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Sustainability Assessment of Traditional and Emerging Treatment Techniques for Refinery Oily Sludges

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Abstract
This study presents the results of a survey of EU refineries waste types production, their sources and management options, with focus on oily sludges and a sustainability assessment of selected traditional versus emerging treatment options for oily sludges wastes. It provides a statistical analysis of waste production by Concawe member company refineries in the years 2019, 2020 and 2021, based on survey data returned from 68 refineries (70.1% response rate) situated in the EU-27 countries + UK, Norway and Switzerland. It includes a breakdown of oily sludge waste tonnage according to its origin and how it was managed. A literature review of emerging and traditional oily sludges treatment technologies provided a selected list of treatment options for detailed assessment of their sustainability. The assessment consisted of a semi-quantitative multi-criteria analysis including criteria assigned to the three main pillars of sustainability: environment, social and economics. A fourth pillar, waste circularity was added to assess technologies based on their preservation of resources and minimisation of waste generation. Each criterion was given a score with a higher score indicating technologies more favourable for each of the selected criteria. The scores were weighted allowing comparison of the assessed technologies for each of the four pillars. The assessment identified overall better sustainability performance for emerging technologies pyrolysis, solvent extraction and biopiles than for more traditional technologies such as incineration in municipal solid waste incinerators, at cement works and disposal to landfill.

Keywords Refineries · Oily sludges · Sustainability

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Introduction

A previous review of European refineries waste data [5] showed that Waste Water Treatment (WWT) and hydrocarbon sludges were the most significant part of refinery waste sludges in terms of tonnages. In recent years, the European Commission (EC) have been adopting a 'Circular Economy package' [12]. The circular economy refers to an economic model whose objective is to produce goods and services in a sustainable manner, limiting the waste of resources and the production of waste. Concawe and its members want to proactively contribute to the circular economy as well as to prepare for upcoming EU legislative activities such as 'zero pollution'.

This study presents the findings from a survey undertaken by Concawe[1] to determine the quantity of waste managed by Concawe member company refineries in the years 2019, 2020 and 2021. The survey requested Concawe company members to report waste production, waste types, waste sources and management options reported with a special focus on refinery oily sludges. Traditional oily sludge treatment/disposal technologies such as incineration and landfilling involve high treatment costs and sit low in the waste hierarchy. They are also becoming less desirable as environmental regulations become more stringent. In recent years, new oily sludge technologies have been developed that can recover the oil contained in the sludge, reduce the amount of waste needing additional treatment or disposal, and potentially having lower environmental and social impacts. To gain further insights into the overall sustainability of traditional vs. emerging techniques, a sustainability assessment was undertaking considering the three pillars of sustainability: environment, social and economics [4]. A fourth pillar, waste circularity was added to assess technologies based on their preservation of resources and minimisation of waste generation.

Sludges are defined as semi-liquid residues from industrial processes and wastewater treatment. Different types of sludges are generated in refinery operations including crude and product tanks bottoms sludges, sludges from API separation units, flocculation and flotation units [3] Oily sludges have highly diverse compositions and represent complex matrices consisting of petroleum products, water, and a mineral portion (sand, clay, silt). The ratio of these components fluctuates over a very broad range. The organic materials on the average comprise from 10 to 56 wt%; water, 30 to 85 wt%; and solids 1–50 wt% [11]. A sample of oily sludge from an API separator at a Canadian refinery had a composition of 50% water, 30% oil and 20% solids, and a density of 0.97 kg/l [17], while oily sludge from a petroleum refinery in China had a composition of 49.5 wt% oil. 33.4 wt% water and 17.1 wt% solids [22]. Li et al. 2020 also reported oily sludge compositions for a petrochemical installation (70.8 wt% oil, 24.3 wt% water and 4.9 wt% solids) and from a second refinery in China (30.1 wt% oil, 24.9 wt% water and 44.9 wt% solids).

Tank bottom sludges result from the settling of crude oil and refined products in storage tanks. Tank bottoms in crude oil tanks typically contain 60% oil, 25% water and 15% solids [14]. Heavier hydrocarbons settle along with water and solid particles. Solids might

[1] Concawe was established as CONCAWE (CONservation of Clean Air and Water in Europe) in 1963 by a small group of leading oil companies to carry out research on environmental issues relevant to the petroleum refining industry. Its membership has broadened and currently includes 40 fuel manufacturing companies operating in EU-27, Norway, Switzerland and United Kingdom, representing approximately 95% of petroleum refining capacity in those countries. Concawe is the Scientific Division of the European Fuel Manufacturers Association.

contain metals that decant from crude oil during storage, such as zinc, lead, copper, nickel and chromium.

The oily phase of petroleum tank bottom sludges typically contains 40 to 60% saturated hydrocarbons, 25 to 40% aromatic hydrocarbons, 10 to 15% resins[2] and 10 to 15% asphaltenes [14].

The survey undertaken identified current pre-treatment techniques and final management options for refinery oily sludges such as incineration with and without energy recovery, destruction in cement kilns and landfill. These traditional oily sludge waste management techniques are associated with adverse environmental and human health impacts and high costs. Incineration requires the use of auxiliary fossil fuels to maintain the desired combustion temperatures generating undesirable fugitive gaseous emissions and hazardous ash residues [7]. Landfilling can release leachate and air emissions to the environment [17].

Oily sludges can be a potential energy source considering its production quantity and calorific value. Energy recovery has received particular attention in recent years given that it can recover valuable resources as well as mitigate potential impacts by reducing disposal volumes of these type of waste [18]. In recent years, several technologies have emerged that can be applied to refinery oily sludges. They present different treatment mechanisms, resource recovery performance, energy consumption and environmental impacts [15]. Their success depends on the substantial reduction of oily sludge volumes, the recovery of energy from the sludge and the final treatment of the unrecoverable residue.

Oily sludge treatment technologies can be divided into those that focus on the recovery of the oil contained in the oily sludges and those considered traditional disposal/treatment methods currently used by the industry (Fig. 1). The degree of application of the oil recovery methods to refineries varies, with some technologies only tested at laboratory or pilot scale, while others are being more routinely used, if not in refineries, in similar applications.

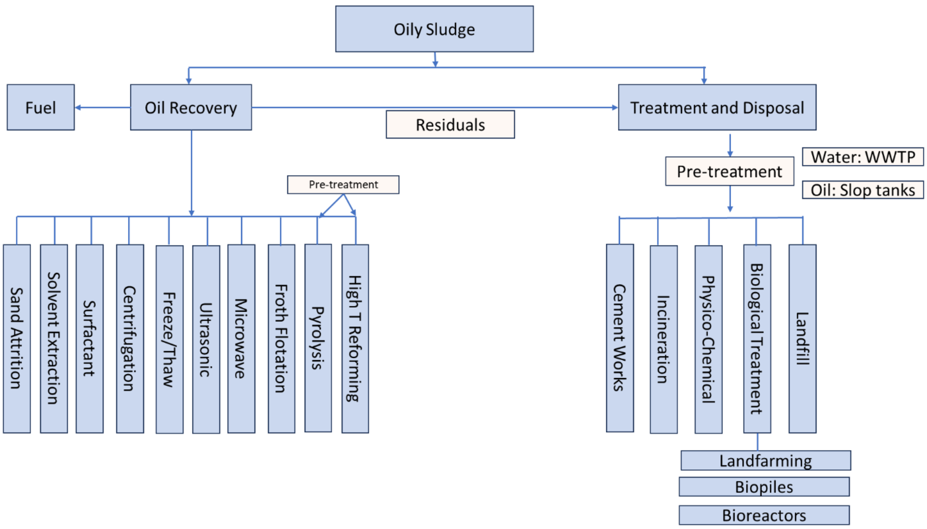


Fig. 1 Oil sludge treatment and disposal technologies (adapted from Murungi & Sulaimon, 2022 [24])

[2] Resins are a highly viscous mixture of organic compounds, typically aliphatic and phenolic compounds when derived from petroleum sludges.

Materials and Methods

Concawe Waste Survey

In 2022, Concawe undertook a waste survey of European refineries to determine the quantity of waste managed by Concawe Member Company refineries in the years 2019, 2020 and 2021 [6]. Survey data was returned from 68 Concawe members' refineries (70.1% response rate) situated in the EU-27 countries + UK, Norway and Switzerland. Given the identification of oily sludges in a previous survey [5] as an important waste in refinery operations, the 2019–2021 survey provided specific analysis of these wastes types, their sources and management options reported under different European Waste Catalogue (EWC) codes[3] and Waste Hazard Codes[4].

The waste survey was constructed in the form of an Excel spreadsheet that was sent to the participating refineries for completion. The excel survey form contained questions on types and quantities of wastes generated in the years 2019, 2020 and 2021, including their EWC codes. If a sludge waste type was selected, the form allowed the user to unlock additional cells with pull down options to collect additional pertinent detail information such as the pre-treatment technologies used, barriers to the treatment of sludges, location of sludges treatment (onsite/offsite), and whether treatment was carried out in country or abroad. Based on the selection of the EWC code the spreadsheet identified if the waste is hazardous or non-hazardous.

The survey results were compiled into a single unified data format to facilitate the analysis and creation of tables and figures. Historic refineries feedstock throughput was requested for the three survey years to normalize the waste quantities reported. Quality assurance and quality control (QA/QC) of the data was carried out by construction of Q-Q plots to identify and investigate outliers for total throughput and each EWC code reported. Waste data was presented both in terms of total waste tonnage (reflecting the environmental burden) and also tonnes per kilotonne of refinery feedstock throughput (a measure of efficiency) and included an analysis of differences in waste production and management between different European Country Grouping (see Annex 1).

The EU Waste Framework Directive [10] sets out a waste hierarchy, or priority order of what constitutes the best overall environmental option in waste legislation and policy (Fig. 2).

To facilitate the analysis, sludge waste management options reported in the survey were grouped to reflect the EU Waste Hierarchy as shown in Table 1 (based on [13]).

