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Sustainability Assessment of Waste Sludges Management Options

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Sustainability Assessment of Waste Sludge Management Options

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ABSTRACT

This report presents a sustainability assessment of waste oily sludges treatment technologies in refinery operations. It provides further analysis of sources, volumes, pre-treatment and final treatment/disposal options of the most important oily sludges per volume, produced by European refineries in the 2019-2021 period, as reported in the 2023 Concawe Waste Survey Report[1]. The project involved a literature review of emerging and conventional oily sludges treatment technologies from which a smaller number of technologies were selected for detailed assessment. 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 conventional technologies such as incineration in municipal solid waste incinerators, at cement works and disposal to landfill. However, it is important to note that emerging technologies will need to be analysed in greater detail taking into account local considerations and availability of the technology itself.

KEYWORDS

Waste, European refinery waste, waste survey, waste framework directive, waste production, waste management options, waste classification codes, waste hazard codes, waste sludges, refinery sludges, circularity, sustainability.

INTERNET

This report is available as an Adobe pdf file on the Concawe website (www.concawe.eu.

[1] Concawe report "A Survey on European Refineries Waste with Focus on Waste Sludges 2019- 2021", 2023

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SUMMARY

Waste surveys of European refineries carried out by Concawe have identified that oily sludges are significant wastes in refinery operations. A waste survey with focus on oily sludges was carried out in 2022 for the years 2019, 2020 and 2021. The survey looked at the sources, volumes, pre-treatment and waste management options for the three main oily sludges in volume and represented the first phase of the project. This report represents the second phase of this project which aims at using the collected data to assess the relative sustainability of oily waste sludge management options.

In the 2019-2021 period, oily sludges in European refineries represented between 19.6 and 22.2% of total produced wastes. On a normalised basis, an average of 0.66 tonnes of oily sludges were produced per kilotonne of oil throughput. The main three types of oily sludges produced by weight were tank bottom sludges, refinery maintenance sludges and wastewater treatment plant sludges. They represented 72% of all oily sludges produced.

Considering the three main types of oily sludges produced, incineration with and without energy recovery, followed by landfill, treatment and recycling were the main management options. However, when considering these three types of sludges separately, the most important management options by volume were different for each sludge type. The survey found that the selection of management options is dependent on the availability and cost of these management options within the country where the sludges are generated. Pre-treatment or lack of pre-treatment prior to final disposal/treatment was dependent on several factors such as sludge type and quality (oil, water and solids content), management options available and costs.

Waste disposal depends on its composition and the local refinery situation. Given the high costs of waste disposal, priority should be given to waste minimisation processes, such as their destruction in a coker, if the refinery has one; maximising the amount of solids that are removed from the desalter unit, since solids entering the crude distillation unit are eventually likely to attract more oil and produce additional emulsions and sludges; and preventing solids entering the refinery sewer solids.

To inform the sustainability assessment of oily sludges management options, a literature review was carried out to describe currently used technologies and to identify emerging technologies that can, once sufficiently tested and commercially available, provide viable alternatives for the management of oily sludges. Several emerging technologies were identified most of which focus on the recovery of the oil contained in the oily sludges. Their degree of application 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. A combination of emerging and conventional technologies was selected for comparison reason. The selected technologies were landfill, incineration, cement works, biopiles, pyrolysis and solvent extraction.

The sustainability assessment involved the identification of relevant "categories of indicators" (assessment criteria) of the three pillars of sustainability: environmental, social and economic, as described in ISO 18504[2] and sustainable remediation guidance[3]. A fourth pillar, waste hierarchy, incorporates the circularity concept into the assessment to account for processes that result in waste minimisation and resources reuse.

The results of the assessment showed the most favourable management option was biological treatment in biopiles, followed by solvent extraction and pyrolysis. These options were judged to be more favourable from a sustainability and circularity point of view than conventional options, such as landfilling, or incineration in cement works or in municipal solid waste incinerators. The assessment demonstrated that the degree of circularity is not necessarily associated with lower environmental or social impacts.

It is important to note that biopiles, pyrolysis and solvent extraction are considered as emerging techniques for the refining sector and their degree of application varies with biopiles being successfully used by one refinery and pyrolysis used by some waste management contractors but not by refineries themselves. Solvent extraction is still at the pilot stage. Their applicability to refineries will depend on specific refinery conditions, the understanding of cross media effects and applicability restrictions.

[2] ISO, 2017. ISO 18504:2017, Soil Quality: Sustainable Remediation. ISO, Geneva. ISO 18504:2017 - Soil quality — Sustainable remediation

[3] Supplementary Report 1 of the SuRF-UK Framework: A general approach to sustainability assessment for use in achieving sustainable remediation (SR1), 2020.

1. INTRODUCTION

Concawe and its members wish to proactively contribute to the circular economy as well as prepare for upcoming revisions of the Waste Framework Directive (WFD) and other associated regulations, including activities around the EU Zero Pollution action plan and the EU Circular Economy action plan, two of the building blocks of the European Green Deal.

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. It involves breaking with the conventional model of a linear economy (extract, manufacture, consume, throw away) and transforming what was once considered ‘inevitable’ waste into a valuable resource.

A previous review of European refineries waste data (Concawe Report No. 12/17) showed that Wastewater Treatment Plant (WWTP) and hydrocarbon sludges were the most significant part of refinery waste sludges in terms of tonnage. With a view to understand how Concawe Member Companies can contribute further to the circular economy, Concawe undertook a waste survey of European refineries for the period 2019-2021, which report was published in December 2023 (Concawe Report No. 12/23). The survey aimed to collect more recent waste data, with particular focus on refinery sludge waste management. This constituted Phase 1 of a wider project started in 2022.

The activities described in this report are part of the second phase of the project that aims at using the data collected during the survey, together with data obtained during a literature review, to inform a sustainability assessment of emerging waste sludges to improve waste minimization and move refinery waste sludge management up the waste hierarchy.

Section 2 of this report provides a summary of sources and volumes of oily sludges as reported in the 2022 Waste Survey (Concawe Report No. 12/23). It also discusses general composition of oily sludges and describes the main management options employed by EU refineries for the three main types of refinery oily sludges by volume: wastewater treatment sludges, maintenance sludges and tank bottoms sludges. This section provides further analysis of pre-treatment and management options per type of oily sludge and provides an assessment of links between pre-treatment and final disposal or treatment for the three types of sludges considered. Such analysis provided further information as to the need for resources in addition to those assessed in the technoeconomic assessment, providing a more complete picture of the overall sustainability of the options assessed.

Section 3 presents the findings of a literature review of conventional and emerging oily sludges management technologies and pre-treatment technologies used currently by European refineries. The literature review comprised a wide variety of sources including scientific journals, industry research reports, case studies, best available technology documents, waste management contractors and waste treatment equipment suppliers and interviews with selected Concawe Member Companies. This Section provides a summary description of each technology and presents the rational for the selection of technologies to include in the sustainability assessment which includes both emerging and conventional technologies for comparison purposes.

Section 4 describes the methods used in the sustainability assessment and presents the results of the assessment together with a description of the processes involved in each of the technologies selected.

Section 5 is a regulatory review of current EU directives and guidance relevant to waste management activities in general and to some of the technologies assessed. The report concludes with some conclusions and recommendations aimed at further understanding the links between impacts, sustainability and general circularity of oily sludges management options.

Finally, **Section 6** provides a summary of the current management options employed by European refineries, and of the sustainability assessment including literature review, selection of technologies for the assessment and the results of the assessment. It also provides a summary of the regulatory review and comments regarding other operational considerations relevant to the assessment. Finally, this Section provides recommendations to improve future assessments of this type.

2. CONCAWE REFINERIES CURRENT WASTE SLUDGES MANAGEMENT OPTIONS

2.1. INTRODUCTION

This Section presents a summary of the survey undertaken by the Concawe special taskforce on refining waste (WQ/STF-36) to determine the quantity of waste managed by Concawe Member Company refineries in the years 2019, 2020 and 2021. The report[1], based on survey data returned from 68 Concawe members' refineries (70.1% response rate) situated in the EU-27 countries + UK, Norway and Switzerland, includes a statistical analysis of waste production, waste types, waste sources and management options reported under different European Waste Catalogue codes[2] and Waste Hazard Codes[3]. Given the identification of oily sludges in a previous survey (Concawe Report No. 12/17) as an important waste in refinery operations, the 2019-2021 survey provided specific analysis of these wastes.

This Section, that draws from the Waste Survey Report[1], is intended to provide an understanding of the current management options used for this type of waste in Europe, including the types and volumes of oily sludges, pre-treatment requirements and main final management options (disposal or recovery). This will provide the basis upon which alternative or emerging technologies are reviewed in later Sections. This Section also discusses the composition of oily sludges, relevant to understand the applicability of management technologies, the nature of residual or secondary waste produced and potential impacts to human health and the environment from the management of these wastes.

Throughout this report, references to recovery and disposal management options are based on the groupings listed in **Table 1** and are the same as those used in the 2019-2021 waste survey.

Table 1 Generic Disposal and Recovery Groupings

Waste Management Option Group	Waste Management Options (per European Waste Catalogue codes[2])	
Incineration	D10	Incineration on land
Landfill	D1/5 D4 D12 D15*	Landfill Surface Impoundment Permanent Storage Storage pending any further operations (D1 to D14)
Multiple Disposal/Other	D14* Other Multiple disposal /recovery methods	Repackaging prior to submission to further operations (D1 to D13) Please specify Please specify
Recovery-Energy	R1	Energy recovery

[1] Concawe 2023. A Survey on European Refineries Waste with Focus on Waste Sludges, 2019-2021.
[2] Annex of Commission Decision 2000/532/EC, as amended by Decisions 2001/118/EC; 2001/119/EC and 2001/573/EC.
[3] Annex III of Directive 2008/98/EC.

Waste Management Option Group	Waste Management Options (per European Waste Catalogue codes[2])	
Recovery – Other	R2/R6 R6 R7/R8 R10 R11 R12** R13**	Regeneration Regeneration of acids and bases Recovery of components Agriculture/ecological benefit Uses of waste for submission to any of the operations R1 to R11 Exchange of waste for submission to any of the operations R1 to R11 Storage prior to recovery
Recycling	R3/R4/R5 R9	Recycle/reclaim Reuse
Treatment	D2 D8* D9* D13*	Land treatment Biological treatment Physico-chemical treatment 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.

