insert the element of PIS minimization or source reduction.

Over time, laws to avoid unintentional releases of dangerous chemicals into the environment, particularly from the petroleum industry, have gotten more stringent (Asia, Enweani & Eguavoen, 2006). Several laws governing the disposal of toxic solid waste have been enacted by various countries as highlighted in Table 3. As part of the land disposal limits program, they created treatment procedures for several hazardous wastes, including hydrocarbons. In Malaysia, petroleum industry sludge is categorized as scheduled waste while in China, it is categorized as hazardous waste (Fadzil et al., 2011). In underdeveloped and some developing countries without national standards for PIS contaminated soil clean-up levels, sludge pollutant concentrations are compared with criteria set in developed countries (Kriipsalu, Marques & Maastik, 2008).

2.2. *Petroleum industry sludge treatment*

An effective petroleum sludge biodegradation process necessitates the use of geology, engineering, microbiology, soil science, and project management (Mohammadi & Mirghaffari, 2015). PIS can be processed in a variety of methods to reduce the volume of sludge, reduce toxicity, and recover petroleum products. The sludge macrostructure and chemical makeup determine their efficiency. Surface discharge, subterranean injection for slurries, burial, and disposal at sea are among the different treatment strategies listed in the literature (Borgheipour et al., 2018). Phytoremediation, soil/slurry/bio-slurry treatment processes, and Surfactant flushing are all examples of biodegradation, bioaugmentation, biostimulation, landfarming, rhizoremediation, biosparging, bioventing, and composting (biopiling) (Jagaba et al., 2021). Wetlands, natural attenuation, ozonation, chlorination, gasification, oxidation of wet air, extraction of solvents, demulsified systems, thermochemical conversion, photo-catalysis, pyrolysis, co-pyrolysis, thermal desorption, coking freezing/thawing, centrifugation using cyclotrons, microemulsion systems, electrokinetic method, solidification/stabilization/encapsulation, microbial fuel cell, advanced oxidation processes (Ahmad, 2017).

There have also been reports of the utilisation of technologies including supercritical water oxidation, microwave radiation, efficient microorganisms, and thermal plasma therapy using a thermal plasma reactor (Birniwa et al., 2022). The harmful effects of petroleum sludge's toxic components on the environment and human health are reduced by the treatment techniques outlined above. Only a few techniques can reconcile adhering to strict environmental rules with using a lot of energy, chemicals, and water because of how resistant the sludge is (Almahbashi et al., 2021). Emulsions that are stable including water and hydrocarbons can occasionally form even after treatment (Ali et al., 2019). Uneconomical GHG emissions, ineffective secondary air pollution, acidification, ozone depletion, large space requirement, ecological toxicity, emission of volatile organic compounds, low molecular PAHs, non-ecofriendly, hazardous gases, and pre-and post-treatment requirements are some of the other disadvantages that these processes face (Suganthi et al., 2018). As a result, environmental scientists should consider environmental protection regulations, treatment cost, resource recovery, toxic chemical treatment, sludge characteristics, and social impact when adopting a petroleum sludge treatment plan.

3. Methodology

Web of science is one of the most widely used databases for article retrieval. Data were retrieved from the online Web of Science core-collection databases on 20th September 2021. Articles that come under the title or keywords or abstract containing the words "petroleum sludge" OR "oily sludge". Similarly, the "petroleum tank bottom sludge" word was used to identify articles dealing with sludge from storage tanks. Finally, the words "petroleum tank bottom sludge" were combined with petroleum sludge" OR "oily sludge" to identify all articles

Table 3
Regulations on PIS management

Country	Law	Significance	Year
United States	Resource Conservation and Recovery Act (RCRA)	Reuse and recycling	1976
	United States Environmental Protection Agency (US EPA) published a final rule (57 FR 37194, 37252)	Reduction	1992
Malaysia	Environmental Quality Act Regulation, under the First Schedule of the Environmental Quality (Scheduled Wastes) Regulations, (SW 314)	Reduction and reuse	2005
China	National Catalogue of Hazardous Wastes, No. HW08, Ministry of Environmental Protection	Reduction	2007
Kuwait	Kuwait Environment Public Authority regulations manage and regulate its waste by Law No. 21/1995 as amended by Law No. 16/1996 and Decision 210/2001 and amended by Law No.42 of 2014	Reuse and recycling	2014
UK	The Waste (Circular Economy) (Amendment) Regulations 2020 was made on 25th August 2020, Laid before Parliament on 27th August 2020, and came into force on 1st October 2020	Reduction, recycling, and reuse	2020
Norway	The regulations relating to Petroleum Product Storing for Emergency Purposes (RPP) and the 2011 Act on Business and Industry Preparedness	Reduction and recycling	2011
Mozambique	Decree No. 34/2015 approves the Regulation of Petroleum Operations	Reduction and reuse	2015

involving the petroleum industry-generated sludge. The search was limited to articles published over ‘2005-2021’, yielding 1219 articles. The research was then fine-tuned by narrowing the outcomes to "search by document type." The documents were classified as “articles, reviews, corrigendum, meeting abstracts, early access, proceeding papers”. Authors then focused on “articles”, thereby decreasing the number to 1061. Following that, the writers conducted paper selection by reading the title and abstract of each publication. 151 articles were found to be appropriate for the current review. The evolution of major publications and countries that worked on petroleum industry sludge is depicted in Fig. 4a and b. It indicated that the research trend in the petroleum industry sludge management is very significant. It’s also evident that petroleum waste has garnered a lot of attention in recent decades, as indicated by the expanding quantity of articles. This might be connected to the damaging effects of petroleum sludge produced by extensive crude oil production on the environment. Consequently, this review aims to identify various applications of the petroleum industry sludge for a sustainable economy and environment and to provide a broad overview of the most recent knowledge on this vast and fascinating subject. It also highlights the possibilities and chances for researchers in this sector in the future.

4. Waste to resource potential of PIS

4.1. *PIS for sustainable construction*

One of the best solutions for the re-utilization of petroleum sludge is its application in several industries including the construction industry. Apart from the utilization of PIS by oil refineries for their purpose, sludge from the petroleum sector is also used in the production of materials such as kilned bricks, cement, asphalt-concrete mixtures, etc. used in the building industry (Shperber, Bokovikova & Shperber, 2011, Jagaba et al., 2021).

4.1.1. *Cement clinker production*

Cement is a vital building material for the world’s housing and infrastructure demands. The cement industry faces increasing problems in terms of material and energy conservation, as well as lowering CO_2 emissions. The production of cement is aiming to become more energy-efficient while also using alternative raw materials. Because of the increasing economic growth of giant regions, the cement industry’s involvement in resource conservation and environmental protection has grown rapidly in recent times (Chatziaras, Psomopoulos & Themelis, 2016). In the construction industry, there is a worldwide high demand for cement. As companies are multiplying their cement production rate, sustainable cement production is a need of the hour. This could simply be achieved by incorporating waste by-products having similar compositions to cement into the production process and will go a long way by reducing natural resource depletion as well as reducing cement clinker production cost. PIS could serve the function of gypsum during strength development as a setting retarder because it contains a high amount of anhydrite ($CaSO_4$). To replace gypsum during cement production in other to delay cement clinker flash setting, 5% PIS was used because it contains a high amount of sulphur trioxide. The mixture yields positive results (Aeslina & Ali, 2017). In another study, findings revealed that even though the application of PIS negatively affects the produced clinker properties, it still meets the required standard. The result of 5% PIS addition tagged as PS5, was of acceptable quality and comparable to those without PIS addition tagged as PS0. The SiO_2 and CaO contents were 20.4% and 71% for PS0, while PS5 had 19% and 70% respectively (Kankia et al., 2021). When gypsum was 100% replaced by PIS, a 28.8% increase in UCS values was recorded after 28 days of curing (Benlamoudi, Kadir & Khodja, 2017). Still, on the application of PIS during cement production, it not only serves as a gypsum replacement but could also serve as an alternative fuel because it is diluted to a level that it can easily be pumped. This is supported by the fact that its heating values, sulphur, carbon, and ash contents are like those of sewage sludge, bituminous coal, petroleum coke, etc. However, its nitrogen content is low with high moisture content (Al-Futaisi et al., 2007). Therefore, it is important to note that, the potential emission of toxic compounds from PIS should be studied before its utilization in cement production plants.

4.1.2. *Mortar*

Portland cement can be fully or partially replaced by geopolymer materials in mortar production. This will produce a mortar with very low carbon emission potential and encapsulation capacity. To improve it by using waste materials, the suitability of petroleum sludge as a cement replacement material was investigated by researchers. Petroleum sludge could be converted to petroleum sludge ash (PSA) after thermal treatment. PSA possesses favourable shape, particle size, functional groups, chemical composition, and mineral phases, making it a potential building material. PSA properties such as particle size, chemical composition, morphology, mineral phases, and functional groups made it a promising sustainable pozzolanic construction material. The strength development of mortar cubes proves that they can replace < 20% cement. The compressive strength of a 10% PSA-containing mix was twice that of the control mix. The microstructure of the mortar sample was likewise well-refined. PSA boosted strength development up to 28 days of curing, after which it remained nearly constant. As a result, it might be classified as a cementing material (Jagaba et al., 2021). An experimental approach for manufacturing geopolymer mortar utilizing petroleum sludge ash (PSA) and fly ash is described by Kankia et al (Kankia et al., 2021). Fly ash replacement percentages ranging from 0% to 20% by weight were used for PSA substitution. After 28 days, it was found that the geopolymer mortar made with 10% PSA had the highest compressive strength (31 MPa). When 20% PSA was added, the mortar’s workability decreased while the hardened density increased. Unconfined compres-