Selection of Emerging Technologies

The identification of emerging technologies for the treatment of oily sludges involved a comprehensive literature search. It included a wide variety of sources including scientific journals [8, 18, 24] for general overview of emerging techniques for the management of refinery oily sludges, industry research reports, case studies, trade journals, industry initiatives, best available technology documents, waste management contractors and waste treat-

[3] Annex of European Commission Decision 2000/532/EC, as amended by Decisions 2001/118/EC; 2001/119/EC and 2001/573/EC and EC 2018, EU Notice on technical guidance on the classification of waste.

[4] Annex III of EU Directive 2008/98/EC.

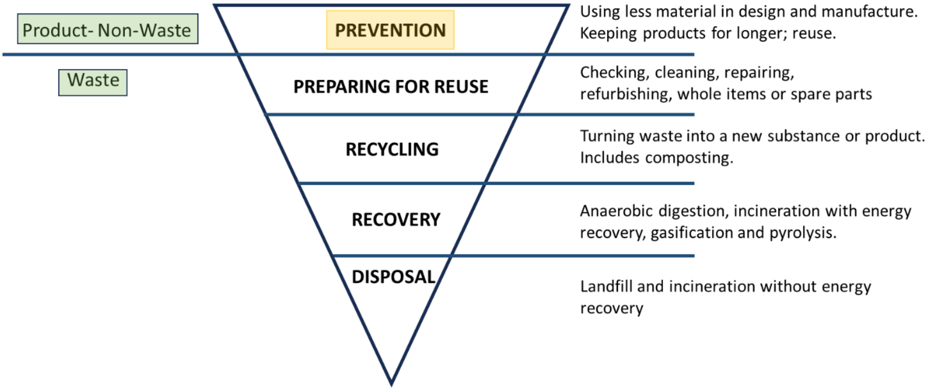


Fig. 2 EU Waste Hierarchy (adapted from DEFRA 2011 [9])

ment equipment suppliers. The literature review was complemented with interviews with technical experts from Concawe Member Companies to identify further new technologies being sought or tested by refineries and to seek clarification on current technologies used. The findings of the desk top literature review and interviews were used to create a list of the technologies included in Fig. 1. A brief description of the technologies evaluated are included in Tables 2 and 3.

To facilitate the selection of technologies that would be carried on to the sustainability assessment, advantages and disadvantages of each technology were identified and used in conjunction with their applicability to a refinery context and their stage of development (i.e., laboratory, field scale, fully implemented). For several novel oil recovery technologies information was not sufficient to indicate their likely use at the refinery scale at present and were therefore not selected. The technologies selected include: pyrolysis, solvent extraction, cement works, biological treatment (biopiles), landfilling and incineration with energy recovery (Fig. 3). Pyrolysis and solvent extraction are technologies tested at field scale, used by waste management contractors but not routinely used by EU refineries. For example, some waste management companies use pyrolysis for the treatment of oily sludges to treat the solid fraction after pre-treatment and dewatering. The traditional technologies selected, landfilling and incineration with energy recovery are currently widely used for refinery sludge waste [17]. The last two technologies selected are incineration in cement kilns and treatment using biopiles. While cement kilns are routinely used for the treatment of oily sludge waste in some countries (e.g., Greece), they are not common in other European countries. Biopiles are routinely used for the treatment of contaminated soils containing organic (hydrocarbon) substances, however, they are not commonly used for oily sludges. The selection of biopiles for the sustainability assessment results from their successful use by one of the reporting refineries.

Configuration of the Emerging Technologies Selected for the Sustainability Assessment

Incineration Incineration is the complete combustion of oily sludge in a controlled environment with excess air and use of auxiliary fuels [17]. Figure 4 shows a schematic flow

Table 1 Waste management options groupings

Waste Management Option Group	Waste Management Options	
Incineration	D10	Incineration on land
Landfill	D1/5	Landfill
	D4	Surface Impoundment
	D12	Permanent Storage
	D15*	Storage pending any further operations (D1 to D14)
Multiple Disposal/ Other	D14*	Repackaging prior to submission to further operations (D1 to D13)
	Other	Please specify
	Multiple disposal / recovery methods	Please specify
Recovery-Energy	R1	Energy recovery
Recovery – Other	R2/R6	Regeneration
	R6	Regeneration of acids and bases
	R7/R8	Recovery of components
	R10	Agriculture/ecological benefit
	R11	Uses of waste for submission to any of the operations R1 to R11
	R12**	Exchange of waste for submission to any of the operations R1 to R11
	R13**	Storage prior to recovery
Recycling	R3/R4/R5	Recycle/reclaim
	R9	Reuse
Treatment	D2	Land treatment
	D8*	Biological treatment
	D9*	Physico-chemical treatment
	D13*	Blending or mixing prior to submission to any of the operations D1 to D12
Not specified		Null
		Missing

*These codes refer to pre-treatment operations which must be followed by one of the other disposal operations

**These codes refer to pre-treatment operations, which must be followed by one of the other recovery operations

chart of the incineration option. Fluidized bed incinerators are commonly used due to lower emissions and high combustion efficiency compared to rotary kiln incinerators [7]. A reduction of the water content in the sludge is typically required prior to incineration, which can reduce the offset achieved by energy recovery. The energy recovery process involves converting heat energy produced during incineration into electricity. This reduces the amount of electricity/energy required for incineration [22]. After incineration, about 10 wt% of the original oily sludge remains as ash residuals which is typically disposed of in a landfill [17]. Air emissions treatment units control toxic emissions while the process emits large quantities of greenhouse CO_2 (refer to Annex 2).

Table 2 Descriptions of oily sludge oil recovery technologies identified during the literature review

Oil Recovery Technologies	
Technology	**Description**
Solvent Extraction	Solvent extraction involves the mixing of oily sludge with suitable organic solvents in a vessel, at suitable ratios, to ensure complete miscibility with petroleum hydrocarbon compounds. Water and solid impurities are not miscible with the solvents and can be separated by centrifugation. Vacuum distillation is then used to separate the oil from the solvent. Solvents such as methyl ethyl ketone (MEK) and liquified petroleum gas condensate (LPGC) are commonly used.
Surfactant Enhanced Recovery	Surfactants reduce the viscosity and surface tension of the oily sludge, enhancing the migration ability of petroleum hydrocarbons between the oil and water phases, and ultimately achieving oil-water demulsification, solid-liquid separation, and the recovery of crude oil. It is a simple process characterized by a large treatment capacity and high efficiency [17].
Microwave Irradiation	This technique uses electromagnetic waves to heat particles of oily sludge and to promote the movement and collision of particles. The process rapidly increases the temperature of oil-water mixtures and accelerates demulsification, such as the separation of oil-water molecules and it also decomposes large molecules of petroleum hydrocarbons into smaller ones. Oil recoveries of 75% have been reported [20].
Ultrasonic Irradiation	Ultrasonic treatment is similar to microwave irradiation but uses a sound field to break the oil and water emulsion in the oily sludge to achieve the separation of oil, water, and solids. Pilot tests have found crude oil dehydration rates of 96% and oil recoverability in the range of 46% to 60%. The addition of a surfactant was found to further increase the recovery rate . The method has been tested at pilot scale with reports of field tests in upstream oil operations. No reported use /test in refineries was found.
Freeze/Thaw Method	This method uses the different freezing/thawing points of the water phase and the oil phase to break-up of the emulsion mixture. Freezing methods have included refrigeration, cryogenic bath, dry ice and liquid nitrogen. Researchers have found that slow freezing tend to have the best results. Application of this method is better suited in cold climates where natural freezing may be possible. The thaw/freeze technique using liquid nitrogen have been successfully tested by oil sand operations in Canada to dewater sludges in tailing ponds for stabilisation purposes.
Froth Flotation	This technique uses air bubbles in an aqueous slurry to capture oil droplets and small solids that are then floated and collected at a top (froth) layer. It is a process similar to the air flotation pool used in sewage treatment. The flotation method requires the mixing of the oily sludge and water to create a liquid slurry, often with the help of surfactants. Then air is injected to generate bubbles in the slurry. After a time, the oil droplets floating on the surface of the slurry can be scrapped off, collected and further purified.
Pyrolysis	Pyrolysis refers to the thermal decomposition of organic materials at high temperatures (400-600^{0}C) in an inert environment. The process turns organic materials in the oily sludge into pyrolysis oil (condensable liquid oil), gaseous products (non-condensable gas) and solid char, in an oxygen free environment.Commercial plants are being used for the treatment of biomass including waste wood, green waste, wood chips, etc, for the production of soil amendment, compost and biochar. Other uses identified include the pyrolysis of waste paper, waste tyres, plastic and sewage sludges. Increasingly, pyrolysis has been applied to the treatment of oily sludges.
Sand Attrition	Sand attrition units utilise high-pressure water to mechanically separate oil/water emulsions and reverse emulsions. The inter-particulate action caused by attrition scrubbers also removes surface contamination from any solids. Separation is achieved by a physical process that does not require either chemicals or high temperatures. Once the bonds in the emulsions have been broken, the sludge can be transferred to a settlement tank where it separates into the oil, water and solid phases.
High Temperature Reforming	This method involves the heating of sludges to high temperatures after which they are allowed to cool down. This allows the separation of hydrocarbon fractions with the lighter fraction undergoing further processing to remove residual water. The end products of the treatment are gas, particulates, and solid residue. This technology is more commonly deployed in the US and has a small footprint, which makes it suitable for a variety of industrial and field settings.