2.2. SOURCE AND QUANTITY OF WASTE SLUDGES

As reported in the 2019-2021 Waste Survey Report (Concawe Report No. 12/23), the percentages of sludges in relation to the total amounts of wastes produced in the period were respectively 22.2% (277,137 t), 20.6% (237,466 t) and 19.6% (236,647 t). The majority of the sludge waste produced was classified as hazardous[4] (81.5%). When the normalised sludge waste production was considered, relative waste production across the country groupings[5] varied between 0.26 t/kt (Iberia) and 0.91 t/kt (Germany), with an average of 0.66 t/kt, when considering total sludge production for the 2019-2021 period. The greatest tonnage (approx. 85%) of sludge wastes reported originated from refinery operations. Lower tonnages of other sludges included hazardous and non-hazardous sludges from other on-site wastewater treatment, sludges from decarbonation and sludges from oil /water separators, clarification and septic tanks.

The three largest waste sludge categories reported were sludge from wastewater treatment plants (WWTPs), oily sludges from maintenance operations and tank bottom sludges, and together represent 72% of the top ten waste sludge categories reported for the 2019-2021 period. Sludges from wastewater treatment on-site containing hazardous substances (Waste Code 05 01 09*)[6] also represented the

[4] Hazardous waste: waste whish displays one or more of the hazardous properties listed in Annex III of the Waste Framework Directive

[5] See Annex D for the geographical extent of country groupings. To ensure anonymity and prevent the identification of individual companies or installations regional country groupings were established by Concawe, with a large enough geographic scope such that each group contained at least 5 refineries. Due to the low number of refineries that responded in UK/Ireland and Northern Europe, these were merged together.

[6] Waste codes ending in an asterix (*) refer to waste that are hazardous. Waste codes without an asterix refer to non-hazardous wastes.

second largest waste by tonnage in the period, after soil and stones not containing hazardous substances (Waste Code 17 05 04).

Normalised wastewater sludges (05 01 09*) tonnage was 0.19 t/kt for the 2019-2021 period, normalised tonnage for sludges from maintenance operations (05 01 06*) was 0.11 t/kt and for tank bottoms (05 01 03*) was 0.10 t/kt.

2.3. REFINERY OILY SLUDGES COMPOSITION

Sludges are defined as semi-liquid residue 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, and DAF units[7].

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.% (S. V. Egazar'yants, et al 2015). 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 (Hu et al, 2019).

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 (Hochberg et al, 2022). Heavier hydrocarbons settle along with water and solid particles. Solids might contain metals that decant from crude oil during storage, such as zinc, lead, copper, nickel and chromium.

The oily phase of petroleum sludges typically contains 40 to 60% saturated hydrocarbons, 25 to 40% aromatic hydrocarbons, 10 to 15% resins[8] and 10 to 15% asphaltenes (Shie et al., 2004; Speight 2006). Benzene, toluene, ethyl/benzene and xylene (BTEX) are commonly found among the aromatic compounds, as are phenols and polycyclic aromatic hydrocarbons (PAH), which are partially responsible for its classification as a hazardous waste (Xia et al., 2006).

2.4. REFINERY OILY SLUDGES MANAGEMENT OPTIONS

As reported in the Waste Survey 2019-2021 Report, hazardous sludges constituted the majority of the waste sludge for most management options. 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.

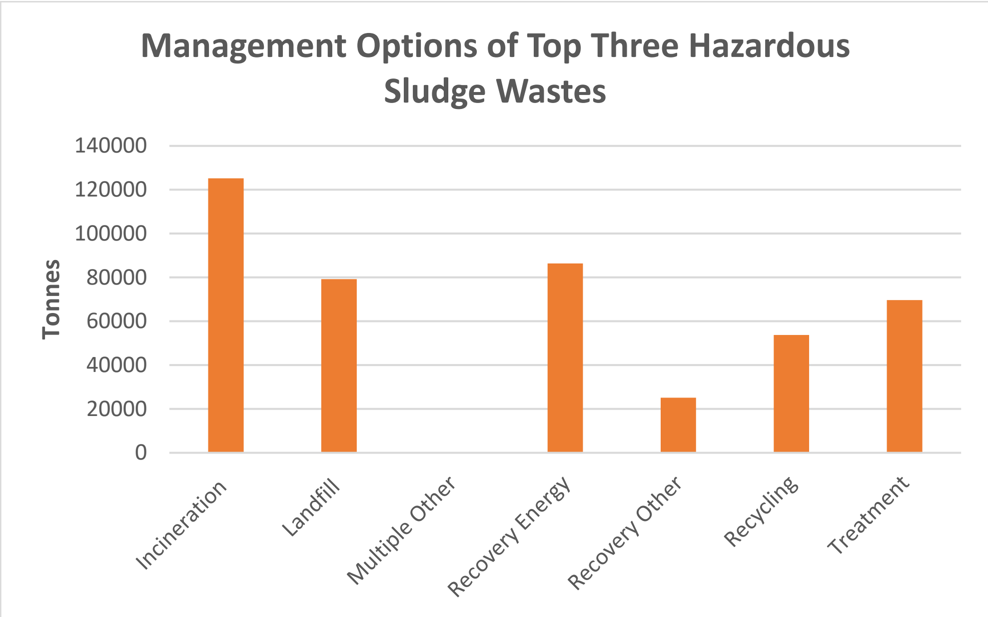
Figure 1 provides a closer look at the waste management options used for the top three waste sludges, namely wastewater sludges (05 01 09*), sludges from maintenance operations (05 01 06*) and tank bottoms (05 01 03*). Incineration and incineration with energy recovery were again the two largest management options by weight, followed by landfill, treatment and recycling in descending tonnage.

[7] Best Available Techniques Reference Document for the Refining of Mineral Oil and Gas, 2015 (REF BREF 2015)

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

Sludge waste going to a landfill (Disposal Code D1/D5) constitutes only 1.6% of the total tonnage. However, Disposal Code D15 (storage pending operations D1 to D14) with 14.5% of the top three waste sludges is also part of the landfill disposal option in **Figure 1**, some of which could also have had final disposal in a landfill.

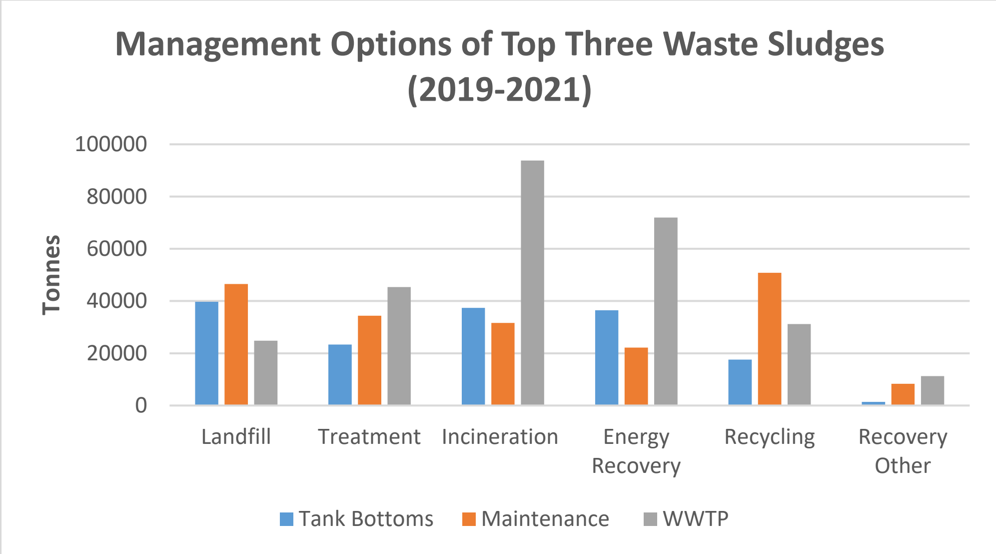
Figure 1 Sum of Top Three Hazardous Waste Sludges (Effluent Treatment Sludges, Oily Sludges from Maintenance Operations and Tank Bottom Sludges) by Management Option



Note: In the figure, each management option includes the following management codes: Incineration (D10); Landfill (D1/5, D4, D12 and D15); Multiple other (D14); Recovery-Energy (R1); Recovery other (R7/R8); Recycling (R3/4/5, R9); Treatment (D2, D8, D9, D13).

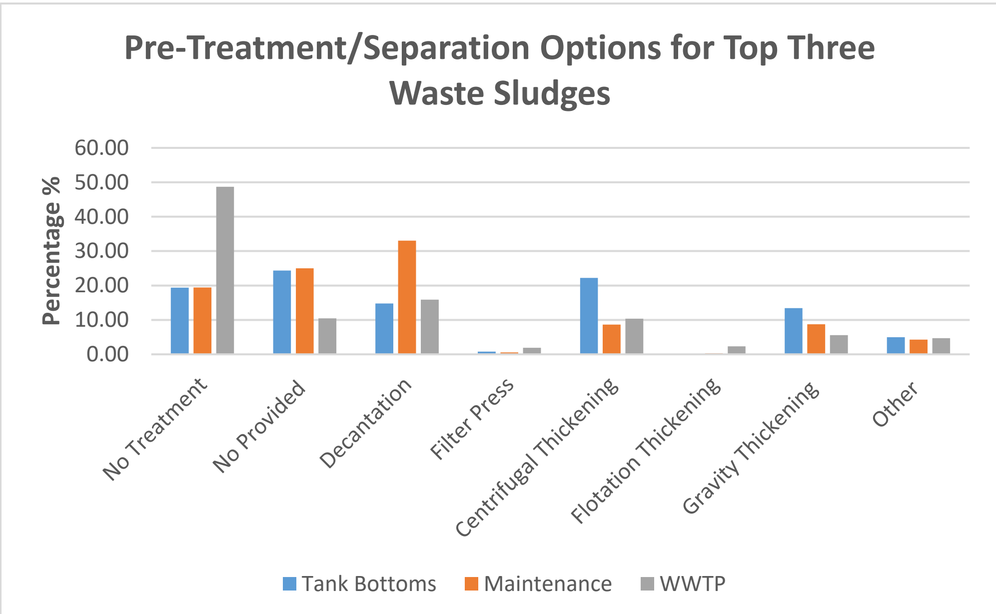
Looking at each of the three waste sludge types separately **(Figure 2***)*, the highest tonnage of tank bottom sludges was managed by Landfill (25%) followed by Incineration (24%) and Energy Recovery (23%). Recycling was the main management option for maintenance sludges (26%) followed by Landfill (24%) and Treatment (18%). Wastewater sludges were mainly managed by Incineration (34%) and Energy Recovery (26%), followed by Treatment (16%) and Recycling (11%).