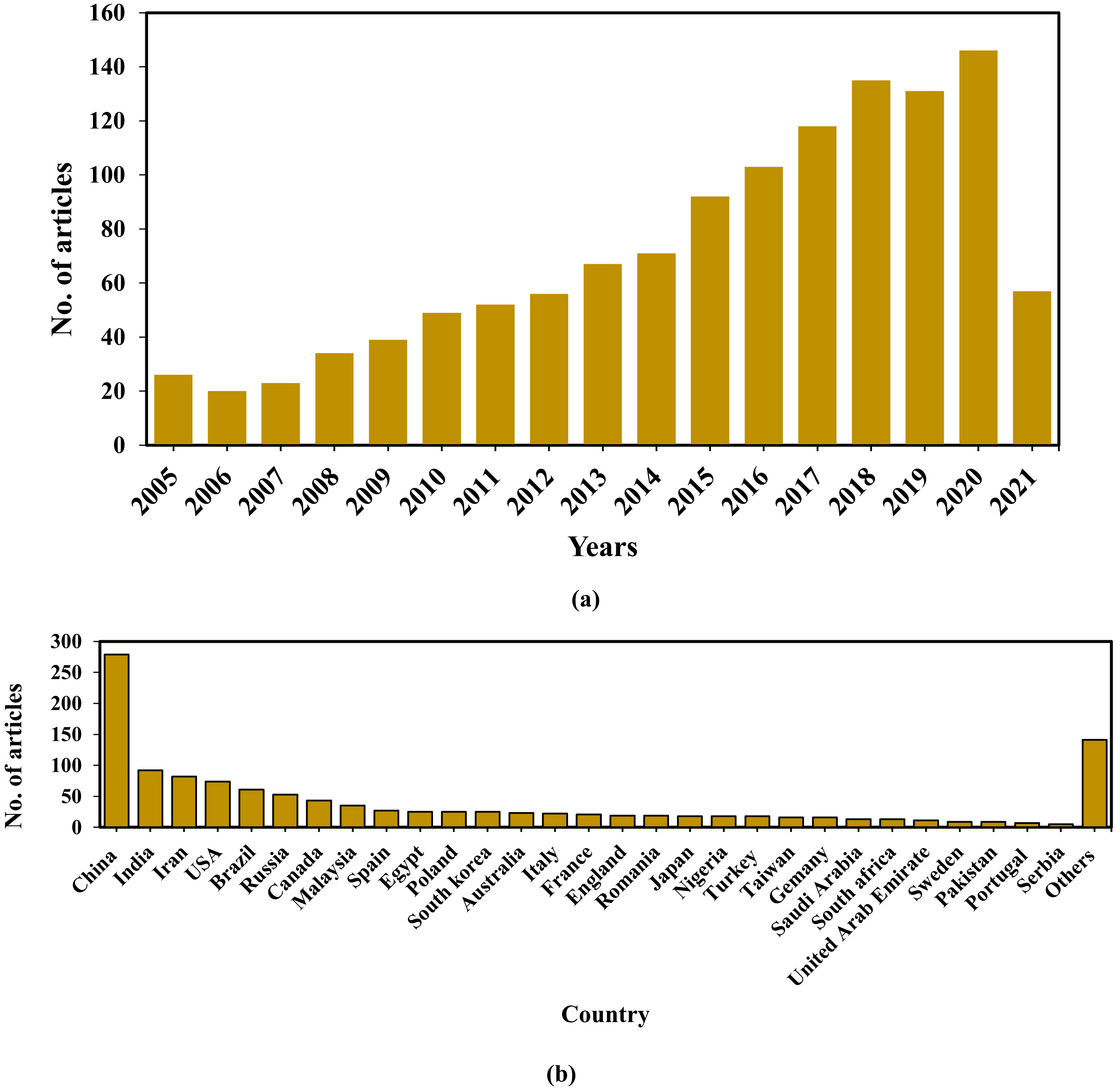

Fig. 4. Graphical representation for the publication trend on petroleum industry sludge in Web of Science database (a) articles per year (b) articles per country

sive strength is marginally reduced when a larger proportion of fly ash is replaced with PSA.

4.1.3. Building block

The use of petroleum sludge for building block manufacturing was investigated. The petrovege block samples were treated with 8–13% liquid content of a mixture of vegetable oil and petroleum sludge for binding purposes. The products complied with the construction block's basic requirements. When compared to traditional construction blocks, the compressive strength was shown to be higher. COD levels were not found to be unsatisfactory in any of the monolithic samples. This confirms the environmental acceptability of petrovege block (Johnson, Madzlan & Kamaruddin, 2015).

4.1.4. Ceramics

The recycling potential of treated petroleum oily sludge in the ceramic industry has been evaluated by several researchers. Based on the composition, several studies reported that the treated PIS could be used in red ceramic, bricks, aggregate, and concrete formulations. Adding conventional carbonates such as $CaCO_3$ and $NaHCO_3$ as expansion agents to petroleum processing industry waste (oily wastes and oil sludge) could yield a ceramic product with properties (density, morphology) like lightweight aggregates (LWA). The output manifests a foam-like structure with rounded cavities. 1.223 g/cm^3 which happens to be 45% < samples without additives, was obtained as the least density value when 40 wt% $NaHCO_3$ was mixed with oily waste and sintered at 900°C. The incorporation of $NaHCO_3$ and the reaction between distinct oily waste and clay elements initiate the synthesis process (Martinez et al., 2018). Encapsulated petroleum waste classified as solid waste is an oily sludge that has been treated with bentonite clay. Most heavy metals present in it are below the maximum allowable limit. As a result, the waste might be used as a low-cost alternative during red ceramics production for potential applications in civil construction without causing any concerns (Pinheiro & Holanda, 2010). It is interesting to note that the incorporation of 30 wt.% PIS improved ceramic pieces' properties. Without changing the red ceramics production process, the red ceramic pieces satisfied the requirements for industrial processing of roofing tiles and clay bricks. However, it lessened the red ceramic fragments' mechanical strength (Yaro et al., 2022).

Petroleum waste sludge (40 wt%) containing Barium and silicon oxide, was combined with bauxite ore (60 wt%) that contains aluminium and silicon oxide to produce qualitative refractory ceramics. At high temperatures, the oxides react to generate barium aluminate and mullite minerals. This helped in improving the refractory properties, microstructure, and physico-mechanical of the formed ceramic specimens. Thus, they can be utilized as linings for industrial furnaces that operate at high temperatures. The authors concluded that the fluctuations in bulk density, compressive strength, linear shrinkage, and porosity values of the manufactured ceramic bodies were influenced by the PIS content and firing temperature (Khalil, Algamal & Saleem, 2018). Investigations were conducted on the thermal properties of sintered ceramic structures with up to 5% PIS, uniaxially crushed at 25 MPa, and sintered between 850 and 1000°C. The findings revealed that there was no substantial change in the structure, leading to significant waste reduction benefits. The charred bodies' mechanical strength rose, although densification was unaffected by the presence of quartz and barite particles (Rodrigues et al., 2005). When PIS is used to make clay aggregate, the volume weight decreases, the production of the large fraction is increased, and fuel consumption is decreased (Shperber, Bokovikova & Shperber, 2011). It can be concluded that petroleum industry waste application in ceramics depends on firing temperature and petroleum oily sludge content.

4.1.5. *Brick and tile fabrication*

The inclusion of petroleum oily sludge into various clay bodies for bricks and tiles manufacturing was successful. Any of the technical features were unaffected by adding up to 5% by weight of a crude oily sludge and its bentonite-treated form. This inclusion, on the other hand, alters the clay body's workability and, in some instances, improves the processing conditions. Potential hazardous metals in the oily waste turned inert once the clayey body was fired (Abdullahi, 2022). Similarly, the effects of replacing natural kaolin with 5% solid petroleum waste in a porcelain stoneware tile body/composition burned at 1240°C were investigated. Findings revealed that it reduces flexural strength, linear shrinkage, and density while increasing water absorption in the tile products manufactured. The amounts of Ba, Cd, Ag, Hg, Cr, Pb, and As in the leachate of burnt porcelain stoneware tile pieces were within regulatory limits. This proves that the waste could be utilized to manufacture porcelain stoneware tiles (Pinheiro & Holanda, 2013). The mineralogical and thermal modifications in floor tile pastes that contain up to 10 wt% of petroleum waste to replace kaolin were investigated. The replacement was reported to have altered the thermal expansion–shrinkage curve with low values of thermal diffusivity which are closely correlated to changes observed in the porosity of the material. It was also discovered that greater petroleum waste quantity, increases floor tile pastes mass loss (Al-Mahbashi et al., 2022). The use of 5% petroleum oily sludge in place of kaolin at an optimal firing temperature allows for the manufacturing of vitrified floor tiles with excellent technical characteristics. Significant morphological changes and phase composition were observed throughout the firing process of floor tile formulations. The floor tile pieces' densification process was affected by the sludge inclusion. However, it was retarded at > 2.5 wt% addition. For a broad kiln temperature range, the floor tile pieces showed good dimensional stability. The technical parameters of the vitrified floor tiles manufactured were comparable to those of porcelain floor tiles (Pinheiro & Holanda, 2013).

4.1.6. *Highway material*

Crude petroleum-containing wastes and soils are employed as organic binders in the construction of filtration-preventing shields, road surface structural beds, and waterproofing interlayers for automobile roadbeds (Shperber, Bokovikova & Shperber, 2011). Leaching tests were used to explore the possibility of heavy oily sludge modification via distillation and its application to solidify other hazardous waste in regulating heavy metal release as a stabilization/solidification (S/S) material. The optimal ratio for regulating the release of heavy metals during solidification was found to be 0.5. The S/S of heavy metals was improved in the modified oily sludge, and the main physicochemical parameters of the asphalt-like emulsion were in line with bitumen 100#. A temperature of 493 K at 2.5 h was ideal for industrial bitumen preparation with reduced penetration and a higher softening point (Li, Guo & Ye, 2015). Similarly, oily sludge was used as a roadbed material, using phosphogypsum as a stabilizer and 20% conventional Portland cement, fly ash, and silica fume combination as a binder, using the S/S process. The findings reveal that adding phosphogypsum-based binders to oily sludge not only improves the solidified samples' 28-day compressive strength but also significantly reduces heavy metal release and refines the pore structure, compacts the microstructure. The solidified body was volumetrically stable, had good freeze-thaw resistance, and was strong enough to withstand water. This S/S technique improves environmental protection while also making the solidified product economically viable (Xiao, Yao & Zhang, 2019).

The use of petroleum sludge from the tank bottom in paving layer mixes with aggregates was investigated. Instead of asphalt cement, treated sludge was employed as the binding medium. The activity values obtained for all sludge combinations in road applications were either very low or negligible when compared to a naturally occurring radioactive mineral limit value of 100 Bq/g. No extraction of sludge applied to roads surpassed the TCLP maximum limitations stipulated by the USEPA (Al-Futaisi et al., 2007). TPH biodegradation and leaching of oily sludge utilized as a dust suppressor for unpaved road maintenance were investigated during natural attenuation processes. On the 129th day of the in-situ study, a 95% TPH removal was found at 5 cm depth. The high TPHs reduction seemed to be due to the leaching process. It was however reported that there was no degradation at 50 and 80 cm. TPH content in the leachate was less than 1 mg/L in the column studies, demonstrating that the leaching procedure had no major influence. The density of microbial degraders was the same whether oily sludge was added or not since the microorganisms had adapted to these circumstances and the utilised road had already been treated with it (Roldan et al., 2010).