Table 3 Descriptions of oily sludge disposal/treatment technologies identified during the literature review

Disposal/Treatment Technologies	
Technology	**Description**
Incineration	Incineration is the process of complete combustion of oily sludge in a controlled environment with excess air and auxiliary fuels. The combustion temperature is often >1000 C. Oily sludges can have high water content and therefore dewatering is often required prior to incineration. Incineration produces gases emissions and residues that required proper management. Incinerators with energy recovery incorporate basic mechanisms to recover heat and energy and more sophisticated mechanisms to clean flue gas [7].
Co-Processing in Cement Works	The fabrication of cement comprises the calcination and fusion of materials comprising cal-careous materials, clays and iron and aluminium oxides in a furnace at high temperature (1450 °C). This furnace produces clinker. Co-processing is the use of alternative fuel and/or raw materials for the purpose of energy and/or resource recovery. The co-processing of wastes in cement kilns provides energy and materials recovery while cement is being produced. It can also reduce CO2 emissions, reduce production costs, and destroy hazardous wastes [17, 27, 28].
Landfilling	Landfill is the most common form of waste disposal, and it is the ultimate destination for most hazardous wastes. Landfills isolate wastes from air and water through the use of layers of impermeable clay of synthetic materials. A leachate collection system is typically used to protect groundwater. When oily sludges are disposed of in a landfill they are typically mixed with soil and the oily material undergoes natural attenuation although the degradation process can be slow [17].
Biological Treatment	Biological treatment is a technology that results in the complete conversion of organic compounds into less harmful end products such as CO_2 and H_2O. It is considered low-cost and environmentally friendly compared to physical or chemical methods for removing contaminants. Various types of biological treatment can be applied to oily sludges such as landfarming, and through the use of biopiles and bioreactors.
Anaerobic Digestion	Anaerobic digestion is a proven technology applied to municipal sludges that has the potential to produce biogas from biomass using microorganisms in an inert environment. Oily sludges lack the nutrients needed to facilitate decomposition reactions while certain petroleum hydrocarbons in the sludges may be toxic for certain groups of bacteria. Co-digestion with other substrates such as sewage sludge, animal waste, etc can provide adequate conditions for digestion, can enhance bacterial diversity and increase biogas yields.
Physico-Chemical Treatment	Most common methods of physico chemical treatment includes stabilisation and oxidation. Stabilization or solidification (S/S) is a waste treatment technique aimed at immobilizing contaminants by converting them into a less soluble or a less toxic form. The use of this disposal method for inorganic wastes has been widely reported, however, it is considered less compatible with organic wastes. Oxidation degrades organic contaminants in oily sludges. Chemical oxidation is carried out by adding reactive chemicals into oily wastes, which oxidize organic compounds to carbon dioxide and water or transform them to other non-hazardous substances such as inorganic salts [15].

Landfilling Oily sludges sent to landfill typically undergo water reduction to reduce the volume and weight of the sludge. The Concawe Waste survey showed that most of the oily sludges sent to landfill underwent thickening or dewatering onsite [6]. Some, however, were sent without any treatment. It is common for landfills' operators to mix oily sludges with soil prior to placing into the landfill [17].

The landfill configuration used in the sustainability assessment (Fig. 5) assumes an engineered landfill with base liner, landfill gas and leachate collection system. The leachate is then treated in a municipal WWTP. For this assessment, it is assumed that methane gas from the landfill is not used for energy generation.

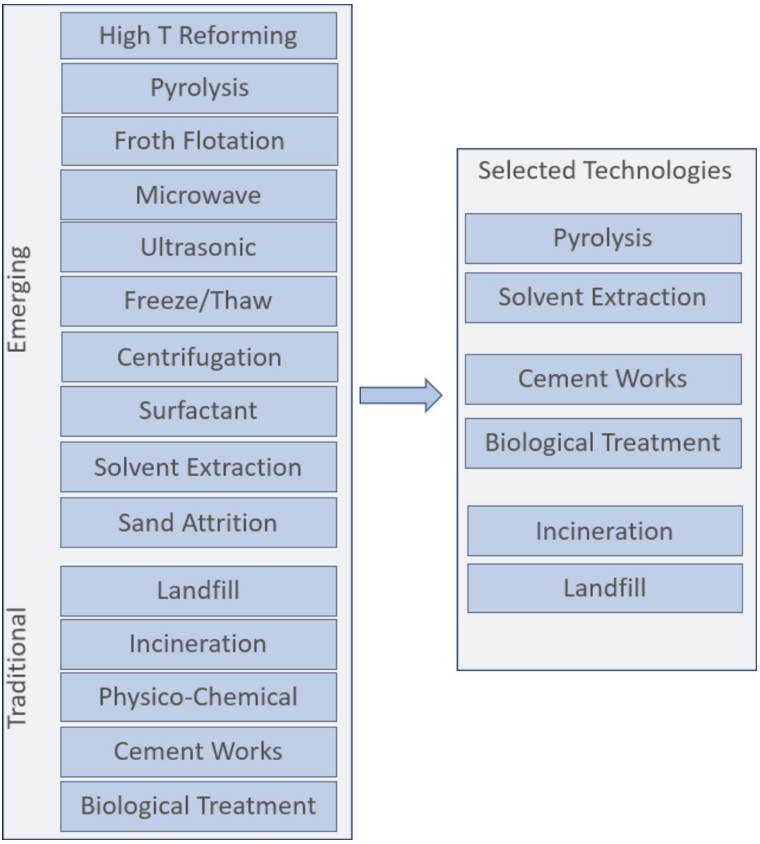


Fig. 3 Technologies selected for the sustainability assessment

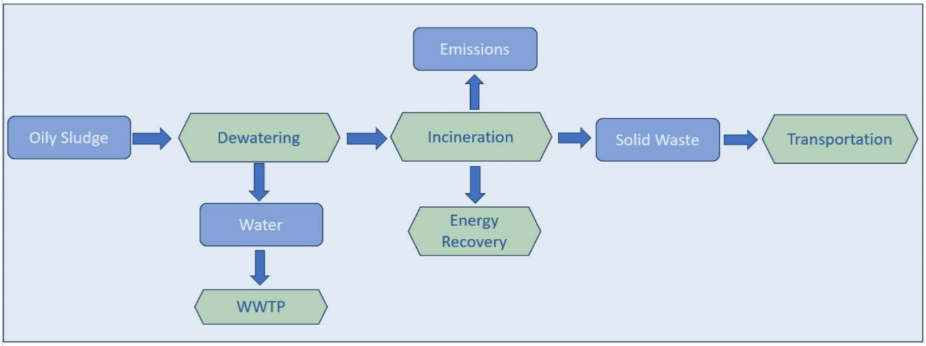


Fig. 4 Flowchart of oily sludge incineration with energy recovery

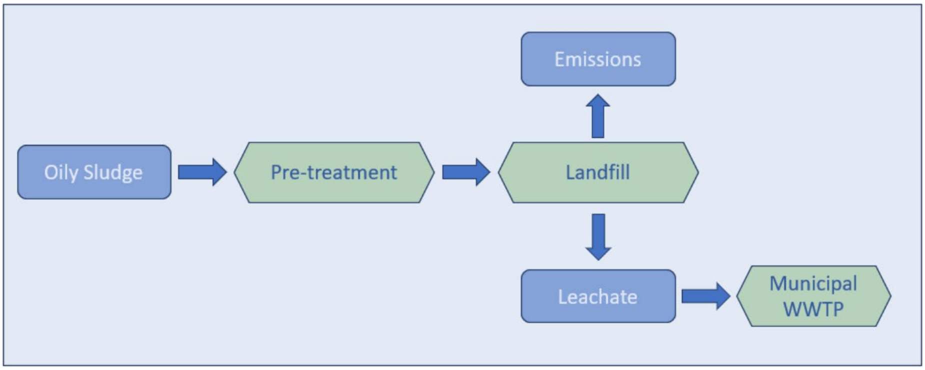


Fig. 5 Flowchart of oily sludge landfilling

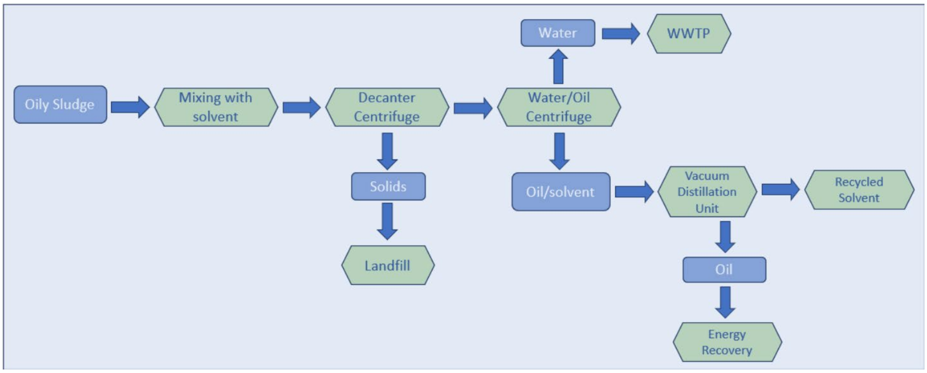


Fig. 6 Flowchart of solvent extraction method

Solvent Extraction With this technique, oily sludges do not require pre-treatment. The oily sludge is mixed with the solvent such as Methyl Ethyl Ketone (MEK), Liquified Petroleum Gas Condensate (LPGC), hexane, xylene, toluene, turpentine and others, in a vessel where the mix is agitated. The mixture is then sent to a decanter centrifuge for separation of the liquid and solid phases. The solid phase (about 10% of the original volume) is typically sent to landfill. About 90% of the liquids can be recovered in the decanter which is sent to an oil/water centrifuge [17]. The separated water is sent to a wastewater treatment plant and the oil/solvent mixture is sent to a vacuum distillation unit. This is the step where more energy is required. Oil and solvent are separated in this unit. The solvent extraction configuration used in the sustainability assessment can be seen in Fig. 6. [17] have shown that more than 90% of the solvent can be recovered and used again in the solvent extraction process. Therefore, there will be some environmental impacts associated with solvent replenishment. The recovered oil (up to 30% of the oily sludge volume) can be combusted and the heat from combustion used to generate electricity which offsets the total impacts of the oily sludge treatment.