Figure 2 Top Three Hazardous Waste Sludges (Effluent Treatment Sludges, Oily Sludges from Maintenance Operations and Tank Bottom Sludges) by Management Options



Respondents to the survey were also requested to answer questions as to the methods and techniques used in the pre-treatment of sludges prior to offsite treatment or disposal of the waste. These questions focused on initial separation of the liquid and solid phases and their further treatment. **Figure 3** shows the reported pre-treatment options for the three top waste sludges. The figure shows that almost 50% of the wastewater sludges received no treatment while decantation was the preferred separation option for the maintenance sludges. Centrifugal and gravity thickening were the main separation techniques used for tank bottom sludges.

Figure 3 Pre-Treatment/Separation Techniques for Top Three Hazardous Waste Sludges (On-Site Effluent Treatment Sludges, Oily Sludges from Maintenance Operations and Tank Bottom Sludges



To help visualise the relationship between pre-treatment and final management option selected for the three main oily sludges discussed, Sankey diagrams were constructed for each waste sludge type and country group. Given the focus of this report on the technological aspects of waste sludges treatment, the country groups were removed from the Sankey diagrams to allow better visualization of links between pre-treatment/separation methods and final treatment or disposal.

Figure 4 shows the links between waste water sludges (05 01 09*) pre-treatment technologies used and management options. Sludges with no pre-treatment constitutes the largest tonnage for this type of sludge (40.8%), followed by centrifugation thickening (approx. 30%) and decantation thickening (approx. 11%) pre-treatment techniques. Four main management options were used for the sludges that did not undergo any pre-treatment including physico-chemical treatment (D9) with approximately 32%, incineration (D10) with approximately 26%, energy recovery (R1) with approximately 24% and recycling (R3/4/5) with 16%.

Centrifugation and decanting thickening pre-treatments technologies constituted approximately 30% and 11% of the wastewater sludges respectively. Sludges that were pre-treated with centrifugation thickening were managed by several management options of which energy recovery and incineration constituted almost 70% of the tonnage pre-treated with this technique. Sludges pre-treated by decantation thickening were managed by two management options: incineration and energy recovery.

Figure 4 Pre-Treatment/Separation Techniques and Management Options of Wastewater Treatment Sludges

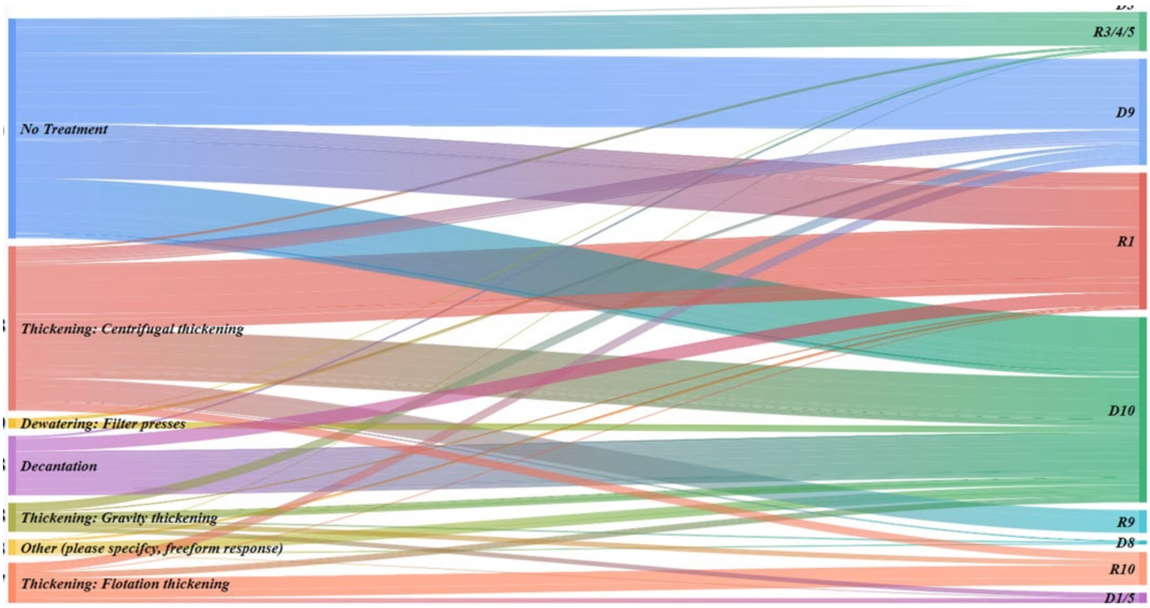
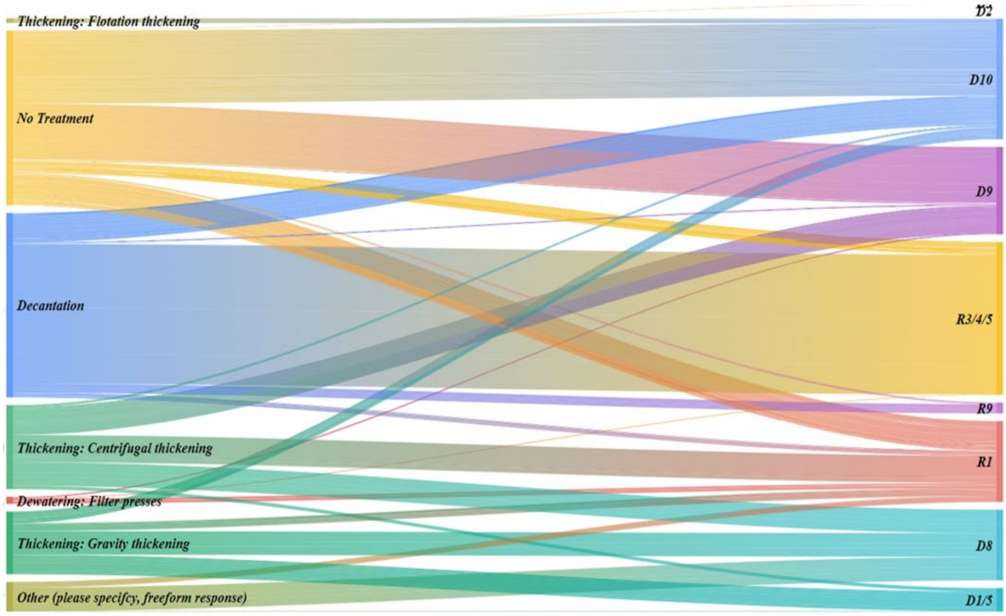


Figure 5 shows the links between pre-treatment and management options for maintenance sludges (05 01 06*). The largest tonnage of this sludge type was treated by decantation thickening (33.7%). The second largest tonnage (32%) received no pre-treatment prior to disposal or recovery. Centrifugal thickening (15.3%) and gravity thickening (11.5%) are the third and fourth pre-treatment methods by tonnage.

For maintenance sludges that had no pre-treatment, incineration (D10) with 42.7% and physico-chemical treatment (D9) with 31.5% were the two main management options. The majority of the maintenance sludge that was pre-treated with decantation thickening (75%) was managed by recycling (R3/4/5), while for those treated by centrifugation, by physico-chemical treatment (37%), followed by energy recovery (R1) with approximately 31%, and biological treatment with approximately 26% were the main disposal/recovery options.

Maintenance sludges that were managed by landfilling (D1/5) or biological treatment (D8) all underwent some form of pre-treatment.

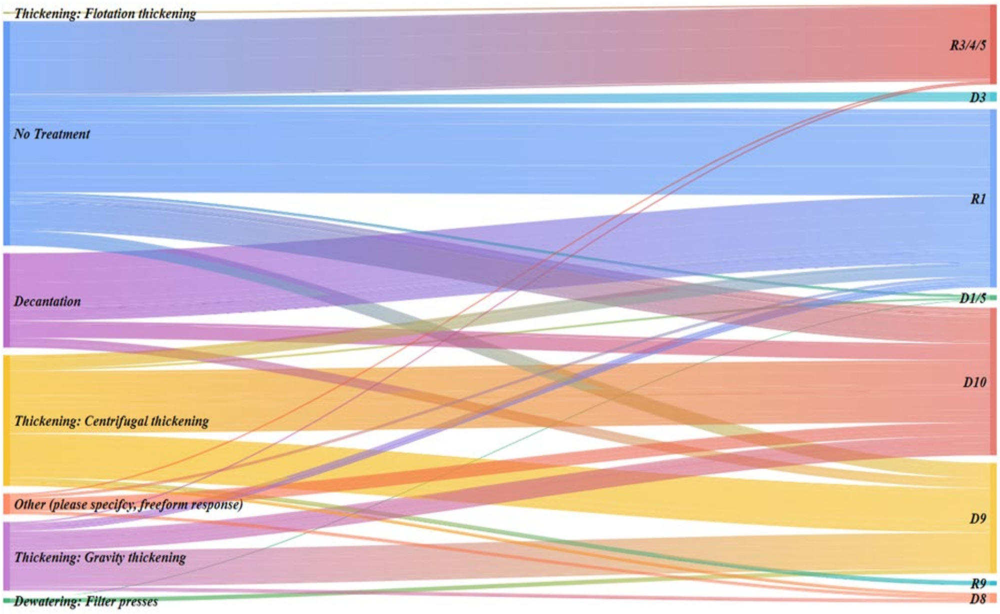
Figure 5 Pre-treatment/Separation Techniques and Management Options of Maintenance Sludges



Finally, **Figure 6** shows the Sankey diagram for tank bottom sludges. Approximately, 41% of tank bottom sludges received no pre-treatment prior to disposal or recovery/recycling. Incineration with energy recovery (R1) was the main management option (37.5%) for tank bottoms with no pre-treatment, followed by recycling (R3/4/5) with approximately 34% and incineration (D10) with approximately 22%. None of the tank bottom sludges that went to recycling (R3/4/5) received any pre-treatment or separation.

Centrifugal thickening constitutes the second largest group per tonnage (approx. 24% of all tank bottoms). Tank bottom sludges treated by this method was primarily sent to incineration (D10) followed closely by physico-chemical treatment (D9). Decantation was the third treatment method employed with some 17% of the tank bottom tonnage. The main management option used for tank bottom sludges pre-treated by decantation was incineration with energy recovery (R1), constituting approximately 61% of the tonnage that underwent decantation.