A study investigates the viability of adding PIS in bitumen to lessen reliance on petroleum-based bitumen. Findings revealed that PIS addition in a petroleum sludge modified bitumen (PSMB) decreases bitumen stiffness. PSMB stiffness has been found to improve as the temperature and mixing speed is increased. The higher ratio of asphaltenes to maltenes fractions in PSMB under intense mixing conditions have been linked to this improvement. Adding PIS to bitumen causes it to become more flexible. When compared to control bitumen, most binders containing PIS had a lower temperature susceptibility. All PSMB binders met the bitumen's storage stability and plasticity index criteria, and no phase separation was observed. The study concluded that PIS could be successfully added to bitumen (Memon et al., 2020). A study investigates the usage of oily sludge in the production of asphalt. Marshall asphalt samples were analysed using oil sludge with bitumen and aggregate. The best outcomes came from a 50% oil sludge in a bitumen mixture, as well as a 2% polymer and 15% oil sludge mixed with bitumen. These mixes are cost-effective. When oil sludge is applied to bitumen, its resistance is lessened since oil sludge diminishes bitumen's adhesive property. Polysulfide formation between bitumen and sulphur molecules was prevented by the oil sludge. The resilience of asphalt samples was improved when bitumen and oil sludge were combined with styrene-butadiene-styrene polymer (Karami & Behbahani, 2018).

A plasticizer resin was suggested from the thermochemical processing of lignite with PIS for the preparation of polymer-bitumen binder. The binder containing 11% resin, 85% bitumen, and 4% styrene-butadiene-styrene polymer, was the best considering its brittleness, penetration, extensibility, softening temperature, and adhesion. Testing the binders after heating at 160°C for 5 h, show that a three-component bitumen-polymer-plasticizer structure is formed. The binders produced a three-component bitumen-polymer-plasticizer complex after being heated at 160°C for 5 hours. This demonstrated that asphalt concrete made with a polymer-bitumen binder has the desired properties. Therefore, resin from the processing of lignite with PIS can be used as a plasticizer in the production of polymer–bitumen binder. This represents an economical means of disposing of waste materials (petroleum sludge) used for resin processing (Noor et al., 2021). To test the thermal behaviour of a petroleum asphalt (PA) binder modified with a mixture of oily sludge and rubber tires in ratios of 85/15% m/m (M1) and 15/85% m/m (M2), M1 and M2 were added to the PA at concentrations of 10% and 20% m/m. The starting decomposition temperatures ranged from 190 to 290°C, which was greater than the processing temperature of asphalt mixtures (160 ± 5°C). The presence of a higher percentage of oily sludge in the M1 mixture resulted in a higher melting temperature of crystalline fractions. The modified binders demonstrated a 25% decline (from 60 to 44 kJ/mol) in activation energy as compared to the PA, allowing for energy savings during asphalt cement manufacturing. As a result, the material under investigation has the prospect to be used to make asphalt concrete for road pavement covering (da.Graca, Cardoso & Mothe, 2019).

4.2. PIS for wastewater treatment

4.2.1. PIS as an adsorbent material

Utilizing PIS to create petroleum sludge-based adsorbent will fully utilise this priceless resource. According to the literature, a lot of petroleum industry sludge has been demonstrated to be a good source of precursor chemicals for making carbonaceous adsorbents, particularly those used in wastewater treatment. This is caused by the sludge's high asphaltene content. Oily sludge was converted into activated carbon in an experiment (AC). Asphaltene became more concentrated, pore size somewhat shrank, and the surface area of the created AC increased from 1103 to 3292 m^2/g when the de-oiling treatment step was applied. Additionally, from 17.8 mL/0.1 g to 64.6 mL/0.1 g, the methylene blue (MB) adsorption capabilities rose, approaching those of ACs manufactured from commercial asphalt. It's interesting to note that the leaching values for heavy metals in the developed ACs were far lower than those for dangerous chemicals. This shows that the de-oiling method may significantly enhance the quality of AC. The MB adsorption of micro-mesoporous enhanced AC material made from raw petroleum oily sludge and rice husk was tested. When compared to ACs produced solely from oily sludge or rick husk, the latter showed far fewer microporosities and significantly more functional groups that contained oxygen. Additional mesopores may have formed because of the asphaltenes in the oily sludge forming a carbon skeleton with the rice husk ash wrapped inside. Due to its higher asphaltene content, the oily sludge had a larger specific surface area (2575 m^2/g) than the mixture with a lower asphaltene content (1849 m^2/g). In the meantime, it appeared that the cellulose in rice husk increased the proportion of oxygen-functional groups in AC products. From 8.3% for rice husk and 4.6 percent for oily sludge, the AC yield increased to 16% when made from mixed waste materials. Oily sludge based ACs and oily sludge/rice husk mixed ACs both had the highest MB adsorption capacities for the AC samples, with 588 and 758 mg/g, respectively. As a result, mixtures of oily sludge and rice husk seem like viable choices for creating porous AC (Wang et al., 2018).

Oily sludge was subjected to pyrolysis to create porous carbonaceous adsorbents, both with and without KOH activation. The activated carbonaceous adsorbent (AC) has much-improved pore characteristics than the non-activated carbonaceous adsorbent due to the formation of micropores and mesopores (NA). For the removal of Cd from mine effluent, the carbonaceous adsorbents performed well. The Cd adsorption effectiveness of the NA and AC was found to be 78 and 98%, respectively (Mohammadi & Mirghaffari, 2015). In a related study, porous carbon was extracted from oily sludge and activated with KOH. The total pore volume, BET surface area, and micropore surface area of the carbon material were 0.21 cm3/g, 328.0 m^2/g, and 289.10 m^2/g, respectively. Leaching in distilled water was moderate and below acceptable limits, even though metals are more prevalent in porous carbons than in oil sludge. 97.4% of the Cd that was present was extracted by the adsorbent. The porous carbon is similar to three commercial activated carbons under the same circumstances (Mohammadi & Mirghaffari, 2015). To remove oil spills from the surface of saline water, the adsorption capability of a chemically treated and untreated PS was compared. Results obtained showed that the adsorption capacities are 2 g/g and 1.388 g/g for chemically treated and untreated PS, respectively. Thus, chemically treated and untreated sludge having higher adsorption capacities is suggested to be recycled during oil spill area remediation (Sayed & Zayed, 2006). $ZnCl_2$ was utilised as a chemical activator to make an adsorbent using used sawdust and oily sludge to absorb crude petroleum. The sludge-based adsorbent was coded (S-AB-$ZnCl_2$). The higher mesopore surface areas and volumes obtained for the two materials are benefitted from the adsorption process. S-AB-$ZnCl_2$ adsorption capacity is higher at 3.5 h, 15 °C/min, 550 °C,1:0.5, and 1:1.5 for activation time, heating rate, activation temperature, sludge-sawdust ratio, and solid-liquid ratio respectively. Even though the heating regeneration loss rate increases over time, the S-AB-$ZnCl_2$ regeneration efficiency of 85% can be accepted after three regenerations.

4.2.2. Bacteria isolates from PIS for wastewater treatment

PIS is a bacterial reservoir with a strong restoration ability. The bacteria identified from PIS have the potential to be effective bioremediation agents.

PIS bacteria were isolated and examined for their capacity to break down various aromatic compounds (Congo Red, PBS, Toluidine Blue, and Reactive Black 5) and emerging (prometryn, fluometuron, and sulfamethoxazole) pollutants. Bacterial isolates belonging to two (2) different bacterial genera: *Bacillus cereus* (MA1) and *Pseudomonas guariconensis* were obtained from PS. MA1 (B. *cereus*) was found to be the most viable and capable of efficiently degrading the focused pollutants (Alhefeiti et al., 2021). *Pseudomonas aeruginosa* AT18 (P. *aeruginosa* AT18) can biosorb the metallic ions Cr^{3+}, Cu^{2+}, $Zn^{2+,}$ and Mn^{2+} in solutions after being isolated from petroleum and heavy metals contaminated regions.

According to equation (1), metal adsorbed by P. *aeruginosa* AT18 biomass was calculated as

$$Q = V\left(C_0 - C_e\right)/X, \tag{1}$$

Where:
Q = specific metal uptake (mg metal/g biosorbent),
X = biomass dry weight (g),
V = volume of the metal solution (mL),
C_0 = initial concentration of metal in the solution (mg metal/L),
C_e = final concentration of metal in the solution (mg/L).

Only 20% of Mn^{2+} was removed because of the metal's low sorption capacity (22.39 mg/g). Cr^{3+} has the highest sorption capacity and was 100% adsorbed at 7-7.72 pH (Silva et al., 2009).

A study was conducted to assess the ability of two bacteria isolated from PIS, *Pseudomonas aeruginosa* PSA5, and *Rhodococcus* sp. NJ2, to metabolise benzo(a)pyrene [B(a)P]. P. *aeruginosa* PSA5 and *Rhodococcus* sp. NJ2 decomposed 50 ppm B(a)P by 88 and 47%, respectively, after 25 days of incubation. P. *aeruginosa* PSA5 had the highest induction of 2-carboxybenzaldehyde dehydrogenase (774 nmol/mg protein), while *Rhodococcus* sp. NJ2 had the highest expression of salicylate hydroxylase (840 nmol/mg protein). The two bacteria were shown to produce biosurfactants (glycolipids). Increased cell surface hydrophobicity, reduced surface tension, and a higher emulsification index were also used to determine the function of biosurfactants in pollutant breakdown (Mishra & Singh, 2014). Still, on bacteria isolation from petroleum sludge, a bacterial strain coded as BB belonging to *Pseudomonas spp* was used for Pyrene degradation. BB was found to degrade 82% of 100ppm Pyrene in 4 weeks incubation period. The degradation process was facilitated by overexpression of protein synthesis activity by increasing the protein amount from 10.275μg to 42.903μg. This results in an increase of bacterial biomass from 1×105 to 4.7×10^6 and a decrease in pH from 6.6 to 7.6. Thus, this indicated that the BB strains were capable of degrading Pyrene (Singh et al., 2013).

4.3. Anaerobic digestion for gas generation

Because considerable amounts of biogas are produced, anaerobic digestion procedures are particularly energy efficient. Three phases make up the mixed-culture fermentation process known as anaerobic digestion: methanogenesis, hydrogen and acetate generation, and hydrolysis and acidogenesis (Ji et al., 2013). Numerous benefits of anaerobic digestion technology have led to its widespread use in both environmental engineering and energy engineering, including the production of huge amounts of biogas with little sludge yield and no need for aeration. In the anaerobic digestion process, gas output and type were crucial indicators. The oily-biological sludge can serve as both a substrate and an inoculum. Studying the anaerobic digestion of PIS in a semi-continuous flow anaerobic bioreactor, the VFA was gradually degraded into CH_4, and the pH was raised. Maximum gas production of 864 ml was achieved after a 40-day sludge retention period. Compositions of methane greater than 60.4% suggest a robust anaerobic process (Zhidong, 2011). Oily-biological sludge has a low carbon/nitrogen ratio (C/N), it, therefore, requires a co-substrate material to suit the anaerobic digestion process' requirements. Sugarcane bagasse as an organic waste with a high C/N ratio is recommended as an ideal material for balancing the batch C/N ratio (Ghaleb et al., 2021).