Pyrolysis The term pyrolysis refers to the thermal decomposition of organic materials at high temperatures (400–600 ^{0}C) in an inert environment [20]. The process turns organic materials in the oily sludge into pyrolysis oil (condensable liquid oil), gaseous products (non-condensable gas) and solid char, in an oxygen free environment [17]. With increasing temperatures, the following stages typically occur: water evaporation, vaporisation of light organic components, cracking decomposition of medium and heavy organic components and carbonates and reduction and decomposition of coke and inorganic materials.

The pyrolysis process starts with reducing the amount of water in the sludge to about 10% (see Fig. 7). Sludge paddle dryers are typically required for this level of dewatering. The dried sludge is then pyrolyzed in the pyrolysis reactor combined with a gas combustion unit to produce so called ‘py-oil’ and ‘py-gas’. The py-gas produced is combusted in the combustion unit to maintain the temperature of the pyrolysis reactor which has associated impacts. The produced py-oil can be combusted for energy recovery, offsetting impacts of the pyrolysis. Approximately 40% of py-gas and just over 30% of py-oil in weight can be produced from the dried oily sludge [16].

Pyrolysis oil has similar physical properties and element composition to a heavy fuel oil and is composed primarily of saturated hydrocarbons, aromatic hydrocarbons, resins and asphaltenes [22, 23]. Major gaseous products include H_2, CO_2, CO, water and approximately 25 wt% of non-condensable hydrocarbons such as methane, ethane and hydrogen sulphide [17]. The solid residue typically has low volatile matter content, high carbon content, lower viscosity and has the potential to be used as solid fuel. Pyrolysis oil and combustible gases products can be used as energy sources.

Biopiles Biopiles are not commonly used in the refinery industry to treat oily sludges. The process description for this option is based on a real case being applied by a Concawe Member Company and is shown in Fig. 8. The process starts with the dewatering of the oily sludge prior to constructing the piles. The Member Company interviewed uses a separation pond after which there was further dewatering of the sludge by centrifugation, but is now done increasingly using Geobags® instead, which have the advantage of using much less energy. The sludges are mixed with woodchips to provide bulking material and facilitate aeration and bacteria growing. The biopiles are underlying by a liner. Oil and water draining from the biopile are collected and the oil is further separated. The separated water is sent to the site’s waste water treatment plant. It was reported that approximately 10 tons of

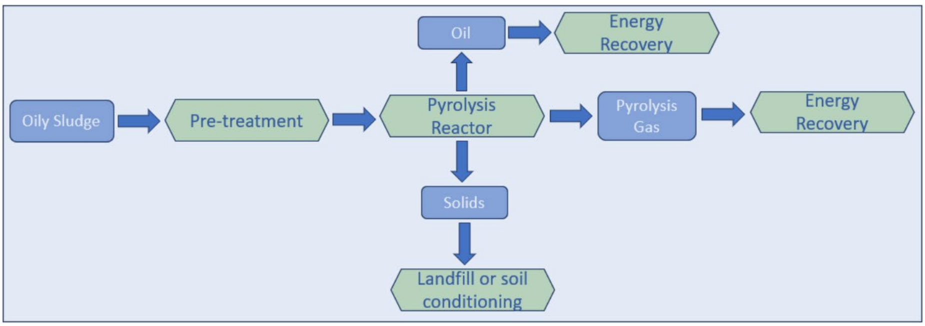


Fig. 7 Flowchart of pyrolysis method

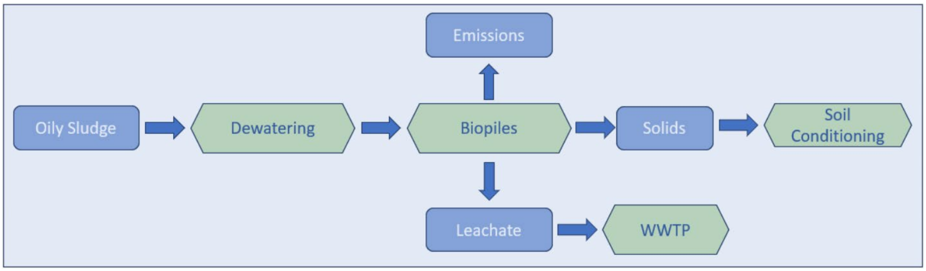


Fig. 8 Flowchart of Biopile Method

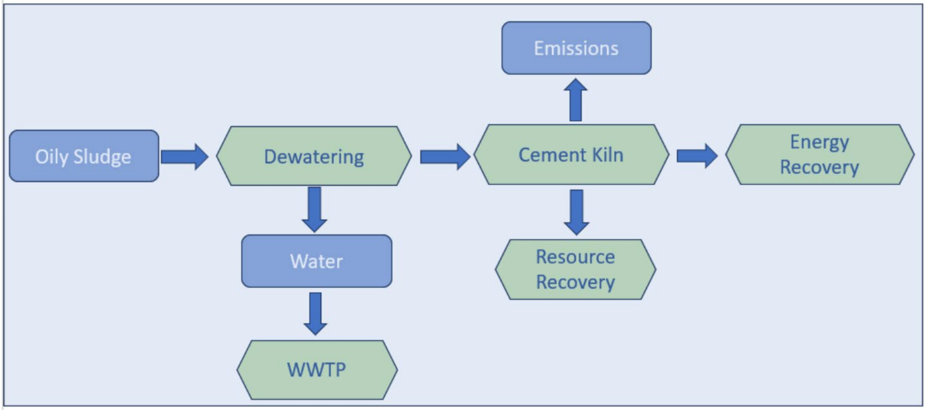


Fig. 9 Flowchart of cement works method

oil is recovered from 9,000 tons of sludge. Treatment time ranges between 9 and 12 weeks depending on the oil content. The treated sludge (soil) is used for landscaping, seeded and restored with low plants/flower that attract pollinators.

Cement Works The co-processing of hazardous waste in cement kilns allows the recovery of energy and mineral value from waste while cement is being produced. A typical configuration of the treatment of oily sludges in cement kilns is shown in Fig. 9. Hazardous wastes that are, in principle, well-suited for co-processing in cement kilns include tank bottom sludges, acid alkyl sludges, oil spills and acid tars from petroleum refining [27]. Since the overall moisture content of the waste may affect productivity, efficiency and also increase energy consumption, the water content of the waste needs to be considered and if necessary reduced by pre-processing the waste which may include drying. Acceptance criteria from cement works may require the reduction of water content onsite prior to transport to the cement work. Solid wastes used as alternative raw materials are typically fed into the kiln system via the normal raw meal supply, the same as traditional raw materials [2].

Whether or not wastes are being used in a cement plant, dust (particulate matter) and NOx and SO_2 emissions cause the greatest concern and needs to be treated. Other emissions to be considered are VOC, PCDDs, PCDFs, HCl, CO, CO_2, HF, ammonia (NH_3), BTEX, PAH, heavy metals and their compounds. Under some circumstances, emissions may also include chlorobenzenes and PCBs [21].

In general, wastewater discharges from cement works are limited to surface run-off and cooling water only and cause no substantial contribution to water pollution [21]. Residues from combustion in the kiln are incorporated into the cement and therefore there is minimum production of solid residues.

Sustainability Assessment Methodology

The sustainability assessment involved a comparison of sustainability indicators of traditional oily sludge treatment/disposal technologies with emerging technologies. The technologies selected are those shown in Fig. 3. While the sustainability assessment approach used does not follow a Life Cycle Assessment (LCA) method, it is a useful tool to identify system boundaries of the management options selected and to provide a better understanding of which parts of the options are responsible for the higher impacts. In general, the processes considered are those from the beginning of the oily sludge treatment to the final landfilling or treatment of the residual solids.

A qualitative/semi-quantitative multicriteria analysis was chosen to undertake the assessment, broadly aligned with ISO 18504 on sustainable contaminated soil remediation [19] and the Surf-UK Framework [4], that is tailored to data availability and the objectives of the project. The approached involved the identification of relevant “categories of indicators” (assessment criteria) of the three pillars of sustainability: environmental, social and economic. A fourth pillar, waste hierarchy, incorporates the circularity concept into the assessment to account for processes that result in a reduction of resources used, waste and emissions.

Environmental, and some of the social indicators were selected from the EU Reference Document on Economics and Cross-Media Effects [25] and complemented with indicators from US EPA’s Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts [1]. Indicators included global warming potential (GWP), acidification (AP) and eutrophication potential (EP), air quality indicators such as respiratory effects (RE) and smog formation (SM), ecotoxicity effects (ECT) and human toxicity/carcinogenic effects (CAR and NCAR). These indicators are based on the environmental effects that the pollutants are most likely to cause.

Additional indicators include energy recovery and the need to treat the residues of treatment technologies (resulting in further emissions), nuisance arising from transport of waste (for offsite treatment), commercial availability and operational costs. Table 4 includes the full list of criteria.

Weightings were applied between 0 and 5, where 0 was considered not specifically relevant, or lacks data to make an assessment. One (1) indicates low importance or data were not conclusive, and 5 indicates high importance and/or more data available. If an assessment criterion was considered to be equally relevant to all remedial options, it was also weighted as 0 and excluded from the assessment.