Figure 6 Pre-Treatment/Separation Techniques and Management Options for Tank Bottom Sludges



The findings of the waste survey report indicate that the selection of management option is dependent on the availability and cost of these management options within the country where the sludges are generated, with the great majority of waste sludges being treated within their country of origin. The separation techniques used, or the lack of any separation or pre-treatment, seem to be a function of the quality of the sludge needing disposal/recovering in terms of water content, solids content and oil composition, the type of available management options in country, and costs related to these management options. This is based on the fact that the same management options accepted the same type of sludge both with prior pre-treatment and without any pre-treatment. In some cases, pre-treatment is carried out by a waste contractor prior to disposal or treatment. While centrifugation thickening was mainly used for tank bottom and wastewater treatment sludges, decantation was the main pre-treatment used for the maintenance sludges.

The waste survey also provided some information as to the solid and liquid phase of oily sludges after separation. 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%).

2.5. INTERVIEWS WITH CONCAWE MEMBER COMPANIES

Concawe Member Companies[9] were interviewed as part of the project to gain additional insights as to the management of refinery oily sludges. To this aim four Member Companies were interviewed in three different country groups. All respondents indicated some pre-treatment for all oily sludges was carried out on site. This is done by decanters, centrifugation, separation ponds and, in one case

[9] https://www.concawe.eu/who-are-we/membership/

increasingly by using Geobags®, as they have sufficient free space in the refinery location to use this technique.

All respondents indicated that water separated from the sludges is typically sent to the WWTP. While oil is typically sent to slop tanks for further reprocessing in the refinery operation when of sufficient quality.

Apart from one company that processes most oily sludges on site (via the use of biopiles), all others send sludge waste to offsite contractors who undertake a variety of management options such as further separation, recovery of oil, and final cake processing/disposal. One company mentioned by two of the respondents uses pyrolysis for further recovery of oil.

When asked about the search for new/emerging, more circular technologies, respondents indicated a lack of knowledge of some of the technologies mentioned and a lack of resources to undertake research projects, relying primarily on waste management contractors. One respondent indicated they were considering solvent extraction for filter cakes produced in a biorefinery[10] and that they were in contact with a contractor who wanted to build a small treatment unit.

Another respondent mentioned the use of the thaw/freeze technique using liquid nitrogen and used by oil sand operations in Canada although the objective was mainly stabilization of tailing ponds. The author did not find examples of full-scale application of this technique in refineries. The sand attrition technique was also mentioned for the separation of oil and water in sludges but had not tested the technology yet. The same respondent also indicated they looked into sending oily sludges to cement works but found several issues with it such as the need of a large and constant supply of waste sludges, something difficult for refineries to comply with. Cement works also have restrictions on some hazardous pollutants.

[10] "Biorefinery is the sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, materials) and bioenergy (biofuels, power and/or heat)" [IEA Bioenergy Task 42 Biorefinery Definition]

3. CURRENT AND EMERGING WASTE SLUDGES MANAGEMENT OPTIONS

3.1. INTRODUCTION

On average, more than 2000 tonnes of the three main hazardous oily sludges types (WWTP sludges, maintenance sludges and tank bottom sludges) were produced each year of the 2019-2021 period (Concawe Report No. 2/23), and this constitutes more than 70% of all sludges produced. The majority of the totality of sludge waste produced (81.5%) was classified as hazardous due the presence of aromatic and aliphatic hydrocarbons, heavy metals and other hazardous substances.

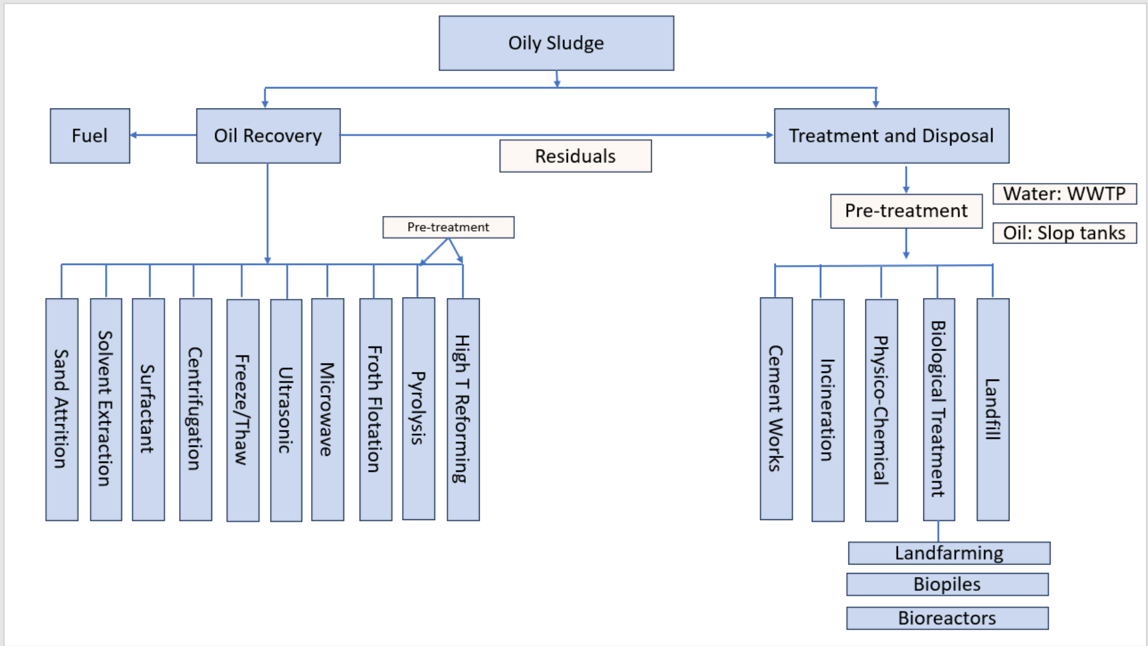
Conventional oily sludge disposal approaches such as incineration and landfilling are associated with adverse environmental and human health impacts and high costs. Incineration requires the use of auxiliary fossil fuels to maintain the desired combustion temperatures generating undesirable fugitive gaseous emissions and hazardous ash residues. Landfilling can release leachate and air emissions to the environment (Hu et al 2019).

Resource efficiency has been on the EU's agenda for more than a decade. The Circular Economy Action Plan forms part of the Commission's strategies on the circular economy (EU Commission Circular Action plan, 2020). It comprises measures to establish the supporting of a regulatory framework and policy orientation, allocate EU funding and monitor the EU's transition to a circular economy. Waste management is part of this agenda and as such, should be improved and transformed into sustainable material management, with a view to protecting, preserving and improving the quality of the environment, protecting human health, ensuring the efficient utilisation of natural resources, and increasing energy efficiency, among other desired outcomes. Furthermore, the waste management hierarchy prioritises the reduction and prevention of waste generation over other management options. This is already recognised in the REF BREF BAT conclusions where in BAT 15 it is indicated that it is BAT to pre-treat and/or reuse the sludge in process units

Within this context, 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. 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 (Hu et al. 2013). 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.

Figure 7 presents some of the technologies that emerged from the literature review. The technologies can be divided into those that focus on the recovery of the oil contained in the oily sludges and more conventional disposal/treatment methods. 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.

Figure 7 Oily Sludge Treatment and Disposal Technologies (adapted from Murungi et al 2022)



For the more novel technologies (such as those shown on the left in **Figure 7**), information found during the literature review was based primarily on results from laboratory and field scale tests, and contained little information on technologies equipment needs, energy consumption, costs and emissions. Opinions regarding whether a technology was an emerging one or was already an established technology also differed greatly among the authors reviewed.

The following sections provide a brief description of the technologies reviewed starting with separation technologies as reported by Member Companies in the 2019-2021 waste survey.

3.2. SEPARATION/PRE-TREATMENT TECHNIQUES

Section 2.4 discussed the amounts of oily sludges that required some pre-treatment, most commonly in the form of thickening or dewatering. Decantation was the preferred separation option for the maintenance sludges in refineries. While centrifugal and gravity thickening were the main separation techniques used for tank bottom sludges. A large portion of waste sludges (between 30 and 40%) received no treatment onsite prior to disposal or recovery offsite.

Oily sludge pre-processing is an essential part of oily sludge management and is typically focused on decreasing oily sludge volume for the purpose of reducing transport and disposal costs when undertaken offsite. For certain treatment processes the removal of water is also required. The pre-treatment techniques reported by Concawe Member Companies in the waste survey act purely to remove water from the sludge to reduce its volume. As a result, the suspended solids concentration of the sludge is increased. These processes are referred to as either thickening or dewatering depending on the amount of water removed.

Thickening and dewatering processes both provide a concentrated, consolidated product, retaining most of the solids from the original sludge, along with a diluted stream which is predominantly water.

Sludge thickening is typically the first step aimed at removing free water and increasing the concentration of solids content, normally to 4 to 15% total solids (TS). In doing so, the finished product retains the liquid, free-flowing characteristics of the feed sludge, so that it can still be conveyed by pumping. Common types of sludge thickening are gravity and centrifugal thickening.

Dewatering removes water from the interstices between sludge particles and can achieve solids concentrations of 18 to 25% TS. This generates a concentrated sludge product, referred to as a cake, which is not free-flowing and instead forms lumps which can only be transported by a conveyor belt, mechanical earth-moving equipment, or spade. Dewatering processes apply a significant mechanical force to achieve increased water removal over that possible from thickening. Common dewatering methods include presses and centrifuges.

Another type of pre-treatment includes thermal drying technologies that can achieve much higher solids concentrations of up to 92% TS. Drying is hardly employed by refineries due to safety risks[11].

The following Sections provide a brief description of the pre-treatment technologies reported by Concawe Member Companies.

3.2.1. Gravity Thickening

Gravity thickeners are one of the easiest and cheaper methods for thickening sludge. They consist of a settling tank that concentrates solids by gravity-induced settling and compaction. They can be used with or without chemical additions. They typically consist of a rectangular or circular tank with a slopped floor and can be operated in a batch or continuous mode. They typically require significant space (in the order of 1000 m^2) and settling times that can range between several hours up to a day (Metcalf & Eddy 2014; Andreoli et al 2007).

3.2.2. Flotation Thickening

Flotation thickening reduces the specific gravity of solids to less than that of water by attaching microscopic air bubbles to suspended solids. The flocculated particles that float to the surface of the tank can be removed by skimming. It can achieve 2%-5% TS. Moderate flocculation polymer dosing is typically required. Flotation thickeners have a large footprint (typically >1000 m^2) and work in continuous mode.