A study, it was investigated how much hydrogen might be created during the gasification of oily sludge (OS) from crude oil refineries and sugarcane bagasse, as well as how it could be applied to the hydrodesulphurization of diesel oil. For a high conversion rate (>90%) of OS compounds, OS thermal conversion requires a working temperature of >1300^{0}C. With a projected H_2 output of roughly 1.8 Nm^3 H_2/kg OS, the gas produced was 2.3 Nm^3/kg OS. Using OS and sugarcane bagasse combinations, however, hydrogen production rises to 3.5 Nm^3 H_2/kg OS. The hydrogen from OS thermal conversion could thus be employed in an integrated system between the OS/biomass co-gasification and hydrotreatment processes to replace around 37% of the total hydrogen required for diesel oil hydrodesulphurization. Significant reductions in greenhouse emissions and non-renewable resources could also be achieved (Gonzalez et al., 2018). To boost biogas yield, a study conducted by Ghaleb et al., (Ghaleb et al., 2020) pre-treated a mixture of oily sludge and sugarcane bagasse under thermo-chemical conditions. Maximum C/N (30), co-substrate/inoculum ratios (0.18), and sugarcane: oily-biological sludge 2:193 yielded the highest biogas yield (9,268 mL). The biogas yield rose as the C/N ratio increased by increasing the sugarcane bagasse component in the batch. This could be caused by increasing the batch's volatile solids content. Because of its high C/N ratio and VS content, sugarcane bagasse has been used as a co-substrate in mesophilic environments to enhance the anaerobic co-digestion of oily biological sludge.

Sugarcane bagasse balanced the unsuitably low C/N ratio for oily-biological sludge degradation and postponed the high-toxicity impact of oily-biological sludge to provide a favourable environment for methane bacteria. 64 mL CH_4/g $VS_{removed}$ was found to be the maximum expected methane output (Ghaleb et al., 2020).

4.4. Diverse potential applications

The bioremediation of PIS using effective microorganism (EM) technology was the subject of a study. The processed sludge was discovered to be high in potassium, nitrogen, phosphorous, and organic matter. Thus, it was combined with clean soil (1:1) to make EM biofertilizer which was later utilized for the cultivation of onion. It was reported that the heavy metal content in the onion was all within the EU 2006 permissible limit. In comparison to the 230 kg yield obtained with farm yard manure, the EM biofertilizer produced a 275 kg yield (Ahmad, 2017). A study found that using land-farmed oil sludge as a carbon source produced acceptable soil conditions for growing jack beans (*Canavalia ensiformis*). It effectively lowered the phytotoxicity of jack beans. During 120 days of growing jack beans, rhizome- and phytodegradation lowered TPHs by 57.4%. Aromatic hydrocarbons were found in the stem, leaves, and bean pods, but aliphatic hydrocarbons remained in the roots. Thus, landfarming and phytoremediation can be used to manage large amounts of oily waste at a low cost (Jagaba, 2022). *Bacillus licheniformis* NS032 was isolated from a PIS and tested for its ability to produce levan. The output grew steadily with increasing sucrose concentrations subject to a maximum of 400 g/L when ammonium chloride was used as the only nitrogen source. The maximum levan yield in the low sucrose (197 g/L) system with 2.4 g/L ammonium chloride and high sucrose (398 g/L) system with 4.6 g/L ammonium chloride were 48 g/L and 99 g/L respectively (Birniwa & Abdullahi, 2019).

Turebekova et al. (Turebekova et al., 2019) recycled petroleum sludge to manufacture tire rubbers. It was explored if it was most acceptable to use the organic portion of oil sludge in the rubber compounds used to make the filler strip for the board side panels. Rubber characteristics comply with inspection standards when conventional softeners are employed in place of the organic portion of the oil sludge. The dose of 8–10 mass shares of the organic portion of oil sludge for the rubber compounds intended for the filler strip produced the greatest results. When the organic portion of the oil sludge dosage is increased, there is a negligible decrease in the tensile indicators and an increase in the elastic properties of the rubbers. This can be explained by the plasticization effect mechanism of the organic portion of the oil sludge and low-molecular compounds, which permeate between macromolecules by reducing the intermolecular interaction of the macromolecules in the rubber substance. The mineral portion of the oil sludge can be partially substituted for the fillers in the receipts of the rubber compounds for the creation of the filler strip.

PIS was used to develop metal catalysts by thermal treatments. The catalysts were mostly made of iron, ranging from 2.5 to 7.5% wt, with a specific surface area of 2.3 to 16.8 m^2/g and a heat capacity of 0.7 to 1.2 kJ/kg K. The employed waste material's thermal-energetic stability was increased as a result of the treatment (i.e. PIS) and the catalytic activity of the synthesized materials was comparable to that of commercial catalysts (Castro-Leon et al., 2020). Biochar was made from oily sludge using a pyrolysis method at 400-700°C. The C/H mol ratios were used to determine biochar's redox capability. At 700°C, the highest degree of condensation and aromaticity of pyrolysis products was achieved, possibly explaining the biochar's comparatively strong electron transfer capability and good cycle performance. The highest performance for lithium-ion batteries was found when the electrochemical properties of the generated biochar at 700°C were investigated as a potential cathode material of the electrode (Abdullahi et al., 2021). Oily sludge samples were processed to yield conductive carbon–clay composites. In contrast to the precursor material, the results showed that the composites created were conductive, with conductivity values typical of semiconductors. The material's potential applications in sensors, catalysts, and electronic devices were also demonstrated.

The accumulation of PIS as an environmentally unfriendly material in landfill is quite disturbing. Therefore, this review tried to extensively discuss its reusability potential. Based on the applications of PIS and summarized in Fig. 5, it can be realized from this section that several researchers put effort into eradicating PIS from the environment in a sustainable manner and raw materials will be less frequently used. Thus, allowing them to be preserved for a significant period. This could be addressed as sustainable disposal means that decreases air pollution and subsequently produces high-quality products with positive economic impact.

5. Sustainability and circular economy

5.1. The circular economy

Through the circular economy, environmental preservation and economic activity are to be combined sustainably. It emphasizes the use of biomass, solar, wind, and waste-derived energy throughout the life-

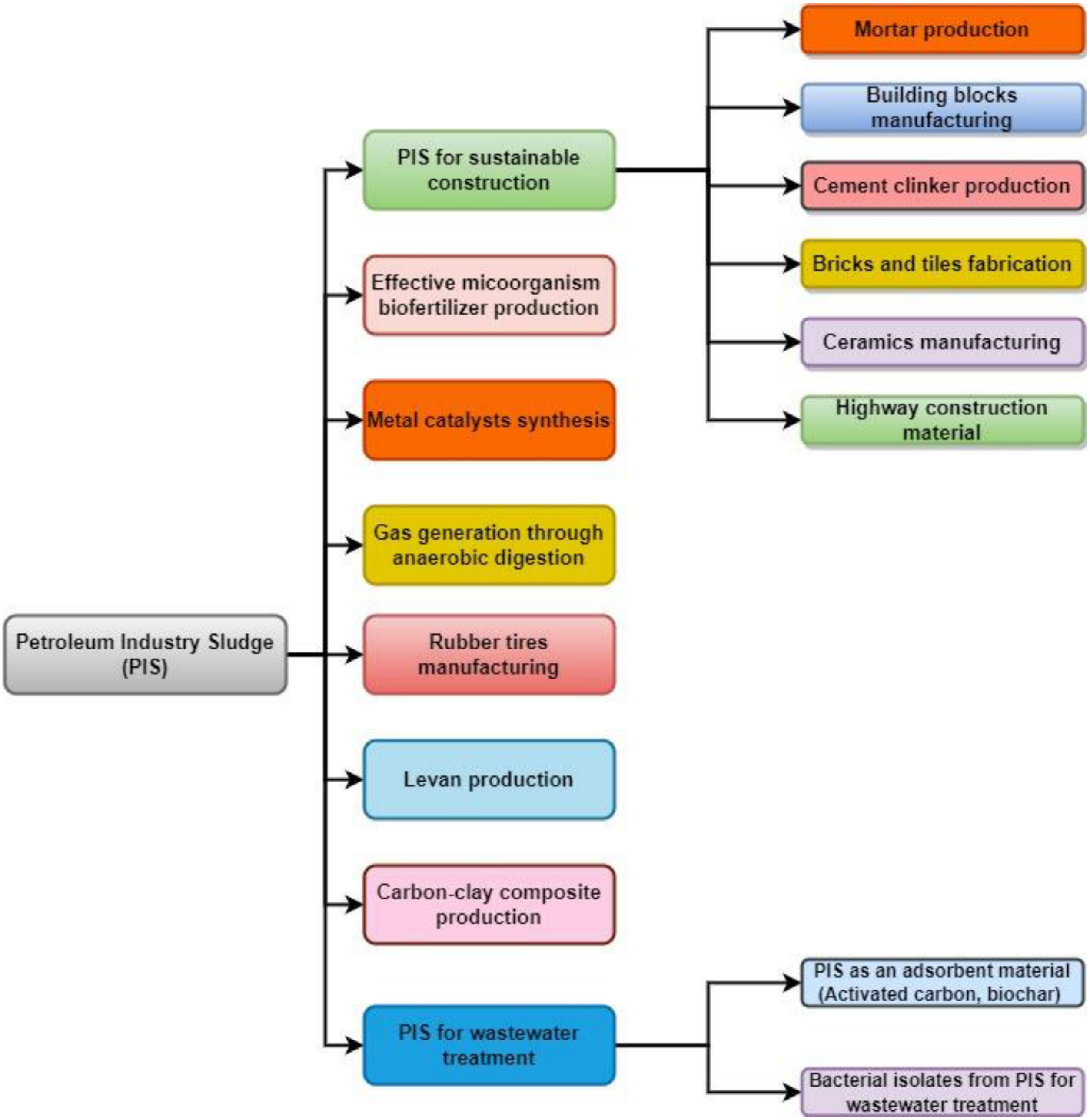

Fig. 5. Resource potential applications of PIS for sustainable development

cycle of the product. Additionally, it promotes the reuse of materials, products, and componentry as well as their remanufacturing, cascading, upgrading, repair, and refurbishing (Jagaba et al., 2022). Embracing alternate manufacturing, utilization, and disposal systems is referred to as a solution for enhancing good environmental benefits while increasing economic growth. It promotes the cyclical deployment and utilization of processes and works to move away from the "make, use, dispose of" philosophy. Nevertheless, because it necessitates consumer behavioural adjustments in terms of perception of values, patterns, and connections, it makes life more difficult for people (de Morais, Pinto & Cruz-Jesus, 2021). To conserve the economic worth of resources for as long as is humanly possible, the primary building blocks of the circular economy advocate the responsible and cyclical use of materials and energy. The circular economy has been positioned as a catalyst for improvement in areas of sustainability, resource management, social equity, social responsibility, and productivity to achieve the Sustainable Development Goals (SDGs) (Mutezo, and Mulopo). The demand is changed from a linear "extract-produce-use-dump" approach to a cyclical flow one, which not only promotes economic growth. Additionally, it is supposed to lessen the carbon footprint (Upadhyay et al., 2021). It's interesting to note that businesses are now incorporating the concept into their regular operations.