Table 4 Assessment criteria and associated weightings selected for the sustainability assessment

Pillar	Assessment Criteria	Media Affected	Assigned Weighting	Key Relevant Indicators	Additional Notes/Justification
Environmental	Ozone Depletion Potential (ODP)	Air	0	Bromofluoroethanes, CFCs	N/A. Ozone depletion is the effect of the stratospheric ozone layer being broken down by chemical reactions with polluting gases released from human activities. Life Cycle Analysis (LCA) study (Hu et al 2019) showed little impact of ODP for landfill, incineration, solvent extraction and pyrolisis. Lack of sufficient data for other management options.
	Global Warming Potential (GWP)	Air	5	CO_2 eq. per ton of sludge	Greenhouse gases arising from burning fossil fuels and hydrocarbon degradation.
	Acidification Potential (AP)	Air, water	1	SOx, NOx	Acidifying substances are often air emissions, that can affect the buffering capacity of ecosystems. Sulfur dioxide and nitrogen oxides from fossil fuel combustion are large contributors to acid rain. Semi-quantitative assessment only.
	Euthrification Potential (EP)	Water	1	Phosphate, Nitrates	Euthrification is the enrichment of an aquatic ecosystem with nutrients (nitrates, phosphates) that accelerate the undesirable accumulation of algal biomass. Semi-quantitative assessment only.
	Ecotoxicity Effects (ECT)	Air, water, soil	1	Metals, PAHs	Discharges to aquatic environments can have a toxic effect on the plants and animals that live in that environment. Scored high on LCA study (Hu et al 2019) for several management options. Semi-quantitative assessment only.
	Further disposal/treatment of residues	Air, water, soil	5	N/A	Additional potential environmental and human impacts from the need to dispose/treat residues from main management options (ash, wastewater, solids).
	Energy Recovery (ER)		5	kW/h	The use of energy from waste as a substitute for fossil fuel.
Social	Onsite vs Offsite Treatment	N/A	3	Noise, Vibrations	Offsite transport causing nuisance, noise, dust vibrations. Onsite treatment is not considered to increase exisisting refinery impacts on neirbourhood in any significant way.
	Carcinogenic Effects (CAR)	Air, water, soil	0	Cr VI	N/A. LCA study of CAR (Hu et al, 2019) showed low impact to humans for landfill, incineration, solvent extraction and pyrolisis. Lack of sufficient data for other management options.
	Non-carcinogenic Effects (NCAR)	Air, water, soil	0	Metals, PAHs	N/A. LCA study of NCAR (Hu et al, 2019) showed low impact to humans for landfill, incineration, solvent extraction and pyrolisis. Lack of sufficient data for other management options.
	Respiratory Effects (RE)	Air	1	$PM_{2.5}$, SOx	Particulate matter is a collection of small particles in ambient air which have the ability to cause negative human health effects including respiratory illness. Semi-quantitative assessment only.
	Smog Formation (SM)	Air	1	NOx, O_3	Photochemical smog formation can cause respiratory health issues. Semi-quantitative assessment only.
Financial	Commercial Availability	N/A	3	NA	Is the option readily availble in the market? If onsite does it need pilot testing?
	Disposal/Treatment Cost	N/A	5	€/ton of waste	Gate/operational cost of treatment/ disposal excluding transport costs. Excludes capital costs.
Circularity Efficiency	Waste Hierarchy	N/A	5	Disposal, Recovery, Recycling	Higher score the higher in the waste hierarchy. For example, an option involving landfilling (disposal) will have lower circularity efficiency than thermal destruction with energy recovery (recovery).

Results

Refineries Waste Quantities and Sources

In total, some 3600 kt of hazardous and non-hazardous waste was produced in the period 2019–2021 by the 68 refineries that participated in the survey (an average of 3.15 t of waste per kt of throughput). To ensure anonymity and prevent the identification of individual companies or installations, regional country groupings were established by Concawe such that each group contained at least 5 refineries. Country groupings for the 2019–2021 survey consisted of Germany, Mediterranean Region, Iberia, UK/Ireland and Northern Europe, Central and Eastern Europe and France (see Annex 1). On average, 505,000 tonnes of total waste were produced in the country groupings during the 2019–2021 period. Germany showed the highest waste production with 789,000 tonnes, and France the lowest with 210,000 tonnes.

The largest amount of total waste originates from refinery operations (approx. 62%), followed by re-construction works (approx. 13%), diverse sources (approx. 9.7%) and remediation activities (approx. 8%). Non-hazardous soils and stones waste associated with construction works were the largest waste type produced in the period with approx. 850 kt. Sludges from waste water treatment containing hazardous substances (approx. 240 kt), and soil and stones containing hazardous substances (approx. 180 kt), were the second and third largest categories overall (Fig. 10).

The percentages of sludges in relation to the total amounts of wastes produced were 22.17% (277,137 t) in 2019, 20.61% (237,466 t) in 2020 and 19.61% (236,647 t) in 2021. The majority of the sludges produced (81.5%) were classified as hazardous. Normalised sludge waste production ranged between 0.26 t/kt (Iberia Country Group) and 0.91 t/kt (Germany Country Group), with an average of 0.66 t/kt across Europe when considering total sludge production for the 2019–2021 period. The greatest tonnage (approx. 85%) of sludge wastes reported originated from refinery operations. Figure 11 shows the top ten waste sludge categories by EWC code for the 2019–2021 period. The three largest waste sludge categories reported were sludge from waste water treatment plants, oily sludges from maintenance operations and tank bottom sludges and represent 72% of the top ten waste sludge categories (62% of the total amount of sludges produced in the period).

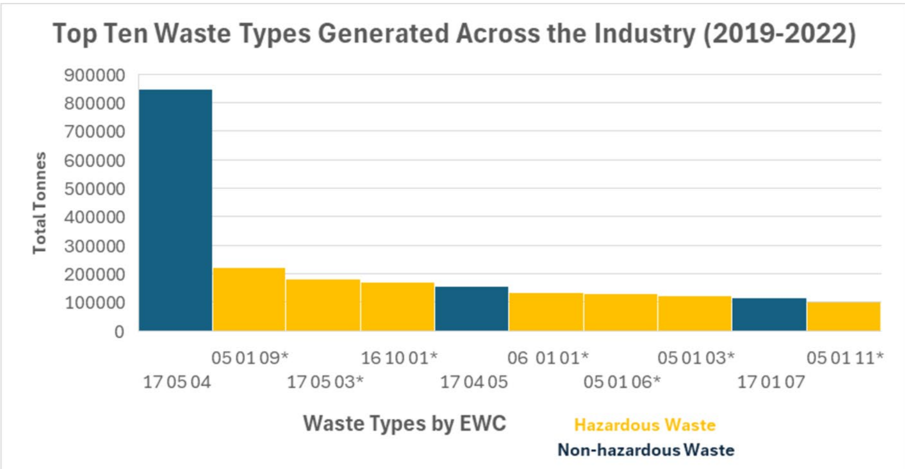
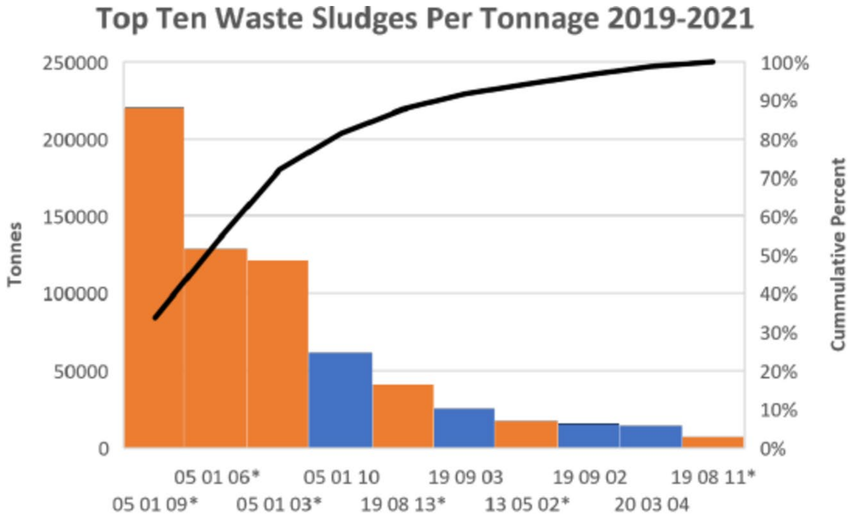


Fig. 10 Top Ten EWC Waste Categories by Tonnage (2019–2021). Numbers along the X axis represent waste codes as per the EU Commission notice on technical guidance on the classification of waste (2018/C 124/01). In order by decreasing volume, the wastes are: soils and stones, WWTP sludges, soils and stones (containing hazardous substances), aqueous liquids, iron and steel, sulphuric and sulphurous acids, maintenance oily sludges, tank bottom sludges, bricks/tiles/ceramics and waste from cleaning fuels with bases



EWC Code	Waste Description	Waste Tonnes
05 01 09*	Sludges from on-site effluent treatment containing hazardous substances	220,289
05 01 06*	Oily sludges from maintenance operations of the plant or equipment	129,023
05 01 03*	Tank bottom sludges	121,578
05 01 10	Sludges from on-site effluent treatment other than those mentioned in 05 01 09	61,522
19 08 13*	Sludges containing hazardous substances from other treatment of industrial waste water	41,357
19 09 03	Sludges from decarbonation	25,351
13 05 02*	Sludges from oil/water separators	17,190
19 09 02	Sludges from water clarification	15,757
20 03 04	Septic tank sludge	14,565
19 08 11*	Sludges containing hazardous substances from biological treatment of industrial waste water	7,513

Fig. 11 Top Ten Waste Sludges per Tonnage 2019–2021 (Hazardous sludges are depicted in orange and non-hazardous sludges are depicted in blue). Numbers along the X axis of the upper figure represent waste codes as per the EU Commission notice on technical guidance on the classification of waste (2018/C 124/01)

Refineries Sludge Waste Management Options

Sludge Waste Management Options

For most management options, hazardous sludges constituted the majority of the waste sludge. Incineration and incineration with energy recovery were the two largest management options by weight. Only 2.6% of the sludges managed by these options were classified as non-hazardous. These two incineration options were followed by landfill, recycling and treatment, all with similar tonnages of hazardous sludges and less amounts of non-hazardous sludges. The recovery-other option is the only option with a larger quantity of non-hazardous sludges in relation to the hazardous fraction (Fig. 12).