3.2.3. Centrifugation

Centrifuges are one of the most versatile dewatering techniques as their operation can be varied to thicken or dewater sludges to desired levels. They comprise of a high-speed process that separates the solids from the sludge by centrifugal force. They have smaller footprints (<50 m^2) than thickening technologies, but they can have higher energy requirements.

[11] Best Available Techniques (BAT) Reference Document for the Refining of Mineral Oil and Gas, 2015.

3.2.4. Belt Filter Presses

Belt filter presses use a combination of gravity and compression to dewater sludges. In a first stage the sludge is conditioned with polymers and placed on a horizontal belt that allows free water drainage. In a second stage, the sludge is further dewatered by compression between two porous belts and by applying pressure and shear force through rollers. They typically operate in a continuous mode and can achieve solids concentrations of between 15% and 18% TS. Belt presses have a low footprint (<50 m^2), moderate electricity usage and high water usage.

3.2.5. Geotextile Bags (Geobags®)

As mentioned earlier in the report, Geobags® are not regularly used for the dewatering of oily sludges in refineries. One refinery, however, stated that they use Geobags® successfully for the dewatering of oily sludges.

Geobags® are made of high-strength polypropylene fabric. The bags are pumped full with the sludge and the fabric retains fine-grain material while allowing effluent to permeate through the walls of the Geobags®. As water is drained, additional sludge can be added. Dewatering times for oily sludges could not be found but can take a few days to weeks for geotechnical applications, but can be reduced by previous decantation.

The use of Geobags® require a significant footprint (approx. 2000 m^2) and can be labour intensive. However, electricity consumption is limited to pumping.

3.2.6. Discussion

The above technologies are well established and regularly used in the industry. Geobags® are also a well-established dewatering technology in civil engineering works but less so in the dewatering of oily sludges. **Table 2** provides some selected performance criteria for the five technologies discussed.

Table 2 Performance Criteria of Pre-Treatment Technologies

Technology	Gravity Thickening	Flotation Thickening	Centrifugation	Belt Filter Presses	Geobags
Parameter					
Odours	Not contained[1]	Not contained[1]	Contained	Not contained	Contained
Mode (Batch/Continuous)	Both	Continuous	Continuous	Continuous	Batch
Expected Solids (%TS)	2-15	2-5	4-20	15-18	>20
Footprint	Medium-Large	Medium-Large	Low	Low	Large
Capital Cost	Low	Low	Low	Moderate	Moderate
Electricity Usage	0-20 kWh/ton solids	Unknown	>1 KWh/m3 sludge	0.1-0.7 kWh/m3 sludge	Unknown
Labour Requirement	very low	Low	Low	Low	High
Polymer used	None	Moderate	Low	Moderate	Unknown
Water use	Unknown	Unknown	Medium	High	None

1 Technologies can be covered to reduce odours emissions

Footprint : Low (<50 m^2); Medium (50 - 1000 m^2); Large (>1000 m^2)

Other established technologies for thickening not reported by Member Companies include gravity belt thickening, rotary drum and membrane filtration among others. Dewatering technologies include screw press, rotary press, membrane filter press and drying beds. These technologies are regularly used in the pre-treatment of municipal/sewage sludges (Sanitation Technology Platform 2018).

3.3. OIL RECOVERY TECHNOLOGIES

The resource utilisation of oily sludges not only reduces disposal volumes and pollution risks but can also reduce the use of non-renewable resources. Oil recovery from oily sludge can be both an economically and environmentally favourable management option as some oil fractions recovered can be used as fuel supplement (Hochberg et al, 2021). The technologies described here allow the demulsification and oil-water and solid-liquid separation of oily sludges, effectively separating the crude oil, water and solid particles. This section provides a brief description of the technologies included in **Figure 7**. More information on these technologies is included in **Annex A**.

3.3.1. 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. Mechanical agitation is commonly used to aid the extraction process. 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. Different solvents have been tried at different solvent/oily sludge ratios including methyl ethyl ketone (MEK) and liquified petroleum gas condensate (LPGC), which are commonly available at many petroleum refineries. Oil recovery amounts of between 30 and 67% have been reported in the literature. Up to 93% of the solvent can be recovered and reused.

3.3.2. Surfactant Enhanced Recovery

The use of surfactants for the recovery of oil from oily sludges, 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 oil recovery. The use of biosurfactants has increased in recent years, due to their generally good surface activity, low biological toxicity, good demulsification performance, and strong selectivity. Compared to other oil recovery methods, the process is simpler, does not require large and complex machinery and equipment, and is characterized by a large treatment capacity and high efficiency. Recoveries of just over 90% have been reported with the use of a biosurfactant such as rhamnose tallow (Hui et al 2020).

3.3.3. Microwave Irradiation

This technique uses a type of 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.

While in conventional thermal heating, heat is transferred to the material through convection, conduction, and radiation, microwave energy is reached directly to the materials through molecular interaction with the electromagnetic field so that heat energy can be generated throughout the volume of the material, therefore achieving rapid and uniform heating across the material. Oil recoveries of 75% have been reported (Johnson et al 2019).

3.3.4. 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. Under the continuous irradiation of ultrasonic waves, the viscosity of oil-water emulsions decreases continuously. The small droplets in the emulsion mixture accelerate, collide, and coalesce, ultimately achieving the purpose of separating the aqueous phase and the oil phase to recover the oil. 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 of oil to 82–90%. The method has been tested at pilot scale with reports of field tests in upstream oil operations (Hui et al 2020). No reported use /test in refineries was found.

3.3.5. 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 (Rima et al 2021).

3.3.6. 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[12], often with the help of surfactants. Then air is injected to generate bubbles in the slurry. As the bubbles move to the surface of the slurry, they collide with oil droplets which spread and remain attached to the surface of the bubble film. After a time, the oil droplets floating on the surface of the slurry can be scrapped off, collected and further purified. Laboratory studies have shown oil recoveries of between 55 and 70% (Hui et 2020 and Johnson et al 2019).

3.3.7. Pyrolysis

Pyrolysis refers to the thermal decomposition of organic materials at high temperatures (400-600°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 anaerobic environment. 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.

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. Major gaseous products include H_2, CO_2, CO, water and approximately 25 wt% of non-condensable hydrocarbons such as methane, ethane,

[12] Liquid slurries have typically less than 50% solids while sludges have >50% solids.

and hydrogen sulfide, as well as other gaseous pollutants that may also be present dependent on the sludge feed composition. 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.

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.

3.3.8. 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. Up to 98% oil recovery efficiency was stated by a contractor.

3.3.9. 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. Gases include H_2S and potential other pollutants that needs to be purified. This technology is more commonly deployed in the US than in Europe and has a small footprint which makes it suitable for a variety of industrial and field settings.

3.4. DISPOSAL/TREATMENT OPTIONS

Various technologies exist for the disposal or treatment of refinery waste sludges. The choice of technology is very much dependent on available options nearby, disposal/treatment costs and regulations. Many of these are proven technologies widely used by the industry. The most commonly disposal routes include incineration with or without energy recovery, landfilling, recycling/reclamation and physico-chemical treatment. While the use of sludge waste in cement works is not common across the EU, it can be important in some jurisdictions (Greece for example).

3.4.1. Incineration and Incineration with Energy Recovery

Incineration is the process of complete combustion of oily sludge in a controlled environment with excess air and auxiliary fuels (Hu et al 2019). 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 require proper management. Incinerators with energy recovery incorporate basic mechanisms to recover heat and energy and more sophisticated mechanisms to clean flue gas (UNEP 2020). Incineration with energy recovery offers the added benefit of using waste as a resource to produce energy.

3.4.2. Co-processing in Cement Works

The fabrication of cement comprises the calcination and fusion of materials comprising calcareous 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 CO_2 emissions, reduce production costs, and destroy hazardous wastes.

3.4.3. 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 (in the order of months to years).

3.4.4. 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.

3.4.5. Anaerobic Digestion

Anaerobic digestion is a proven technology applied to municipal sludges that has the potential to produce biogas (principally methane) from biomass using microorganisms in an anaerobic 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. Residual by-products of anaerobic co-digestion are compounds of nitrogen and phosphorous that can be added to soil as fertilizers.

3.4.6. 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 (i.e., stabilization), and encapsulating them by the creation of a durable matrix with high structural integrity (i.e., solidification) (Hu et al 2013). The use of this disposal method for inorganic wastes has been widely reported, however, it is considered less compatible with organic wastes.

Oxidation treatment degrades organic contaminants in oily sludges through chemical or other oxidation processes. 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 (Badrul Islam, 2015). The oxidation can be carried out by Fenton's reagent, hypochlorite, ozone, permanganate and persulphate, that generate a sufficient amount of free radicals such as hydroxyl radicals (OH*), which can quickly react with most organic and many inorganic compounds.

3.5. SELECTION OF CURRENT AND EMERGING TECHNOLOGIES FOR SUSTAINABILITY ASSESSMENT

For some of the most novel technologies information is scant and while many references were found, many relay on the same source(s), therefore providing little new insights into the technology. Most research papers were based on laboratory/small field scale tests, and consequently, there was little, and in some cases, insufficient information on technologies equipment needs, energy consumption, costs and emissions.

To facilitate the selection of technologies that would be carried on to the sustainability assessment, **Tables 3** and **4** provide a summary of advantages and disadvantages for each technology reviewed, some additional relevant information and whether the technology can be considered current or emergent in the petroleum refinery context. Selection of a technology for further assessment was primarily based on evidence of performance at a refinery scale and on whether it is likely to be successful given simplicity or extrapolation from pilot scale tests. However, no cross-media effects nor applicability restrictions[13] were not considered given the lack of sufficient information. For several novel oil recovery technologies information was not sufficient to indicate their likely use at the refinery scale in the near future and were therefore not selected.