5.1.1. Principles of a circular economy

The Ellen MacArthur Foundation has identified three pillars of a circular economy. These include (i) Remanufacturing, refurbishing, and recycling products and services to create new value while redistributing capital. (ii) a finite supply of natural resources will be saved and fully utilized possible by dematerializing and virtualizing service delivery as well as encouraging green technologies and procedures. (iii) Use of sustainable and resilient resources, damage mitigation, and waste elimination are top priorities for industrial success (Mutezo, and Mulopo).

Fig 6. 4Rs of the circular economy model

5.1.2. Approaches to foster circular economy

The following strategies have been highlighted as supporting the circular economy: (i) Dematerialization using digital and virtual services. (ii) Ecosystem rejuvenation and repair: regeneration. (iii) Optimization, including increased productivity, remote sensing and control, waste reduction, and big data use. (iv) Exchange: putting new technological advancements, services, and business models into practice. (v) Loop: Biochemically extracted outputs from the processing, remanufacturing, and extraction of organic waste are employed as inputs in the economy. (vi) Sharing: updating, sharing, and asset reuse (Upadhyay et al., 2021). Numerous business models can be used to implement the circular economy. They are circular economy and: (i) Waste Management (ii) Manufacturing (iii) Energy (iv) Supply Chain Management (v) Consumer (Mutezo, and Mulopo). Researchers have noted that the refining of crude oil can provide significant amounts of different biomass wastes, which is relevant to the circular economy of the petroleum sector. Petroleum sludge is a product that has demonstrated success in establishing a wholesome and sustainable circular economy by serving as a feedstock, energy source, and chemical source. The application of the 4Rs in the development of the new circular economy paradigm, as seen in Fig. 6, cleared the way for the effective use of greasy petroleum sludge. The use of petroleum sludge for the numerous industrial applications included in this assessment is beneficial to the environment and the well-being of the community in light of the circular economy plan. (Sadeghi et al., 2015).

5.2. Circular economy potential of PIS

Owing to the negative impacts associated with PIS, it has received immense attention in the last few decades. PIS treatment is a complex and time-consuming process. There are currently no cost-effective and waste-free PIS treatment solutions available. As such, to comply with legislation enacted in several countries that supports the integration of industrial wastes such as PIS as sources of secondary raw materials in economic turnover, several researchers have worked on the sustainable use of the sludge in various aspects of life to meet the sustainable development goals (SDGs). Several waste materials have been employed for the treatment of petroleum sludge for the recovery of beneficial resources and environmental safety (Dey et al., 2022). Waste-to-resource potential applications of PIS for reusability in sustainable construction, wastewater treatment applications, gas generation, and several other applications were also highlighted.

More so, a circular economy was adopted to reduce the environmental impact caused by PIS discharge. The circular economy adoption which represents a new way of creating value and wealth by extending product lifespans and shifting the trash from the end of the supply chain to the beginning is critical (Birniwa et al., 2021). The circular economy emphasizes on limiting the use of virgin resources and enhancing resource recovery and reuse. It has the potential to understand and implement new patterns that enable society to reach increased sustainability at low or no energy, material, and environmental cost. As the circular economy focuses on a closed-loop approach in contrast to the linear approach, it has the added advantage of greater environmental protection from non-degradable pollutants and as well the elimination of secondary pollution (Antunes et al., 2022). Thus, the circular economy potential of PIS to achieve self-cycle operation through the concept of "wastes-treat-wastes" in the petroleum industry was extensively discussed. This includes the potential of reusing isolated environmental microbes from petroleum sludge within the oil refining industry, petroleum coke improvement through co-mixing by petroleum industry sludge, etc.

6. The concept of "wastes-treat-wastes" in petroleum industry sludge to achieve self-cycle operation

The use of waste materials produced by companies is essential from the standpoints of economics, ecology, and non-renewable resource conservation (Manogaran et al., 2022). The "wastes-treat-wastes" process in the petroleum industry has been discussed in this section with numerous advantages as it is cost-effective and environmentally friendly. The practical applications found in the literature have also been summarized in Table 4. This approach would guide to further environmental gains due to the removal of PIS. Creating a sustainable and clean environment, it would also result in a reduction in environmental contamination.

In the catalytic ozonation of petroleum refinery effluent, the use of biochar made from waste sludge as catalysts were studied. According to the findings, the biochar increased oxidation by forming •OHs and when compared to single ozonation, the overall organic carbon removal was multiplied by two in the catalytic ozonation. During the pyrolysis process, the carbon, silicon, and metals contained in the activated petroleum waste sludge resulted in the development of active sites. Contaminants containing sulphur, oxygen, and nitrogen were reduced by 12.5%, 33.4%, and 58.2%, respectively (Chen et al., 2019). Biochar tagged as (biochar-WPS) was made from waste petroleum-activated sludge and then used to treat petroleum refinery effluent. The Biochar-WPS had 0.28 cm3/g and 229.77 m2/g as values for the pore volume and surface area respectively alongside a porous structure with a significant level of hydrophilicity due to the high amounts of metals and functional chemical groups. These characteristics allowed for quick aerobic granular production, bigger granule sizes, improved reactor efficiency, resistance to OLR shock loading, microbial colonisation, and adhesion, and maybe particle aggregation. In comparison with the control, biochar-WPS enabled the development of larger and more stable aerobic granules 15 days beforehand. The addition of biochar-WPS increased the average removal efficiencies of chemical organic demand (3%), oil (4%), and total nitrogen (10%) compared to the control. The produced granules showed increased microbial richness and diversity, as well as a higher (4%) proportion of denitrifying bacteria. More so, its addition also increased the total nitrogen, oil, and chemical oxygen demand removal efficiencies by 10%, 4%, and 3% respectively. Within the produced granules, enhanced microbial abundance and variety were detected, as well as a higher percentage of denitrifying bacteria (4%). These findings suggest that employing biochar-WPS for rapid granulation in SBR is a viable alternative that can provide an efficient, environmentally friendly, and cost-effective approach for the treatment of petroleum refinery wastewater (Wang et al., 2020).

Table 4
Waste-treat-waste in PIS

Waste material	Application	Remarks	Ref.
Waste sludge derived biochar	Catalyst for petroleum refinery wastewater treatment	In comparison to a single ozonation (26.9%), catalytic ozonation of refinery wastewater utilising sludge biochar made from activated petroleum waste sludge twice the total organic carbon removal (53.5%). During pyrolysis, the C, Si, and metals in the sludge create active sites. The charcoal stimulates oxidation by producing OHs.	(Chen et al., 2019)
Petroleum activated sludge derived biochar	Adsorbent for petroleum refinery wastewater treatment	The substance (biochar-WPS) was used to treat wastewater from oil refineries. The porous design and high level of hydrophilicity made it easier for microbes to attach to and adhere to the material, which helped particles to assemble. In comparison to the control, the biochar-WPS caused the development of more significant and stable aerobic granules 15 days earlier. Additionally, compared to the control, it improved the average removal efficiency of chemical organic demand by 3%, oil by 4%, and total nitrogen by 10%. The produced granules showed greater microbial variety and richness, and a higher (4%) proportion of denitrifying bacteria.	(Wang et al., 2020)
Petroleum refinery activated sludge	Real refinery wastewater Treatment by biological process	The treatment of a real refinery wastewater using an activated sludge biological reactors provided with or without sludge recycle system was successfully achieved, obtaining high removal efficiencies for COD, TOC and TSS, of 94–95, 85–87, and 98–99%, respectively. Organic matter removal efficiency in the system with biomass recycle was slightly higher than the one achieved in the system without biomass recycle.	(Santo et al., 2013)
Composite made from crushed attapulgite and petroleum tank bottom sludge	Oily refinery wastewater treatment	Adsorbent prepared from locally available raw materials and a commercial one were used for oil refinery effluent treatment. Attapulgite was crushed, its mixture with petroleum tank bottom sludge was carbonized, and a date-palm based carbonaceous materials were activated, to obtain adsorbents. The composite exhibited greater oil removal than the commercial sample before the effluent stream reached the limit concentration. This was associated mainly with difference in pore sizes and distributions in the surface areas of the composite sample	(Sueyoshi et al., 2012)
Porous activated carbon synthesized from petroleum sludge	Acts as an adsorbent, catalysis supports, electrochemistry, carbon precursor in refinery wastewater treatment	Sludge waste consists of 47.10% carbon, and some functional groups such as hydroxyl, alkene, alkane, and others. No crystalline pattern was found, means it could be still in carbon chain form or other amorph compound. Thus, has the potential to be converted into activated carbon.	(Guritno, Sihombing & Krisnandi, 2016)
Oil sludge ash	Oil sludge pyrolysis	Oil sludge ash was utilised as a solid heat carrier. Its presence boosted oil output while lowering the ideal reaction temperature to 450°C from 500°C. The reduction in coke yield and carbon residue of the oil product was caused by the presence of pyrrhotite in the oil sludge ash. More so than quartz sand, it raises the oil product's light oil/heavy oil ratio. As a result, using oil sludge ash instead of quartz sand as a solid heat carrier in the pyrolysis process of oil sludge for oil production has some potential.	(Cheng et al., 2016)
Petroleum industry sludge	Filter material for crude oil-contaminated wastewater treatment	Polyhydroxyalkanoate plays a functional role in bacterial survival and stress tolerance in hazardous settings and low nutrition availability. Polyhydroxyalkanoate can be produced from oil-contaminated locations and used for the bioremediation of crude oil-polluted sites.	(Goudarztalejerdi et al., 2015)
Petroleum sludge	Wax recovery from petroleum sludge	Wax was extracted from petroleum oily sludge with the use of a microwave. The greatest wax recovery was around 79.57% at a reactant volume of 300 ml, a microwave power output of 400 W, a retention time of 7.6 minutes, and a toluene/MEK to sludge ratio of 56.56%.	(Kumar & Mohan, 2015)
Petroleum-contaminated sludge	Acrylic acid production	A novel versatile acrylonitrile-bioconverting strain isolated from a petroleum-contaminated sludge sample and identified as Rhodococcus ruber AKSH-84 was used for optimization of medium and biotransformation conditions for nitrilase activity to produce acrylic acid. This can be utilised to produce acrylic acid through green biosynthesis for application in biotechnological operations.	(Kamal et al., 2011)
Petroleum sludge	Microbial lipase (Cryptococcus *diffluens* D44) production	Organic solvent stable lipase from Cryptococcus diffluens D44, isolated from petroleum waste, was used to lower the cost of biodiesel manufacturing. The wide stability of D44 lipase in aqueous methanol makes C. diffluens D44 lipase appropriate for biodiesel manufacturing since oil-based fuel requires more aggressive reaction conditions and higher concentrations of organic solvents.	(Yilmaz & Sayar, 2015)
Petroleum sludge	Petroleum coke water slurry enhancement	To synthesize coke-oily-sludge slurry (COSS) and track changes in the rheological properties of coke-water slurry, oily sludge and high-sulfur petroleum coke were combined. The viscosity, yield stress, thixotropy, and stability of COSS are all improved by the addition of modified oily sludge (MOS). The COSS is changed from a dilatant fluid to a pseudoplastic fluid by the MOS.	(Xu et al., 2014)
Petroleum coke	Absorber in oily petroleum sludge microwave pyrolysis	The microwave pyrolysis reaction temperature can be raised by using petroleum coke as an absorber. The findings showed that by hastening the drying process, the injection of petroleum coke increased the heating rate.	(Mokhtar, Ethaib & Omar, 2018)
Acinetobacter radioresistens strain KA2 isolated from petroleum sludge	Petroleum hydrocarbons biodegradation	In a two-phase composting process, the study examined the efficacy of stimulating a natural bacterial strain isolated from a PS in the biodegradation of petroleum hydrocarbons. Both in the mineral-based medium and during the composting process, the native strain that was isolated was successfully able to break down petroleum hydrocarbons. The ability of the isolated bacteria to remove TPH was greatly improved by stimulation.	(Poorsoleiman et al., 2021)