The reported data showed regional differences in the management options for hazardous waste sludges, which could reflect the availability of waste management options and local policy differences. For example, landfill disposal is more important in the Mediterranean, Germany and the UK/Ireland/Northern Europe Country Groups, whilst incinera-

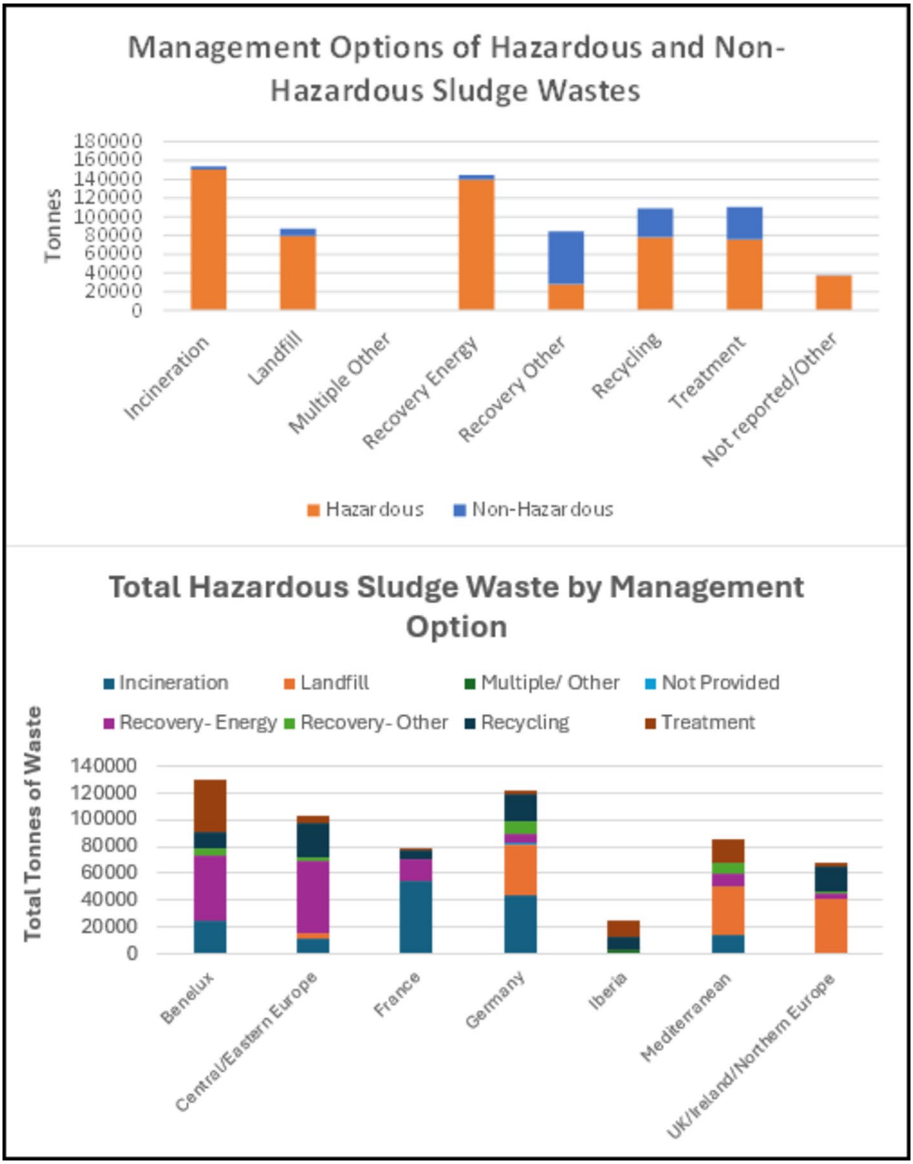


Fig. 12 Hazardous and non-hazardous sludge wastes by management option. The upper figure shows management options for all regions including hazardous and non-hazardous sludges. The lower figure shows management options per country grouping for the hazardous sludges only, which constitute most of the sludge waste

tion and recovery-energy constituted the main management options in Benelux, Central/Eastern Europe and France. Treatment is a significant management option in Benelux and is also used in Iberia and Mediterranean Country Groups. When asked about methods and techniques used in the pre-treatment of sludges prior to final disposal of the waste, respondents indicated that approximately 35% of the sludge waste did not undergo any form of pre-treatment. For the sludges that were pre-treated (i.e., typically separation of the liquid and solid phase), centrifugal thickening was the main separation technique used, followed by decantation, and gravity and flotation thickening. When oil was separated from the liquid phase this was undertaken mainly with oil/water separators. In some cases, oil was treated together with the water phase. Only a small percentage (approximately 2%) was treated offsite. Water separated from the sludge waste was treated primarily onsite by biological treatment (42%) with a small quantity treated also biologically but offsite (5%).

Waste Water Sludges Management Options

Approximately 44% of the Wastewater Treatment (WWT) sludges received no treatment prior to final disposal or the information was not provided by the respondents. All Country Groups reported a mixture of treatment/separation and no treatment prior to final disposal with the exception of UK/Ireland/Northern Europe which reported all WWT sludges treated by thickening (centrifugal, flotation and gravity thickening). Energy recovery (R1) was the main management option for this type of sludge waste with a reported 25.2% of the total volume. This was followed by physico-chemical treatment (approx. 14.4%) and recycling (approx. 6.8%)[5]. Disposal into landfill constituted only 1.7% of the total. Overall, more volume of waste water sludge was treated than not treated prior to incineration (D10) and energy recovery (R1), while more sludge volume was not treated than treated when the management option selected was physicochemical treatment (D9). Recycling (R3/4/5) seemed to have similar volumes of waste water sludges that received both treatment and no treatment prior to recycling.

Maintenance Sludges Management Options

The largest management option (approx. 15%) for this type of sludges was physico-chemical treatment (D9), followed in decreasing volume by recycling (R3/4/5), energy recovery (R1), incineration (D10) and oil re-refining (R9), with percentages of between approximately 10% and 13%. Different management options were used in some Country Groups. Germany used recycling (R3/4/5) and incineration (D10) as their main option while Central/Eastern Europe used biological treatment (D8); the only country group to use it as the main waste management option for this type of sludge. Iberia and Benelux's most used option was physico-chemical treatment (D9) while energy recovery (R1) was the main option used in France. The disposal into landfill (D1/5) was low, with approximately 1.8% of the total maintenance sludge managed by this option (in UK/Ireland/Northern Europe, Central/Eastern Europe and Iberia Country Groups).

[5] Examples of category D9, physico-chemical treatment, includes oxidation/reduction, precipitation, neutralisation, immobilisation, etc. Examples of recycling options include composting, anaerobic digestion, gasification and pyrolysis.

For maintenance sludges there does not seem to be a pattern between final management options and sludge separation or lack of separation onsite. For more than 40% of the maintenance sludges, separation prior to final disposal was not provided by the respondents or received no treatment.

Tank Bottom Sludges Management Options

Almost half (approx. 47%) of all tank bottom sludges received no separation/treatment prior to disposal or a response was not provided. France was the only country group that reported no separation/treatment of tank bottom sludges prior to final management which included primarily incineration (D10) and energy recovery (R1). For Benelux, more than 50% of the tank bottom sludges that did not undergo separation were recycled (R3/4/5) although the actual recycle process used is unknown. There doesn't appear to be consistency between sludge that underwent separation and sludge that didn't, and disposal options, with both treated (separated), and not treated (not separated) sludge both resulting in incineration with or without energy recovery (R1, D10), physico- chemical treatment (D9) and recycling (R3/4/5). Of particular attention are treated sludges sent to landfill in UK/Ireland/Northern Europe (about 30% of all tank bottom sludge) and the approximately 30% of sludges sent to deep injection (D3) in the Iberia Group. Overall, energy recovery was the management option most used (approx. 24.5%), followed by incineration (approx. 22%), physico-chemical treatment (approx. 13.3%) and recycling (approx. 8%). Only 1.8% of the tank bottom sludges where disposed of in a landfill.

Sustainability Assessment Results

Following the weighting process described in "Sustainability Assessment Methodology" section, each assessment criteria was scored. The scores were applied on a relative basis, with reference to the relevant indicators in Table 4. The scores range between 1 and 5, where 1 represents the least favourable technique and 5 is the most favourable for that particular criterion (i.e., causes the least impact, has the lower cost, etc.). The scores were then multiplied by the assigned weighting. For each pillar (environmental, social, finance and waste circularity) a percentage score was then calculated (percentage of maximum possible score, reflecting the number of assessment criteria). This serves to illustrate those options that score high/low for a given pillar. The assessment then combined (and normalised) the score for the four pillars, to provide a balance overall score for each management option. For a given option, this balanced overall score can be compared against the other options and is intended to assist in the identification of the most favourable options.

The results of the assessment are shown in Fig. 13. The most favourable management options are biopiles, followed by solvent extraction and pyrolysis. These options are more favourable from a sustainability and circularity point of view than traditional options such as landfilling, cement works and incineration with energy recovery. However, these are considered emerging techniques and their degree of application to refineries varies, with some technologies only tested at laboratory or pilot scale. Therefore, a conclusion as to their applicability to refineries'sludges can only be drawn once their availability, cross media effects and applicability restriction are determined.