[13] Limitations or conditions that specify the circumstances under which a process or system can be used

Table 3 Selection of Oil Recovery Technologies

	Advantages	Disadvantages	Other Comments	Innovative/Current (in a refinery context)	Take to Technoeconomic Evaluation?
Oil Recovery Technologies					
Solvent Extraction	Low energy requirements ,simple process, fast, requires simple equipment, solvent can be recovered	Cost of solvents, large quantities of solvent needed, variability in eficiency depending on type of sludge and solvent used. Environmental and health/safety concerns.	MEK is widely available in refineries. Proven technology in other industries. None of the refineries interviewed are using the technology	Innovative/Current (in a refinery context)	Possibly
Centrifugation	Established Technology. High yield.	High energy consumption. Noise can be a concern. Better efficiency with use of surfactants, solvents or temperature	Refineries used various thickening and dewatering techniques	Current	Possibly
Surfactant Enhanced oil recovery	Simple. Efficient. Large Handling capacity	High cost. Some surfactants can be toxic and resisitant to biodegradation.Limited treatment of heavey metals.	Surfactant are already used in some refineries to enhance other separation techniques	Innovative	Yes
Freeze/thaw treatment	Suitable for cold regions	High energy consumption. High cost. Uncertain efficiency.	No knowledge of applicability to refineries	Innovative	No
Pyrolysis	Efficient. High quality oil recovered. Large handling capacity. Low emissions of NOx and SOx	Energy intensive. Not suitable for sludges with high water conent. If dewatering required this can increase treatment costs	Well established technology for treatment of plastic, plant material and tyres, less so for oily sludges although some waste management companies in Europe have pyrolisis plants in their waste manageent facilities.	Innovative	Yes
Microwave irradiation	Fast and efficient. No environmental pollution	Energy intensive. Possible high operating costs	Not known application at industrial scale in refineries.	Innovative	Possibly in combination with pyrolysis
Ultrasonic irradiation	Fast, efficient. No environmental pollution.	High cost	Not known application at industrial scale in refineries.	Innovative	No (similar to Microwave)
Froth Flotation	Simple and low energy	Low efficiency, high water consumption. Not suitable for high density sludge	Laboratory scale testing	Innovative	No (similar to surfactant method)
High Temperature Reforming	Destruction of PAHs.	Hi energy consumption	Little information found on this method	Innovative	No

Table 4 Selection of Disposal Technologies

	Advantages	Disadvantages	Other Comments	Innovative/Current (in a refinery context)	Take to Technoeconomic Evaluation?
Sludge Treatment/disposal options					
Incineration (with energy recovery)	Fast and efficient. Oily sludge can be a source of energy. Steam generation can be used in turbines. Waste volume is removed. Complete removal of PAHs.	Sludge dewatering required. Additional fuel required. Need to managed residual ash/sludge. High capital and operaitng cost. Environmental pollution	Incineration and Incineration with energy recovery are the most used management options for hazardous oily sludges in Europe (app. 60%)	Current	Yes
Co-processing into cement works	Complete destruction. Provides fuel to the cement works	Requires constant and large volumes of sludges to be provided. Restrictions on some hazardous pollutants. Additional fuel needed. Significant pollutant emissions load.	One respondent stated interest in option but many disadvantages. Potential to recover energy.	Innovative	Possibly
Landfill			1.2 % of hazardous sludges are disposed in landfills. Disposal of hazardous waste discouraged in Europe.	Current	Yes for comparison purposes?
Landfarming	Low cost. Support large scale treatment. Low resources needed.	Slow process requiring large areas. Poses environmental concerns of soil and groundwater contamination	Stringing regulations to avoid pollution. Generally applicable for non-hazardous sludges and liquids. Insignificant volumes disposed in this way by EU refineries.	Current	No
Biopiles	Large capacity, faster treatment than land treatment. Destruciton of pollutants. Potentially lower costs than other disposal options even when considering capital costs.	Requires large area for treatment.	Not widely used due to lack of space. One refinery interviewed are treating all their sludges (including tank bottoms) in this way.	Commonly used for contaminated soils. Not common for oily sludges	yes
Stabilization/Immobilisation/Solidification	Low sofistication, basic equipment.	Only for sludges with low water content. End product needs management/disposal. Less compatable for organic substances. Added materials need to ensure no leachate occurs.	Well tested technique for metals in soils/waste. Less so for organic substances. No field scale use of this technique for oily sludges found in the literature. Mainly laboratory scale information	Innovative	No
Oxidation	Fast and efficient	High cost. Environmental pollution	Well tested technique for comtaminated soils. No large scale field information for oily sludges	Innovative	No
Anaerobic Co-digestion	Other wastes can be used as feeds. May not require other fuels to maintain reaction.	Long residence times. Biogas may require further treatment to use for energy recovery	Well known for the treatment of municipal wastwwater treatment sludges. No knowledge of large scale use in refineries.	Innovative	Possible

The assessment of technologies in **Tables 3** and **4** allows the selection of a reduced number of technologies to take to the sustainability assessment. It allows the comparison of well-known and currently used technologies by refineries with less tested innovative ones. While cement works is treated as a current technology, its use for the treatment of oily sludges is not widespread across Europe, but it is used for refinery sludges in some locations. Similarly, some waste management companies do make use of pyrolysis for the treatment of oily sludges to treat the solid fraction of sludges after pre-treatment and dewatering. Based on the observations included in **Tables 3** and **4**, the technologies selected for further assessment include innovative technologies Pyrolysis, Solvent Extraction and Biopiles and the current technologies Co-processing in Cement Works, Landfill and Incineration. The innovative technologies selected are already being applied or have the most potential to being applied at commercial scale in the near future. Alternatively, emerging technologies excluded have been tested primarily at laboratory or pilot scale and therefore full-scale operational data is less available.

4. SUSTAINABILITY ASSESSMENT OF SELECTED TECHNOLOGIES

4.1. INTRODUCTION

The aim of the project is to assess overall environmental, and more broadly, sustainability performance of emerging technologies and to compare these with conventional oily sludges treatment approaches. As per the scope of the project, a Life Cycle Analysis (LCA) approach was not considered given the significant amount of quantitative data required for this type of analysis, which is difficult to obtain from a literature review. Instead, a qualitative/semi-quantitative multicriteria analysis was chosen to undertake the assessment, that is tailored to data availability and the objectives of the project and was broadly aligned with ISO 18504 (on sustainable contaminated soil remediation). 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.

4.2. ASSESSMENT PROCESS

Several environmental impact, safety/human health and sustainability indicators were used to assess the selected technologies based on their impacts to the environment via their emissions to air, water and soil, their impacts to people via emissions and nuisance issues, their energy and resource efficiency, their position in the waste hierarchy and their cost.

Environmental, and some of the social indicators were selected from the EU Reference Document on Economics and Cross-Media Effects (ECME June 2006) and complemented with indicators from US EPA’s Tool for the Reduction and Assessment of Chemical and other environmental Impacts, EPA 2012. 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. Collating the pollutants into themes allows different pollutants to be compared with each other. For each theme, the effect may be only or primarily in one medium, or there may be effects in more than one medium such as air or water.

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, commercial availability and operational costs.

The depletion of earth's resources is a common indicator used in environmental/ LCA assessments. Although resources depletion remains an important issue, it is difficult to identify from the literature review and is unlikely to represent as much impact against the other indicators selected. As a result, and following the ECME Document, this parameter was not included in the assessment.

Table 5 provides the full list of indicators and the rational on the assigned weighting.

Table 5 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	PM2.5, 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, O3	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).

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.

4.3. DESCRIPTION OF SELECTED MANAGEMENT OPTIONS PROCESSES

While the assessment approach does not follow a LCA method, it is still a useful tool to identify system boundaries of the management options and to provide a better understanding of which parts of the selected 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.

Data used in the assessment comes primarily from the literature review and Concawe Member Companies interviews (primarily costs). Especially useful for the assessment was a published LCA study (Hu et al 2019) on some of the options selected, where actual emissions for each part of the process were quantified.

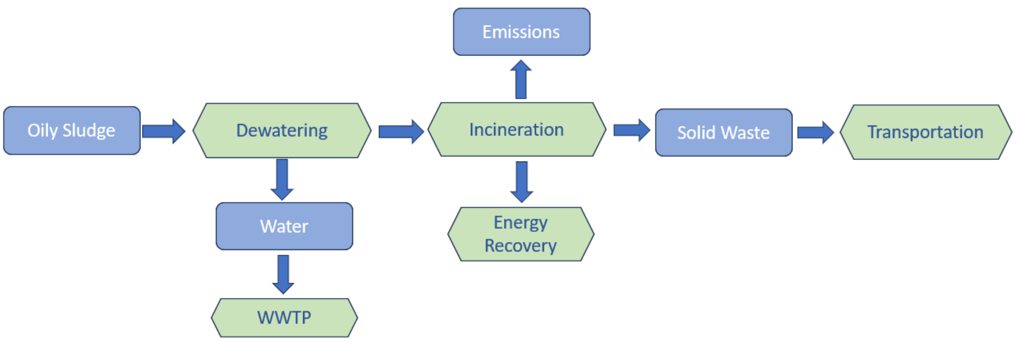
The current or conventional management options selected were incineration (with energy recovery), landfilling and co-processing of waste in cement works. The emerging options selected were solvent recovery, pyrolysis and biodegradation using biopiles. Although the use of waste in cement works is commonly used for the treatment of hazardous waste in some jurisdictions, it is less used/known in others. Incorporation of cement works in this assessment can bring more attention to this option.

4.3.1. Incineration

Incineration is the complete combustion of oily sludge in a controlled environment with excess air and use of auxiliary fuels. **Figure 8** shows a schematic flow chart of the incineration option. Fluidized bed incinerators are commonly used due to lower emissions and high combustion efficiency compared to rotary kiln incinerators. A reduction of the water content in the sludge is typically required prior to incineration.

The energy recovery process involves converting heat energy produced during incineration into electricity. This reduces the amount of electricity/energy required for incineration. After incineration, about 10 wt% of the original oily sludge remain as ash residuals which is typically disposed of in a landfill. Air emissions treatment units control toxic emissions while the process emits large quantities of greenhouse gases (CO_2).