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Table 4 (*continued*)

Waste material	Application	Remarks	Ref.
Mixture of the isolated strains KA1 and KA2 from petroleum sludge	TPH degradation	The scale up for bioremediation of petroleum hydrocarbon-rich sludge from a liquid medium to a composting process bioaugmented with two native bacteria capable of breaking down large amounts of crude oil was investigated. Combining two isolated strains was able to efficiently digest a variety of crude oil concentrations in liquid media. In the composting process, the strain mixture also decomposed extremely high quantities of TPH.	(Koolivand et al., 2019)
KA3 and KA4 isolated strains from petroleum sludge	Scaling-up of heavy oily sludge bioremediation	The effect of two-step inoculation of native strains and their synergistic effect were explored, when scaling up HOS bioremediation from mineral-based medium (MBM) to the two-phase composting system, The strains successfully eliminated TPH from MBM and composting processes. The findings demonstrated the consortium of the strains KA3 and KA4 had greater synergistic potential than either strain's separate cultures. Each strain's second-step inoculation alone significantly increased the TPH clearance rate.	(Parhamfar et al., 2020)
Indigenous oil refinery sludge isolated *Bacillus* strains	Bioremediation of petroleum refinery sludge (TPH degradation)	A combined biostimulation-bioaugmentation technique was used to establish an efficient method for the bioremediation of petroleum refinery sludge. The addition of nutrients to the sludge caused a change in the native microbial community that encouraged the abundance of populations in the sludge microbiome that are methanogenic, sulfate-reducing, hydrocarbon-degrading, syntrophic, and fermentative.	(Roy et al., 2018)
Rhodococcus ruber Z25 isolated from production fieldsludge of an oil field	TPH degradation and oil sludge recovery	The bioremediation of petroleum refinery sludge was successfully accomplished using a combined biostimulation-bioaugmentation strategy. The sludge's native microbial community was altered by the addition of nutrients, which promoted the proliferation of methanogenic, sulfate-reducing, hydrocarbon-degrading, syntrophic, and fermentative populations in the sludge microbiome.	(Zheng, Yu & Huang, 2012)
Ralstonia pickettii isolated from oil-sludge	Phenol containing produced water treatment	Phenol-degrading bacterial strains (R. *pickettii*), were isolated from oil sludge samples obtained from a nearby refinery. They were discovered to be comparable to a mixed culture that was offered commercially. In a bubble column bioreactor, the bacteria in immobilized form were also able to remove phenol. Each of the bacterial suspensions were used to examine the effect of substrate inhibition.	(Al-Zuhair & El-Naas, 2012)
Mycobacterium sp. *Lysinibacillus fusiformes, Bacillus* sp. And *Acinetobacter* sp., isolated from oil-sludge	Degradation of asphaltene fractions present in oil sludge	Sludge oil was used to identify the native bacteria that can break down asphaltene components from a sample. The four isolates (Bacillus sp., *Lysinibacillus fusiformes, Acinetobacter* sp., and *Mycobacterium* sp.) were tested for their capacity to break down asphaltene fractions. The ability was highest in *Bacillus* sp. and *Lysinibacillus fusiformes*, with biodegradation percentages of asphaltene fractions of 50% and 55%, respectively.	(Aditiawati & Kamarisima, 2015)
Bacterial strains isolated from petroleum sludge	*in vitro* degradation of fluoranthene	The in vitro degradability of fluoranthene by four bacterial strains (PSM6, PSM7, PSM10, and PSM11) obtained from petroleum sludge was investigated. Bacterial strain growth always correlated with fluoranthene degradation ability. It was demonstrated that catechol 2,3-dioxygenase had a substantial part in the breakdown of fluoranthene by the fact that it was 38 times more active than catechol 1,2-dioxygenase.	(Kumar et al., 2011)
Pseudomonas aeruginosa IBB$_{ML1}$, isolated from petroleum sludge	Saturated and aromatic petroleum hydrocarbons degradation	Using petroleum sludge, *Pseudomonas aeruginosa* IBB$_{ML1}$ was able to tolerate and break down both saturated and aromatic hydrocarbons. The ability of *Pseudomonas aeruginosa* IBB$_{ML1}$ to tolerate hydrocarbons may result from a variety of mechanisms, and both short-term and long-term mechanisms may work in concert to promote the cells' full adaptability to saturated and aromatic hydrocarbons.	(Lazaroaie, 2009)
Stenotrophomonas sp. IRB19 (S. pavanii IRB19) bacteria isolated from petroleum sludge	TPH biodegradation	The biodegradation capability of TPH was examined utilising a native bacterium isolated from petroleum refinery sludge (PRS). S. pavanii IRB19, the isolated bacterial strain, was successfully able to break down 65±2.4% of the TPH of PRS in just 28 days of culture. The tolerance research proved that the IRB19 strain could successfully use various hydrocarbons.	(Behera et al., 2020)
Rhamnolipid generated by (P. *aeruginosa*) isolated from petroleum sludge	Crude petroleum oil removal from contaminated sites	Pseudomonas aeruginosa-produced rhamnolipid biosurfactant was employed to extract oil from oil tank bottom sludge. Given its low moisture content, the recovered oil may reenter the refining process. Oil recovery was made more challenging by the oil sludge's porous solid particle structure, which could absorb a lot of oil. It has been demonstrated that biosurfactant-assisted oil recovery is a highly successful technique with acceptable performance.	(Liu et al., 2018)
Biosurfactant-producing microbes isolated from oily sludge	Enhanced oil recovery from petroleum sludge	A total of sixteen isolates from the oily sludge and petroleum-contaminated soil were able to lower the growing medium's surface tension from 71 to less than 30 m Nm^{-1}. The recovery rates of oil from oily sludge were calculated using these bacteria to treat the sludge. Different isolates had oil recovery rates that ranged from 39% to 88%. Of the isolates, BZ-6 proved most effective at separating oil from oily sludge. B. amyloliquefaciens was identified as isolate BZ-6. It generates a biosurfactant that contains four fengycin A homologues. This bacterial isolate may be used to remove oil from huge oil fields' contaminated oily wastes.	(Liu et al., 2012)

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Table 4 (*continued*)

Waste material	Application	Remarks	Ref.
Biosurfactant producing isolate *Microbacterium maritypicum* ABR5 isolated from a petroleum sludge	Enhanced oil recovery from petroleum sludge	Oil refinery petroleum yielded the high biosurfactant-producing strain *M. maritypicum* ABR5. A glycolipoprotein served as the biosurfactant. After 5 days of incubation, the supernatant derived from *M. maritypicum* ABR5 was able to extract up to 70% of oil from oily sludge.	(Akbari et al., 2020)
Bacillus subtilis and *Pseudomonas aeruginosa* isolated from oily sludge oil	TPH degradation and oil recovery from petroleum sludge	B. *subtilis* PT2 and P. *aeruginosa* SP4 were isolated as two different types of biosurfactant-producing bacteria from sludge oil and petroleum-contaminated soil for oil recovery applications. The strain SP4 was discovered to be able to grow in the culture medium better than the strain PT2, resulting in a reduction in the amount of time needed to cultivate the biosurfactant and an increase in the yield of the extracted biosurfactant. It appears that the two biosurfactants generated by the bacteria PT2 and SP4 have excellent potential for use in applications for microbial enhanced oil recovery (MEOR).	(Nejad et al., 2020)

The treatment of refinery wastewater with a petroleum refinery-activated sludge biological reactor resulted in high COD (94.5 %), TOC (86 %), and TSS (98.5 %) removal efficiency. According to findings, the organic matter removal efficiency in the system with biomass recycling was also marginally greater than in the system without biomass recycling (Santo et al., 2013). In a similar study, adsorbents were made using locally sourced raw materials. The first is crushed natural attapulgite, and the second is crushed attapulgite mixed with petroleum tank bottom sludge carbonized at 650°C. An oily water solution containing around 500 mgoil/L was run through columns containing both adsorbents until the column effluent concentration surpassed a target limit of 10 mgoil/L in an experiment. At this level, adsorption was computed at 155 and 405 mg-oil/g-adsorbent, respectively. This was less than a commercial activated carbon sample's performance. The two adsorbents had varied properties and adsorptive capabilities. The porous structures evolved in the activated carbonaceous materials, forming flawed graphitic sheet ensembles that function as supplementary adsorption sites in the sample (Sueyoshi et al., 2012). Using mesoporous MCM-41 as a silica template, porous activated carbon was synthesized from petroleum sludge. This sludge can be a useful carbon precursor since it has a high carbon content (47.10 %) and hydroxyl, alkene, and alkane functional groups, with no crystalline pattern. The resulting activated carbon's pore size and volume distribution were chosen to match the hexagonal arrays found in mesoporous MCM-41 (Guritno, Sihombing & Krisnandi, 2016). A pyrolysis experiment was carried out on oily sludge with and without oil sludge ash and quartz sand as solid heat carriers. According to the study, the incorporation of oil sludge ash produced isomerization of the oil product, increased oil yield, and the light oil/heavy oil ratio of the oil production to a larger extent than quartz sand. It reduced the degree of ring system condensation, aromatic carbon ratio, number of heteroatoms in the oil product molecule, ideal reaction temperature from 500 to 450°C, and the total ring number of the oil product. Attributed to the prevalence of pyrrhotite in the oil sludge ash, it also reduced the oil product carbon residue and coke yield addition (Cheng et al., 2016). Oily sludge and oil-contaminated sites can be key sources for polyhydroxyalkanoate producers, that could be employed for crude-oil-polluted sites bioremediation. According to a report from one study, polyhydroxyalkanoate was generated by *Pseudomonas* strains isolated from oily sludge, and significant biopolymers were found in the monomer composites. In hazardous conditions with limited nutrient supply, polyhydroxyalkanoate plays a role in bacterial survival and stress tolerance (Goudarztalejerdi et al., 2015).