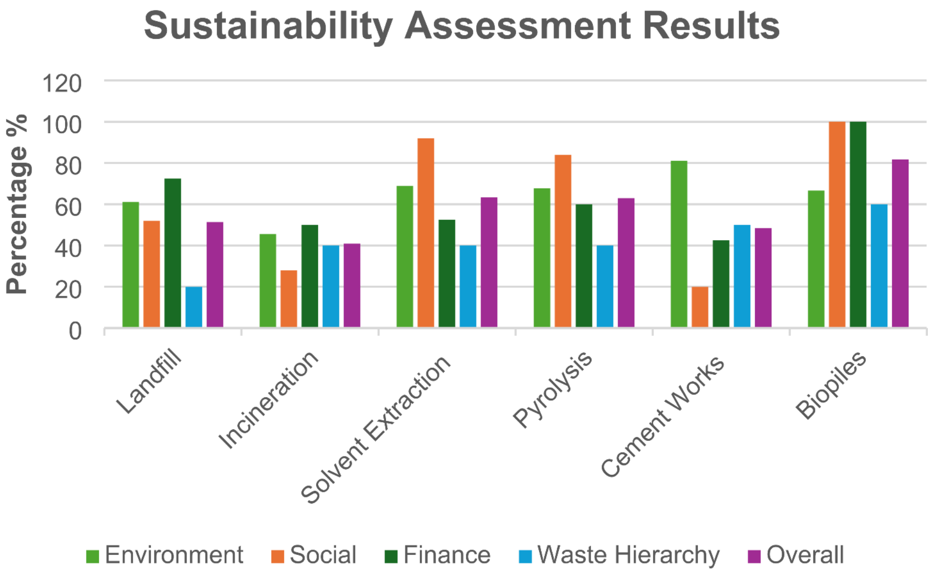


Fig. 13 Sustainability assessment results (high bar is judged more sustainable)

The following Sections present a general discussion on the data used in the assessment with particular attention to some of the criteria and main differences between the management options.

Environmental Pillar

The emission of greenhouse gases is an important environmental impact for all options, primarily associated with CO_2 emissions from combustion and biological degradation, and methane emissions in the case of landfilling. Biological degradation options are favourable with some 300 kg of CO2 eq. per ton of sludge [26], while incineration is the least favourable option with 1000 to 2000 kg/ton of CO2 eq. per ton of sludge and much higher when the use of auxiliary fuels to achieved required combustion temperatures is considered. Pyrolysis also scores less favourable when combustion of py-gas and py-oil is considered together with the energy required to maintain the temperature in the pyrolysis reactor.

Ecotoxicity criteria (ECT) impacts derived primarily from the potential risk of soil and groundwater contamination by heavy metals and toxic hydrocarbon compounds such as PAHs. Cement works, incineration, landfill and biopiles resulted less favourable options due to combustion emissions, disposal of residues or leachate production, with pyrolysis and solvent extraction the most favourable options. In fact, it was estimated that pyrolysis and solvent extraction ECT impacts amounted to only 5% of the impact represented by incineration and landfill [17].

Acidification potential (AP) is associated with emissions of NOx and SOx substances to air and water (via atmospheric deposition) and, therefore, options with combustions processes tend to be less favourable for this criterion. Eutrophication potential (EP) impacts are generally low, with cement works resulting the most favourable option due to the almost complete lack of water emissions.

Environmental criteria ECT, AP and EP were given low weightings given the lack of quantified data encountered during the literature review. While some data relevant to these criteria (SOx, NOx, Nitrates) was available for options such as incineration or cement works, this was not found for the other options.

The final treatment/disposal of solid residues is another category in the Environmental Pillar. It considers the additional potential environmental impacts from the need to dispose/treat residues (ash, wastewater, solids) from the selected management options. Pyrolysis and cement works resulted the most favourable options. Solids residues from pyrolysis are essentially a char that can be used for soil conditioning while in cement works solid residues are incorporated into clinker. Biopiles have no solid residues since after degradation in the biopiles the remaining soil can be used as a soil conditioner. However, biopiles and landfill produce leachate that requires treatment.

Incineration and solvent extraction scored the least favourable due to the amounts of solid residues produced by these options (between 10 and 20% of the original sludge) and the amounts of separated water that needs to be treated in a waste water treatment plant in the case of solvent extraction.

Finally, the Energy Recovery criteria includes the use of energy from waste as a substitute for fossil fuel. Landfill (without CH_4 capture) and biopiles are the least favourable, whilst incineration and cement works obtained higher scores with over 1300 kW/h of produced energy per ton of sludge. Solvent extraction and pyrolysis result in similar production of grid electricity of between 1000 and 1150 kW/h per ton of (oily) sludge using the heat energy from the combustion of recovered oil.

Social Pillar

The criteria in this pillar refer to impacts to people due to emissions. Emissions refer not only to emissions to air and water but also nuisance issues such as noise, vibrations and odours. As such, options requiring offsite transport were selected as the least favourable ones as they can cause additional nuisance due to transport such as noise, dust, vibrations, etc. Contrary to this, onsite treatment was not considered to increase existing refinery impacts on neighbourhoods in any significant way. It is acknowledged that the great majority of oily sludges are currently being managed by disposal or treatment offsite. However, handling more waste onsite has the potential to increase overall sustainability and circularity as long as proper management of the waste can be achieved in a cost-effective way. Options such as solvent extraction and pyrolysis can be scaled up to operate within a refinery depending on permitting requirements given contractors are available who can build these plants to various capacities.

Biopiles are already used by one Company Member, and it is acknowledged that sufficient available space within the refinery is required for this option to be viable. Incineration, cement works, and landfilling are clearly offsite options unlikely to be viable or permitted in refineries and therefore received a lower score.

Air emissions causing air quality issues with consequences for people, such as respiratory effects and/or smog formation, were also considered in this category. Smog Formation (SM) is caused primarily by NOx and SOx emissions while Respiratory Effects (RE) main causes are SOx and particulate emissions ($PM_{2.5}$), all the result of combustion processes. Cement works was found to be the least favourable option with landfill and biopiles the most favourable. Given the lack of quantification for SM and RE for some of the options selected, they were provided with a low weighting.

Toxic, carcinogenic effects of emissions from the selected management options are criteria commonly used in LCA studies. However, there is little information available to assess these criteria and were therefore not considered.

Financial Pillar

Gate costs for disposal or treatment of hazardous waste are difficult to obtain from waste management contractors without actual analysis of the waste to be received. Consequently, costs (in €/ton of waste) for some of the options assessed in this assessment were obtained from interviews with Concawe Member Companies who provided ranges of costs to dispose of oily sludges in general. Other costs were obtained from the literature review and do not necessarily represent commercial rates. Costs for solvent extraction and pyrolysis in the assessment are operational costs and exclude capital costs since no information could be found on these. Biopiles assigned costs also represents operational costs only. For solvent extraction, costs are based on pilot tests rather than commercial operations.

A second criteria in the Financial Pillar refers to the commercial availability of the options selected. Given the fact that some options (landfill, incineration) were deliberately selected because of their widespread availability to compare against selected emerging options, they would by definition result in more favourable scores. Due to this bias a lower weighting was chosen for this criterion. Solvent extraction received the lowest score as information available for this option derives mainly from pilot tests and has an apparent lesser widespread availability.

Circularity Pillar

For the purpose of the assessment, each Waste Hierarchy in Fig. 2 was allocated a score of 1 to 5 in ascending order, i.e., 1 for disposal and 5 for prevention. In this way, landfill (D1/5) was provided a score of 1 and incineration with energy recovery (R1) a score of 2. Incineration without energy recovery (D10) would have been assigned a score of 1. Pyrolysis (R3) and solvent extraction (R3) also falls into the recovery hierarchy and are assigned a score of 2.

The co-processing of wastes in cement kilns is a mix of recycling and thermal recovery. The mineral portion of the waste is reused during the process and replaces virgin raw materials. At the same time, the energy content of the waste is very efficiently recovered into thermal energy (R1), thus saving conventional fuels. Therefore, in the waste hierarchy co-processing of waste in cement works generally has a position just below recycling (R5, recycling of inorganic materials) as it is more beneficial than incineration with energy recovery [28]. Accordingly, the cement works option was assigned a score of 2.5.

Sustainability Assessment Discussion

The overall score of the sustainability assessment is a weighted average of all criteria. As such, an option resulting in an overall favourable score may have still scored low in one or more of the pillars. For example, while biopiles resulted in an overall favourable score, it scored less favourably in the environmental criteria than other options due primarily to the lack of energy recovery. In fact, cement works scored the highest in the environmental pillar helped by high scores on energy recovery, lack of residues requiring further treatment and lack of water emissions. This was followed by pyrolysis, solvent extraction and biopiles. Should methane collection and electricity generation be assigned to the landfilling option, it would score much higher in both the environmental pillar and in the overall score.

As for social impacts, biopiles and solvent extraction were the most favourable with incineration and cement works the least favourable. Biopiles and solvent extraction had the highest scores on the Financial Pillar, again with cement works and incineration obtaining the lowest score. Finally, on the waste hierarchy pillar, biopiles and cement works obtained the highest scores with landfill the lowest, as expected.

For options such as incineration and cement works, the majority of the environmental and social impacts occur at the combustion stages of the management option and are related primarily with air emissions of CO_2, contributing to global warming, and substances such as NOx, SOx, and particulates, affecting air quality and acidification. General ecotoxicity is also high due to the emission of heavy metals and toxic organic substances contributing to water contamination. The transport of ash residues to landfill contribute much less to the impacts of incineration.

For solvent extraction the highest impact is associated with the combustion of recovered oil, followed by vacuum distillation, water separation and mixing. In the case of pyrolysis, the impacts from the pyrolysis process and from the combustion of pyrolysis products are the two main processes identified with the highest (and similar) impacts associated with this option. Both processes have similar emissions of CO_2 and ECT impacts via the presence of heavy metals in soot from the combustion of fuel for maintaining the temperature in the reactor.

The above demonstrate that the evaluation of cost and benefits may sometimes identify that an option lower down the waste hierarchy may give a better environmental or social outcome than one higher up the hierarchy. It is worth noting that the selection of an option may also be affected by the local environment operational considerations, i.e. what is available and not in a certain location.