Figure 8 Flowchart of Oily Sludge Incineration with Energy Recovery

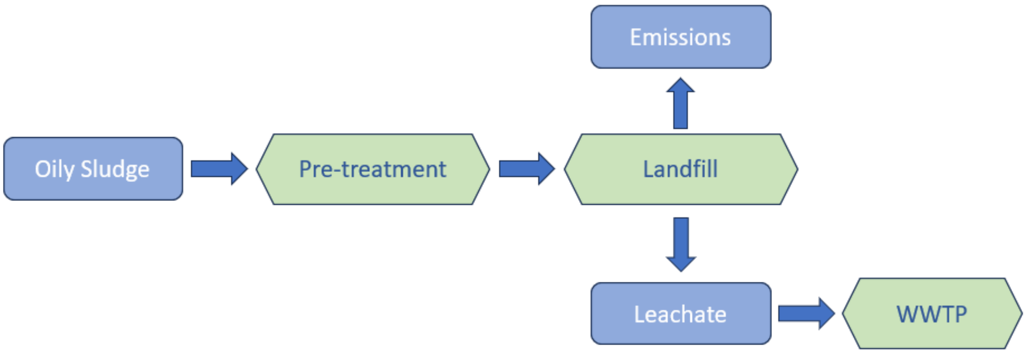


4.3.2. Landfill

Oily sludges sent to landfill typically undergo water reduction to reduce the volume and weight of sludge. The Concawe Waste survey showed that most of the oily sludges sent to landfill underwent thickening or dewatering onsite. 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 (Hu et al, 2019).

The landfill option 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.

Figure 9 Flowchart of Oily Sludge Landfilling

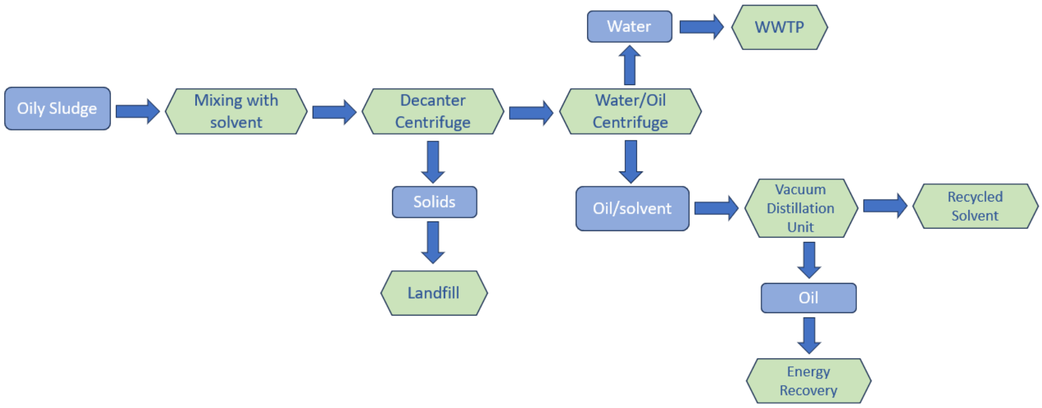


4.3.3. Solvent Extraction

In this option, oily sludges do not require pre-treatment. The oily sludge is mixed with the solvent in a vessel and 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. 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. Some studies (Hu et al, 2019) 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. Combustion in turn emits gases and particles that can impact human health and the environment.

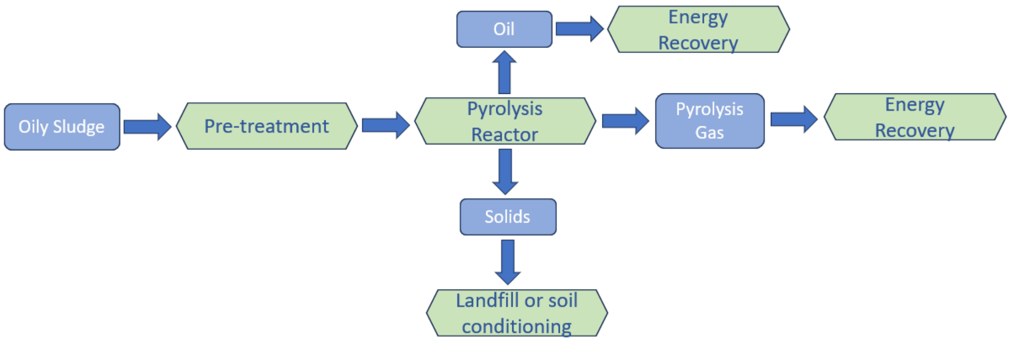
Figure 10 Flowchart of Solvent Extraction Method



4.3.4. Pyrolysis

The pyrolysis process starts with reducing the amount of water in the sludge to about 10%. 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. The combustion of py-oil and py-gas produce emissions that can impact human health and the environment. Pyrolysis scored low with regards to CO2 emissions and lower than other techniques when NOx and SOx emissions are considered. Approximately 40% of py-gas and just over 30% of py-oil in weight can be produced from the dried oily sludge (Hu et al. 2017).

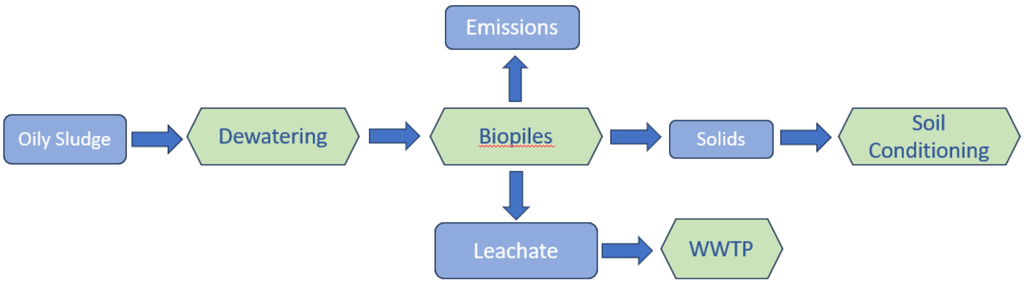
Figure 11 Flowchart of Pyrolysis Method



4.3.5. 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 Member Company. 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 WWTP. Oil recovery is generally low. It was reported that approximately 10 tons of oil is recovered from 9000 tons of sludge. Treatment time ranges between 9 and 12 weeks depending on the degree of oil content. The remediated sludge (soil) is used for landscaping, seeded and restored with low plants/flower that attract pollinators.

Figure 12 Flowchart of Biopiles Method



4.3.6. Cement Works (Cement Kilns)

The co-processing of hazardous waste in cement kilns (**Figure 13**) allows the recovery of energy and mineral value from waste while cement is being produced. 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.

Since the overall moisture content of the waste may affect productivity, efficiency and also increase energy consumption, the water content of 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.

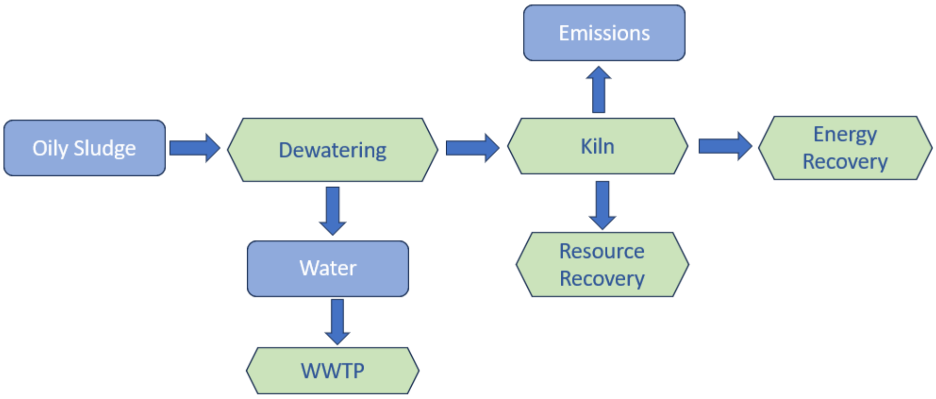
Liquid waste fuels are normally prepared by blending different products with suitable calorific values and chemistry, such as spent solvents or used oil. Liquid wastes are typically injected into the hot end of the kiln. Solid wastes used as alternative raw materials are typically fed into the kiln system via the normal raw meal supply, the same as conventional raw materials.

Whether or not wastes are being used in a cement plant, dust (particulate matter), NOx and SO_2 emissions cause the greatest concern and needs to be treated. Other emissions to be considered are VOC, PCBs, PCDDs, PCDFs, HCl, CO, CO_2, HF, ammonia (NH_3), BTEX, PAH, heavy metals and their compounds (EIPPCB, 2010). Under some circumstances, emissions may also include chlorobenzenes and PCBs (SBC, 2007).

In general, wastewater discharges from cement works are usually limited to surface run-off and cooling water only and cause no substantial contribution to water pollution (EIPPCB, 2010). Nevertheless, in the European Union the use of wet scrubbers is a Best Available Technique (BAT) to reduce the emissions of SOx from the flue-gases of kiln firing and/or preheating/pre-calcining processes (EIPPCB, 2010). In this context, for cement kilns co-processing hazardous and other wastes in the European Union, the requirements of Directive 40 2000/76/EC for the discharge of wastewater from the cleaning for exhaust gases apply, so as to limit the transfer of pollutants from the air into water.

Residues from combustion in the kiln are incorporated into the cement and therefore there is minimum production of solid residues.

Figure 13 Flowchart of Cement Works Method

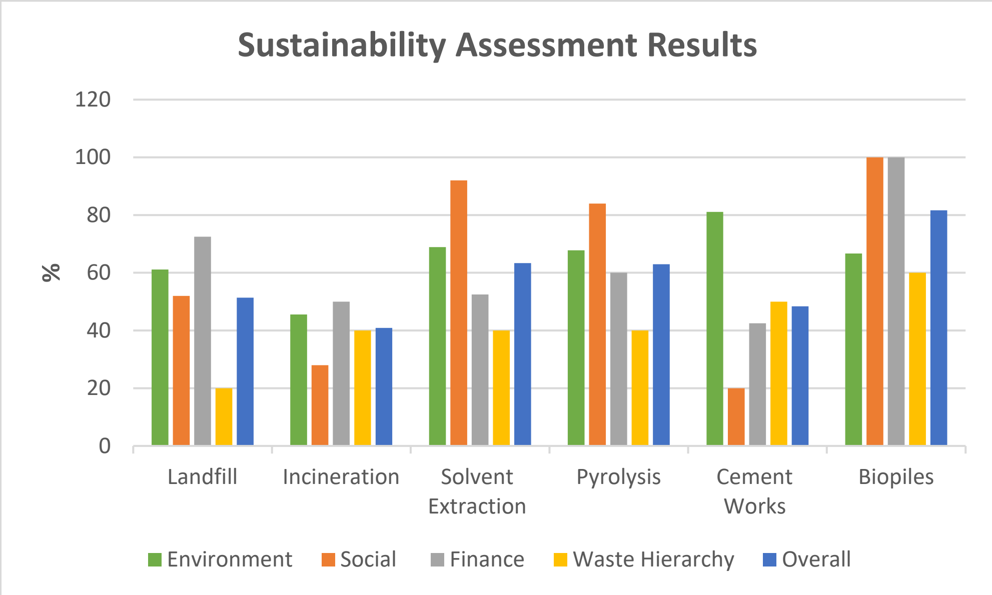


4.4. ASSESSMENT RESULTS

Following the weighting process described in Section 4.2, each assessment criteria was scored. The scores were applied on a relative basis, with reference to the relevant indicators in **Table 5**. 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. Further explanation of the calculation methodology is included in Annex B.