Traditional filter materials such as polypropylene, ceramsite, and activated carbon were compared to a new filter material, tagged M-1. It was prepared from a petroleum industry sludge by activating the raw material with carbon dioxide at a high temperature. The filter media was utilized in a bed coalescence process and could replace polypropylene, ceramsite, and activated carbon since it had a greater efficiency for oil removal from oil-contaminated wastewater than polypropylene and ceramsite and was significantly less expensive than activated carbon (Saeed et al., 2021). Wax recovery from petroleum sludge employing a toluene/MEK mixture and following de-crystallization will reduce sludge volume to be disposed of while also acting as an effective approach for wax synthesis from sludge created by oil companies. A maximum wax recovery of about 79.57% was attained by (Kumar & Mohan, 2015). Thus, this process will help in reducing pollution and hydrocarbon resource conservation.

6.1. Petroleum coke improvement by petroleum sludge

Petroleum coke (PC) sometimes referred to as petroleum coke slurry (PCS) or petroleum coke water slurry (PCWS) is a liquid fuel that can be used as a material for gasification and a replacement for oil (Ma, Duan & Liu, 2013). The poor storage stability of PCS, on the other hand, severely limits its applicability. Aside from that, PC/PCS/PCWS is a very complex dilatant fluid (Liu, Duan & Ma, 2015). To cater to this weakness and find an alternative to efficiently disposed and/or economically utilize the petroleum industry waste, several authors have tried to combine petroleum coke and petroleum sludge to utilize their complementary advantages and form petroleum coke–sludge slurry (PCSS). PCSS samples were prepared by mixing PC with PS. Good stability of PCSS was attained despite the maximum mass concentration of PCSS being reduced to approximately 8 wt% compared to PCWS after almost 10 wt% of sludge was added. The greatest mass concentration of PCWS without a stabilizer was 71.3%. When stabiliser at 0.1% was added, this was reduced to 63.5%. The maximum mass concentration of PCSS was reduced from 64% to 62% when 8-12% sludge was injected (Liu, Duan & Li, 2013). The co-slurryability of oily sludge and modified oily sludge (MOS) was investigated. The experimental results showed that with a 5 wt% adding ratio of $Fe_2(SO_4)_3$ pre-treated oily sludge, PCSS with a maximum solid loading of 68.7 wt was obtained. The stability, thixotropic loop area, viscosity, and yield stress of PCSS steadily rise as the fraction of MOS increases. Because MOS acted as a stabilizing agent, the storage duration of PCSS may be extended to > 15 days (Xu et al., 2014).

6.1.1. Properties of PC/PCS/PCWS, PS, and PCSS

The hydrophobic surface of petroleum coke particles is quite strong, but the hydrophilic surface of sludge particles is very strong. The sludge particles associate with the petroleum coke particles via physicochemical reactions after co-mixing PC/PCS/PCWS and PCSS to build a firm spatial structure. Petroleum coke particles are usually caught by the stable network structures built by organic matter contained in the flocculent sludge particles Oxides, mineral salts, and organic matter make up most sludge particles, whereas organic carbon makes up most petroleum coke particles. As a result, the size, pore structure, and surface area of PCSS manage to increase after alteration. Sludge has the potential to replace the carboxyl methyl cellulose stabilizer currently used in the production of PCWS. When sludge addition is in the range of 10-15 wt.%, the appropriate mass concentration for industrial use of PCSS was found to be 62–64 wt.%. (Liu, Duan & Ma, 2014).

6.1.2. Advantages and disadvantages of PC/PCS/PCWS and PCSS co-mixing

PCSS can produce high-quality slurry fuels with low viscosity and excellent stability. Gasification reactivity and combustion performance of PCWS can be enhanced by co-mixing with petroleum sludge. It aids in disposing of large a amount of sludge (Liu, Duan & Ma, 2015). The increased amount of sludge enhances the static stability of PCSS/PCWS. At < 6 wt.% PS addition, PCSS has similar rheological properties to PCWS. However, with the injection of too much sludge, the fluid goes from shear-thickening to shear-thinning (≥ 6 wt.%). It has pseudoplastic properties as well as good fluidity. PCSS wall slip velocity rises as the wall shear rate and the applied petrochemical sludge increase. It is greater than that of PCWS (Wang et al., 2012).

The significant solid-liquid separation caused by petroleum coke's considerable surface hydrophobicity is one of the drawbacks of PC/PCS/PCWS and PCSS co-mixing. Modifying raw sludge at a high cost before use because it makes it more slurryable. Free water would inevitably be trapped in the slurry by the complex floc structure of the sludge, which would further increase the blocking and frictional forces between the solid particles (Liu, Duan & Li, 2013). Therefore, adding sludge from refinery wastewater may make the slurry less slurryable and fluid. Most of the sludge was made up of organic materials that are abundant in hydrophilic hydroxy, carboxy, or amide groups. These organic materials connected to one another and established a solid network structure, which impacted the slurryability and stability (Xu et al., 2014)

6.2. Potential applications of petroleum sludge isolated environmental microbes in the oil refining industry

There is a huge demand for crude acrylic acid. Therefore, a new versatile acrylonitrile-bioconverting strain identified as *Rhodococcus ruber* AKSH-84 was isolated from a petroleum-contaminated sludge sample using whole cells. To manufacture acrylic acid, the isolated strain was employed to optimize the medium and biotransformation conditions for nitrilase activity. The nitrilase from *Rhodococcus ruber* strain AKSH-84 exhibited wide substrate specificity and was able to hydrolyze different nitriles at 100 Mm concentration. Higher substrate affinity was observed towards aliphatic mononitriles followed by succinonitrile and fumaronitrile whereas lower affinity was observed towards mandelonitrile and 2-cyanopyridine. At optimum conditions, the yield of bioconversion using whole resting cells was recorded to be 63% (acrylic acid concentration was 126Mm) after 120min. This could be due to the slower mass transfer of the substrates and products into and out of the cells. The yield of bioconversion using purified nitrilase (50 U/mg) was observed to be 92% (acrylic acid concentration was 183 Mm) after 30 min (Kamal et al., 2011).

Microbial (yeast) lipases are widely utilized in biodiesel production when reaction conditions are mild, and the organic solvent content is low. As a result, developing stable enzymes under severe conditions is critical for lowering biodiesel manufacturing costs. The features of a *Cryptococcus diffluens* D44 lipase isolated from petroleum sludge were studied. D44 lipase activity was found to be boosted in the presence of Ca^{2+}, $K^{+,}$ and Mg^{2+}, throughout at an optimal Ph of 9, and requires metal ions as co-factors. The wide stability of D44 lipase in aqueous methanol up to 20% renders C. *diffluens* D44 lipase suitable for biodiesel synthesis. Na^{+} and Ni^{+} did not affect enzyme activity (Yilmaz & Sayar, 2015).

In a two-phase composting strategy, researchers tested the efficiency of an *Acinetobacter radioresistance* strain KA2 isolated from petroleum sludge for petroleum hydrocarbon biodegradation. In just 120 days, 72–88% of TPH was removed. In both the mineral-based media and the composting process, the isolated strain was able to break down petroleum compounds (Poorsoleiman et al., 2021). The compatibility and efficacy of a mixed culture of two indigenous bacterial strains in the bioremediation of petroleum hydrocarbon-rich sludge in Bushnell-Haas media and the composting process were explored in a similar study by the same authors. In a liquid media, the isolated strains (*Sphingomonas olei* strain KA1 and *Acinetobacter radioresistance* strain KA2) were able to metabolize a wide range of crude oil concentrations. In the composting process, the strainstrainedre decomposed 30–50 g/kg TPH (Koolivand et al., 2019). The impact of two-step inoculation of two native strains "*Enterobacter hormaechei* strain (KA3) and *Staphylococcus equorum* strain (KA4)" and their synergistic effect in the scaling-up of heavy oily sludge bioremediation from mineral-based medium to the two-phase composting system were investigated. The results indicated that the consortium of the two strains degraded 16-61% of crude oil in the mineral-based medium while in the composting reactors, 20 g/kg TPH were removed at 63.95%, 61%, and 89.35% for the strains KA3, KA4, and their consortium. This revealed the synergistic potential of the consortium as compared to their cultures (Parhamfar et al., 2020).

The biostimulation of indigenous bacteria by supplementing manure was used to undertake in situ bioremediation of oily sludge-polluted soil. TPH concentration in the treated plots was lowered by 58.2% after 360 days of bioremediation. The soil's physicochemical qualities were greatly improved because of this. Adding manure significantly increased nutrient elements, activity, and biodiversity of soil microbial communities in the treated area, polycyclic aromatic hydrocarbon (PAH), and TPH degraders in the contaminated soil. Bioremediation lowered the soil's toxicity as was proven significant in the EC50 value obtained (Birniwa et al., 2021). According to one study, nutrient-induced native microorganism population dynamics and metabolic interaction inside oil refinery sludge might be a motivating factor behind rapid bioremediation. This is because the addition of nutrients to the sludge caused a shift in the native microbial community, favouring the predominance of sulfate-reducing, fermentative, hydrocarbon-degrading, syntrophic, and methanogenic populations in the sludge microbiome. TPH degradation increased by 46–55% after nutrients were added to the sludge. Bioaugmentation and the use of native *Bacil*lus strains, in combination with nutrients, led to 57–75%. TPH reduction (Roy et al., 2018). Bioaugmentation of aerobic cultures with refinery sludge was more efficient in TPH degradation (~65% degradation) than the anaerobically enriched consortium (~36% TPH degradation) in a 30-day microcosm-based bioremediation trial, while a combination of bioaugmentation and nitrate amendment with sludge led to an increase in hydrocarbon absorption (86% TPH degradation) (Sarkar et al., 2020).