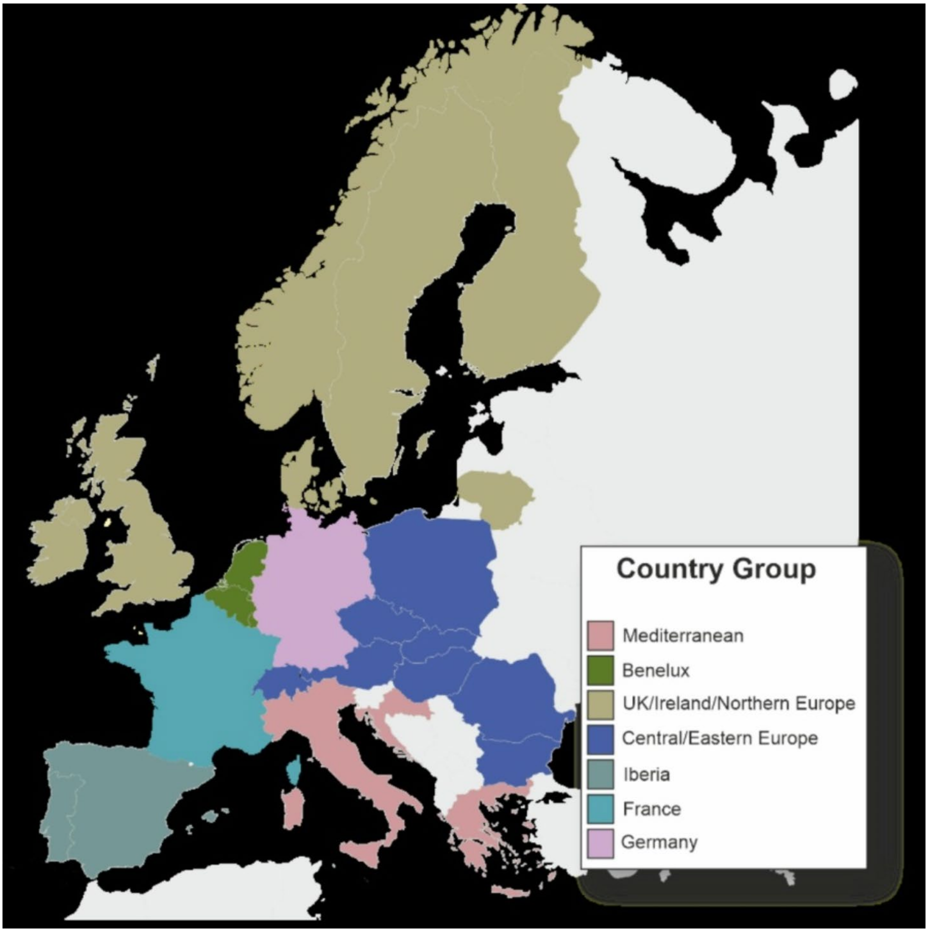
Conclusions

Concawe waste surveys are a useful tool to identify the main types of waste generated by European refineries, as well as the current practices used to manage these wastes. Recent waste surveys have identified that oily sludges are significant wastes in refinery operations, in particular WWTP sludges, maintenance sludges and tank bottom sludges. Incineration, with and without energy recovery, followed by landfill, treatment and recycling are the main management options for hazardous oily sludges. The selection of management options is dependent on the availability and cost of these management options within the country or region where the sludges are generated, with the great majority of waste sludges being treated within their country of origin.

A sustainability assessment was undertaken to compared the environmental sustainability of currently used oily sludges management techniques (incineration, cement works and landfill) to selected emerging techniques (pyrolysis, biopiles and solvent extraction) to evaluate their overall sustainability with regards to their environmental and social impacts and benefits, their costs and their capacity to reduce resources used, and generated waste and emissions. The assessment indicated biopiles as the most favourable management option, followed by solvent extraction and pyrolysis. These options are more favourable from an overall sustainability point of view, including environment, social, financial and waste circularity criteria, than the traditional options selected. However, these are considered as emerging techniques and their degree of application to refineries varies, with some technologies only tested at laboratory or pilot scale. In addition, oily sludges have a highly diverse composition and therefore, a conclusion can only be drawn once their availability, cross media effects and applicability restrictions are determined and the specificities of the refinery, including oily sludges composition, are taken into account.

The multicriteria assessment undertaken provides a rapid, semiquantitative method to compare potential environmental and social impacts of different technologies together with their cost and degree of circularity. However, the assessment did not consider other cross-media or operational considerations which can be significant in certain cases. For example, the use of biosurfactants instead of surfactants in the pre-treatment of oily sludges may reduce certain environmental impacts but can affect water treatment of effluents with increasing risks to receiving water bodies. The need to provide a guaranteed stream of waste to a treatment facility (cement works for example) can be a disincentive to the use of this options in some locations. More quantitative sustainability appraisal tools, such as LCA tools, are widely used to evaluate environmental impacts of various waste management practices. However, these types of studies required information not always available or require the undertaken of costly demonstrations at pilot or larger scales.

Annex 1: Concawe Country Groups



Annex 2: Sustainability Assessment Data and Sources

		Management Options						
Pillar	Assessment Criteria	Landfill[1]	Incineration[2]	Solvent Extraction[3]	Pyrolysis[4]	Cement Works[5]	Biopiles[6]	Justification of Scores
Environmental	Ozone Depletion Potential (ODP)	NA	NA	NA	NA	NA	NA	Not included in assessment. Insufficient data.
	Global Warming Potential (GWP) in kg of CO2 eq/per ton of sludge	648	700-1700[2] -MW- 1040-2080 dewatered oily sludge + up to 12000 considering auxiliary fuels	1140	2240	900-1000[5]	300	1. Hu, et al, 2019; 2. REF BREF CO2 per tonne of municipal waste incinerated. 1040-2080 kg/ton based on combustion of diesel fuel for dewatered TB sludges (80% oil) and WWTP sludges (40 %oil). The higher figure includes the use of auxiliary fuels; 3. Hu, et al, 2019; 4. Hu, et al, 2019; 5. Cement Works BREF and UNEP; 6. Tsiligiannis et al 2020 for landfarming.
	Acidification Potential (AP)	5	2	4	3	1	5	From Hu et al 2019, from higher to lower emissions: incineration pyrolysis, solvent extraction and landfill. Incineration SO_2 5-78 mg/Nm3 max daily average and NOx 68-329 mg/Nm3 (REF BREF). Cement Works: SO_2 <4837 mg/Nm3, NOx 145-2040 mg/Nm3 (Cement Works BREF).
	Euthrification Potential (EP)	2	1	4	3	5	2	Hu et al 2019: from higher to lower emissions: Incineration, landfill, pyrolysis and solvent extraction. Cement work has almost no water emissions. Biopile assumed similar to landfill.
	Ecotoxicity Effects (ECT)	3	3	4	5	2	3	Hu et al 2019 from higher to lower emisisons incineration/landfill, followed by pyrolysis and solvent extraction with much lower impact. Metals from combustion higher in cement works than incineration (REF BREFs and Cement Works BREF). Incineration (Hg <0.025 mg/Nm_3 and sum of metals 0.3-0.5 mg/Nm3), cement works (Hg <0.005-0.12 mg/Nm3, sum of metals 0.085-2.67 mg/Nm3. Biopile assumed similar to landfill.
	Further disposal/treatment of residues (kg)	Assumed Low	Bottom ash: 150-350 kg. Boiler ash: 20-40 kg/ton waste.	200 kg/ton sludge solid. 500 kg/ton sludge wastewater	44 kg solid	0	Assumed Low	Leachate generation for landfills was assumed low after closure of the landfill on a long-term basis. Leachate generation in open landfills will depend primarily on precipitation rates. This was not taken into account for the assesssmnt. While biopiles can be both oen to rainfall or closed under linings, "closed" biopiles were assumed for the assessment. Soil treated in biopiles is being used for soil conditioning and therefore no considered residue. Ash residues in cement kilns are incorporated into the clinker so no end products that require further management (UNEP).
	Energy Recovery (ER) kW/h/per ton of sludge	0	1366	1150	1015	1366	0	Assumes no methane recovery for electricity generation in landfill. Cement works assume the same as incineration with energy recovery. Sources Hu et al 2019 and REF BREF
Social	Onsite vs Offsite Treatment	1	1	5	5	1	5	No quantification
	Carcinogenic Effects (CAR)	NA	NA	NA	NA	NA	NA	Not included in the assessment. Insufficient data.
	Non-carcinogenic Effects (NCAR)	NA	NA	NA	NA	NA	NA	Not included in the assessment. Insufficient data.
	Respiratory Effects (RE)	5	2	4	3	1	5	Hu et al 2019 from high to low emissions: incineration followed far much lower down by pyrolysis, solvent extraction and landfill in that order. Cement works have higher SOx (<4387 mg/Nm3) and PM (0.27- <30 mg/Nm3) than incinerators (SOx <40 mg/Nm3, PM 14.6 mg/Nm3) . Biopiles assumed similar to landfill.
	Smog Formation (SM)	5	2	4	3	1	5	Hu et al 2019 showed from higher to lower emissions Incineraiton, pyrolysis, solvent extraction and landfill. Biopiles assumed similar to landfill. Cement Works have higher NOx emissions (145-2040 mg/Nm3) than incinerators (68-329 mg/Nm3). . Other options as per LCA data. From LCA
Financial	Commenrcial Availability	3	5	2	3	4	3	Based on avalability in most countries (5); not available in all locations (4); available at waste contractors facilities, there are available contractors that can build onsite and available but with growing restriciton such as landfill (3); not known waste contractor or tested mainly at pilot scale (2).
	Disposal/Treatment Cost (in Euros per ton)	300	100-2000[2]	230-380[3]	115-538[4]	100-2000[5]	93	Gate fees from: 1. UK Typical gate fee for hazardous waste; 2. Incineration BREF; 3. Hui et al 2020; 4. Minimum -maximum range for waste disposal of oily Sludges in Netherlands with multiple treatment options including pyrolysis. 350 to 550 from Hui et al 2020; 5. assumed the same as incineration ; 6. provided by member company (exclude capital costs).
Circularity Efficiency	Waste Hierarchy	D1/5	D10/R1	R3	R3	R1/R5	R10	From Waste Hierarchy

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3. Jacob Oehrig: Formal Analysis, Data Curation.
4. Konstantinos Sakkalis: Conceptualisation, Supervision.
5. E. Vaiopoulou: Conceptualisation, Project administration, Supervision.

Declarations

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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