The bacterial strain *Gordonia alkanivorans* CC-JG39 was isolated from oil-contaminated sludge. The extract was able to develop on a diesel-containing medium and withstand a variety of chemical additives commonly found in petroleum products. Extracellular surface-active material was formed by the CC-JG39 strain, resulting in reduced surface tension of about 33 Mn/m. It was also capable of floating towards the oil/water contact. These characteristics could help improve the mass transfer efficiency between the oil substrate and the bacterial cells (Young et al., 2005). Oil-sludge samples were used to extract phenol-degrading bacterial strains. *Ralstonia pickettii* was discovered to be able to use phenol as its only carbon source. Using various initial phenol concentrations, the growth kinetics of mixed and isolated *R. pickettii* suspensions were examined. The results were compared to those of a commercially mixed bacterial suspension that was either habituated to a concentration of 100 g/m3 phenol, derived from PVA particles that were exposed to actual petroleum refinery wastewater containing phenol, or an isolated strain that was identified as *Pseudomonas putida* and developed on a culture media (Al-Zuhair & El-Naas, 2012). For the in vitro breakdown of fluoranthene, four bacterial strains (PSM6, PSM7, PSM10, and uncultured Acinetobacter sp. [PSM11]) obtained from petroleum sludge were utilized. PSM11 was reported to be the most effective degrader of 4-ring PAH fluoranthene after 168 hours of incubation (61%). This was followed by 48%, 42%, and 41% respectively. The study confirmed the tetrameric nature of catechol 2,3-dioxygenase isolated from uncultured Acinetobacter sp. PSM1. As evidenced by the quick increase in its activity, it also had a substantial influence (Kumar et al., 2011). To break down asphalt tic fraction, *Mycobacterium sp.*, *Acinetobacter sp.*, *Lysinibacillus fusiformes, and Bacillus sp.,* were isolated from a sludge oil sample. It was revealed that, at rapid growth rates of 4.21×10^7 CFU/Ml.days and 7.17×10^7 CFU/Ml.days, 55% and 50% asphaltene components were degraded by *Lysinibacillus fusiforme* and *Bacillus sp.* Respectively (Aditiawati & Kamarisima, 2015).

The effects of exploiting the synthetic combination of indigenous and exogenous bacteria on the biodegradation of refineries' oily sludge contaminants for 60 days were investigated. *Citrobacter amalonaticus, Staphylococcus spp.*, and *Lysinibacillus fusiformis* were found to have the ability to degrade petroleum compounds. Due to biosurfactants' significant production, the combined consortium was able to further reduce the surface tension of the broth. In addition, it has the best biodegradation ability in 1% (w/v) oily sludge. Exogenous bacteria were reported to have boosted oily-sludge degradation by 11.4% in liquid media and 17.6% in soil when mixed with indigenous bacteria. As a result, it was determined that combining exogenous and indigenous bacteria resulted in a considerable increase in oily sludge biodegradation (Gholami-Shiri et al., 2017). Isolated from petroleum sludge, *Pseudomonas aeruginosa* IBB_{ML1} was able to withstand and break down both saturated and aromatic hydrocarbons. When *Pseudomonas aeruginosa* IBB_{ML1} cells were cultured in the presence of either 5% or 10% (v/v) saturated or aromatic hydrocarbons, the *lacZ* gene was significantly induced, as compared to cells incubated without hydrocarbons. Rhodamine 6G accumulation was higher in *Pseudomonas aeruginosa* IBB_{ML1} cells cultivated in the presence of 5% and 10% (v/v) saturated hydrocarbons than it was in cells grown in the presence of 5% and 10% (v/v) aromatic hydrocarbons (Lazaroaie, 2009).

The biodegradation potential of TPH using *Stenotrophomonas* sp. IRB19 (S. pavanii IRB19) bacteria isolated from petroleum sludge were investigated. The research findings demonstrate that after 28 days of incubation, the isolated bacterial strain was able to degrade 65% TPH in the petroleum sludge. Degradation kinetics revealed a significant decrease in the half-life period of PHCs which signifies performance enhancement of *S. pavanii* IRB19 in aerobic conditions (Behera et al., 2020). During the TPH biodegradation process, the self-cycle operation was achieved by producing a biosurfactant from *Rhodococcus* ruber Z25 and employing it for oil sludge recovery. *Rhodococcus* ruber Z25 cultivation produced 1.27 g/L of biosurfactant, thereby achieving 93.88% oil recovery efficiency. The initial TPH was 507 g/kg, but only 31 g/kg of residual TPH remained in the oil sludge after the crude/biosurfactant-suspension treatment, thus, achieving 93.88% oil-recovery efficiency. The initial residual 507 kg/g TPH was drastically degraded to 1.4 g/kg (Zheng, Yu & Huang, 2012).

6.3. Biosurfactants producing bacteria isolated from PIS for TPH polluted environment

Despite being ecologically friendly, using microorganisms for pollutant biodegradation is a time-consuming procedure. As a result, most research uses expensive biosurfactants for bioremediation. Biosurfactants are surface-active amphiphilic compounds produced by living cells that offer a viable alternative to chemically produced surfactants due to their low toxicity, great biodegradability, and environmental safety (Cheng et al., 2017). The activity of a biosurfactant is primarily determined by its concentration. Glycolipids, lipoproteins, lipopeptides, fatty acids, and phospholipids are examples of biosurfactants. Biosurfactants can lower surface tension by aggregating and forming micelles, resulting in increased oil solubility and mobility in water. Biosurfactants are used in a wide number of fields, including environmental biotechnology and petroleum microbiology. In the petroleum sector, their use to reclaim oil from harmful oily wastes is regarded as an environmentally effective approach. Biosurfactants are produced by a variety of microorganisms. Emulsan, surfactin, rhamnolipids, and sophorolipids were generated by *Bacillus subtilis, Starmerella bombicola, Pseudomonas aeruginosa,* and *Acinetobacter calcoaceticus*, respectively. *Arthobacter spp.*, *Brevibacterium spp., Streptomyces spp., Achromobacter spp.,* and *Rhodococcus spp.* are some of the other species that produce biosurfactants (Bezza, Beukes & Chirwa, 2015).

One of the most efficient surfactants for cleaning up contaminated sites with crude petroleum oil is Rhamnolipids. The rhamnolipid produced by *Pseudomonas aeruginosa* (*P. aeruginosa*) was employed as a biosurfactant for oil sludge treatment to extract oil from oil tank bottom sludge using mineral salt media. When 5.4 g/L rhamnolipid biosurfactant concentration was added to the fermentation broth, the volume fraction of 2% (v/v) was the optimal value. The fermentation broth of *P. aeruginosa* can be utilized to recover oil from oil sludge and has significant industrial applications, according to the findings (Liu et al., 2018). In a comparable investigation employing *Rhamnolipid generated* by (*P. aeruginosa*) isolated from petroleum sludge, the surface tension of water was lowered to 31.1 Mn/m by the biosurfactant with a critical micelle concentration of 45 mg/L. It has greater emulsifying properties against a wide range of hydrocarbons, with a peak emulsion index of 82% for diesel. At 8 μg/ml minimal inhibitory concentration, the isolated biosurfactant exhibited great antibacterial activity against Staphylococcus aureus (Bharali & Konwar, 2011). Oily sludge and petroleum-contaminated soil were used to isolate biosurfactant-producing bacteria. After 72 hours of growth, the bacterial isolates formed biosurfactants, that lowered the surface tension of the growth medium from 71 to 30 Mn/m. After 24 hours of treatment with the isolates' fermentation broth, the oil recovery efficiency ranged from 39% to 88%. The *Bacillus amyloliquefaciens* (BZ-6) bacterial isolate was determined to be the most effective as the sediment, oil, and water phases were set apart during the treatment process (Liu et al., 2012). *Microbacterium maritypicum* ABR5, the greatest biosurfactant-producing isolate, was isolated from an oil refinery's petroleum reservoir. *Glycolipoprotein* was the resultant biosurfactant. The strain reduced surface tension from 72 to 34.6 Mn/m. After 5 days of incubation, mixing *M. maritypicum* ABR5 culture medium with oily sludge boosted the oil recovery rate by up to 70% (Akbari et al., 2020).

A biosurfactant-producing bacteria (halo-tolerant strain *Pseudomonas balearica* strain Z8) was used for oily sludge treatment. The produced biosurfactant reduced the solution surface tension to 41 Mn/m. The highest TPH removal of 35% was obtained after 80 days for nitrogen source of NH4Cl, sludge/water ratio of 1:7, and temperature of 40°C (Nejad et al., 2020). According to a study, the optimal cultivation times for biosurfactant synthesis by *Bacillus subtilis PT2* and *Pseudomonas aeruginosa SP4* were found to be 51 and 48 hours, respectively. The biosurfactants decreased the concentration of pure water to 26.4 and 28.3 Mn/m with critical micelle concentrations of about 25 and 120 mg/L, respectively, after microbial cultivations at 37°C. The biosurfactant produced by *B. subtilis PT2* had a greater oil recovery ability than that produced by *P. aeruginosa SP4* based on the findings of the oil recovery experiments. Furthermore, both biosurfactants were found to be more successful at recovering oil than three synthetic surfactants (Pornsunthorntawee et al., 2008).

Conclusion

Globally, the PIS generation rate continued to rise due to the increased need for energy. Hazardous elements have been discovered in the sludge, which could have serious environmental consequences. Thus, the release of PIS into the environment must therefore be controlled. Various treatment and disposal strategies aimed at removing petroleum compounds, and reducing toxicity, and volume of sludge have been investigated. However, because of the sludge's tenacious character, only a few technologies can meet strict environmental laws while using a sizable amount of water, electricity, and chemicals. This review began with highlighting the sources of different sludge types from petroleum refineries. The information obtained was supported by the discussing the characteristics and environmental effects of the PIS. Standard regulations for PIS management and disposal covering different continents across the globe were left out in this review. The review proved that PIS treatment methods that are both toxic-free, environmentally friendly, and cost-effective are currently unavailable. The major advances in the aspect of waste to resource potential of PIS for reusability in sustainable construction, wastewater treatment applications, gas generation, and several other applications such as effective microorganism (EM) biofertilizer production, levan production, manufacture rubber tires, metal catalysts synthesis, carbon–clay composites for use in sensors and electronic devices were also highlighted. Based on the PIS applications, it can be realized that several researchers have put effort towards its sustainable eradication from the environment along with a reduction in raw materials utilization be reserved for a lengthier duration. This could be addressed as sustainable disposal means that decreases air pollution and produce high-quality products with economic impact. Furthermore, discussions on the sustainability and circular economy potential of PIS were not left out in this review. The review also shows the potential of the "wastes-treat-wastes" processes to achieve self-cycle operation in the petroleum refining industry. This includes the application of PIS for petroleum coke improvement. Meanwhile, the potential applications of PIS isolated environmental microbes and biosurfactants producing bacteria isolated from PIS within the same industry were discussed.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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