The results of the assessment are shown in **Figure 14**. 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 conventional options such as landfilling, cement works and incineration with energy recovery. 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. Therefore, a conclusion can only be drawn once their, cross-media effects and performance at operational scale are determined.

Figure 14 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. Input data into the assessment can be found in Annex C.

4.4.1. 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 CO_2 eq. per ton of sludge (Tsiligiannis et al 2020 for landfarming), while incineration is the least favourable option with 1000 to 2000 kg/ton of CO_2 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, heavy metals, PCBs and other substances. 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, based on Hu et al 2020, pyrolysis and solvent extraction amounted to only 5% of the impact represented by incineration and landfill.

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 WWTP 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.

4.4.2. 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 evaluated in the assessment. It is recognised, that their omission may result in a somewhat more favourable assessment outcome for those oil recovery techniques evaluated in the assessment such as solvent recovery and pyrolysis.

4.4.3. Financial Pillar

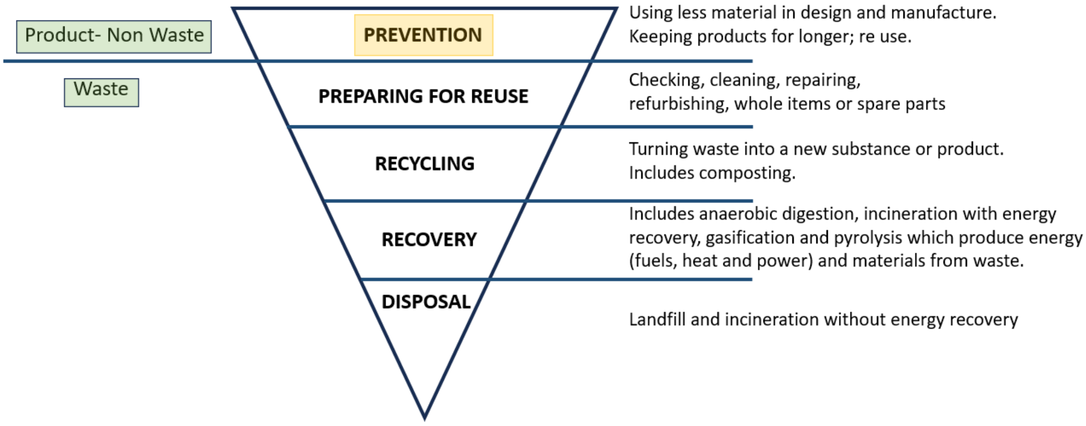
Gate costs for disposal or treatment of hazardous waste are difficult to obtain from waste management contractors without actual analysis of the waste to be received. Consequently, costs (in €/ton of waste) for some of the options assessed in this assessment were obtained from interviews with Concawe 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 an apparent lesser widespread availability.

4.4.4. Circularity Efficiency Pillar

The Waste Framework Directive (2008/98/EC) sets out a waste hierarchy, or priority order of what constitutes the best overall environmental option in waste legislation and policy. This hierarchy is illustrated in **Figure 15** below.

Figure 15 The Waste Hierarchy (adapted from Defra Government Review of Waste Policy in England. 2011).



For the purpose of the assessment, each Waste Hierarchy in **Figure 16** 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 (ref. Cement Sustainability Initiative, CSI). Accordingly, the cement works option was assigned a score of 2.5.

4.4.5. General Discussion

This section provides further information and insights in terms of the processes that make up each management option, and the major differences observed between the scoring of the options. It is important to note that the overall score 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. It should be noted that biopiles require a large area for treatment and thus sufficient available space is required for this option. 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.

The sustainability assessment undertaken provides a rapid method to compare potential environmental and social impacts of different technologies together with their cost and degree of circularity. Where quantification of emissions is available, the EU Reference Document on Economics and Cross Media Effects, 2006, provides a simple methodology to quantify their impacts. However, the assessment does not consider other cross-media or operational considerations. 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.

4.4.6. Pre-Treatment and Management Options

Section 3.2 included a general description and operational information (**Table 2**) of the main pre-treatment options reported by Concawe Member companies. They include both thickening and dewatering processes. Their selection appears to be dictated primarily by operational cost, degree of dewatering required by waste management contractors and amount of flocculant polymers required.

As discussed previously, a large portion of oily sludges are pre-treated onsite to reduce the volume (and cost) of sludges sent to treatment or disposal. Similarly, large volumes of refinery sludges are not pre-treated onsite, and it is assumed that, where required, these are pre-treated by the waste management contractor.

Adding pre-treatment options to the circularity and sustainability assessment of the management options was not considered useful in this case, given their selection depend on many site-specific factors. Also, such assessment would have necessitated the comparison of many possible configurations reducing the focus on the management options selected. **Table 2** provided some information that can be used to aid in the selection of the most favourable pre-treatment options according to site-specific criteria, which may differ widely from one refinery to the next.

For example, if space is available, the use of settling lagoons can be a low cost and low energy option, as is the use of Geobags®. In cases of lower footprint availability and higher dewatering rates, filter presses may be more appropriate.

4.5. PREVENTION/ MINIMISATION OF OILY SLUDGES

As mentioned earlier, the waste management hierarchy prioritises the reduction and prevention of waste generation over other management options. This is already recognised in the REF BREF BAT conclusions where in BAT 15 it is indicated that it is BAT to pre-treat and/or reuse the sludge in process units.

Moreover, oil retained in sludges or other types of waste represents a loss of product and, where possible, efforts should be made to recover the oil. Waste disposal depends very much on its composition and on the local refinery situation. Because of the high costs of waste disposal, priority should be given to waste minimisation processes.

As mentioned in BAT 15 of REF BAT Conclusions, one way to reduce oily sludges generation is to process oily sludges in a coker, if the refinery has one, where they become part of the refinery products. Oily sludges can affect coke quality and a balance must be achieved between the amount of sludge waste sent to the coker and the coke quality (Best Available Techniques (BAT) Reference Document for the Refining of Mineral Oil and Gas, 2015). Water content reduction is typically required such as for sludges from wastewater treatment processes. Refineries with a coker are able to greatly reduce its oily sludge production.

Another way to reduce the generation of oily sludges is to maximise the amount of solids that are removed from the desalter unit, since solids entering the crude distillation unit are eventually likely to attract more oil and produce additional emulsions and sludges. This can be achieved in a number of ways including use of low-pressure water in the desalter to avoid turbulence, the use of mud rakes again to reduce turbulence when removing settled solids, use of combined hydrocyclone desalter with hydrocyclone de-oiler and incorporation of a sludge wash system.

Preventing solids entering the refinery sewer system is another way to reduce the formation of oily sludges. This is because particles entering the sewer system become coated with oil and are deposited as oily sludges in the API oil/water separator. It has been estimated (Best Available Techniques (BAT) Reference Document for the Refining of Mineral Oil and Gas, 2015) that preventing 1 kg of solids from entering the sewer system can eliminate 3 to 20 kg of oily sludges (for a typical oily sludge solids content of between 5 and 30% TS).

Segregation of the relatively clean rainwater run-off from the process streams is another way to reduce oily sludge generation. This is because a large amount of oily sludges are generated in combined process/stormwater sewers.

BAT number 15 of the Best Available Techniques (BAT) Reference Document for the Refining of Mineral Oil and Gas, 2015 specifies techniques to reduce the amount of oily sludges in refinery operations by the pre-treatment of sludges including dewatering and de-oiling, and their reuse in process units such as the processing of oily sludge in the coking unit as described earlier.

BAT number 14 of the Best Available Techniques (BAT) Reference Document for Common Wastewater and Waste Gas Treatment/Management Systems in the Chemical Sector, 2016 also specifies the need to reduce the volume of wastewater sludge requiring treatment or disposal by a range of techniques including conditioning, thickening/dewatering, stabilisation and drying.

5. REGULATORY REVIEW

Several European Directives are relevant to waste management activities. **The Waste Framework Directive** (Directive 2018/851 of the European Parliament and the Council on amending Directive 2008/98/EC on waste), sets out the basic concepts and definitions related to waste management, such as definitions of waste or recycling. It introduces the waste hierarchy, the Polluter Pays principle and the Extended Producer Responsibility. It lays down measures to protect the environment and human health by preventing or reducing the generation of waste and the adverse impacts of the generation and management of waste. Such measures are important for the transition to a circular economy.

The Directive describes the waste hierarchy that should be applied as a priority order in waste prevention and management and encourages the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by life cycle thinking on the overall impacts of the generation and management of such waste.

The Directive also requires establishments or undertakings intending to carry out waste treatment to obtain a permit from the competent authority. On permitting waste treatment activities Member States shall take the necessary measures to ensure that waste management is carried out without endangering human health and without harming the environment, in particular:

(a) without risk to water, air, soil, plants or animals;

(b) without causing a nuisance through noise or odours; and

(c) without adversely affecting the countryside or places of special interest.

Finally, the Directive requires that permits covering incineration or co- incineration with energy recovery should have as a condition that the recovery of energy takes place with a high level of energy efficiency.

The **Industrial Emissions Directive (Directive 2010/75/EU,** amended in 2024) is the main EU instrument regulating pollutant emissions from industrial installations and livestock farms in an integrated manner, on a sector-by-sector basis through Best Available Techniques Reference document (BREF), to prevent and control the environmental impact of their activities. All industrial installations, undertaking industrial activities listed in Annex I of the Directive are required to operate in accordance with a permit granted by the Member States. Included in Annex I are industrial activities such as oil refining and several waste management activities such as biological treatment; physico-chemical treatment; recycling/reclamation of inorganic materials, oil re-refining; disposal or recovery of waste in waste incineration plants or in waste co-incineration plants, landfills, temporary storage of hazardous waste, pre-treatment of waste for incineration or co-incineration and treatment of slags and ashes.

The Directive's **integrated approach** means that permits must take the whole environmental performance of the plant into account. This covers emissions to air, water and land, generation of waste, use of raw materials, energy efficiency, noise, prevention of accidents, and restoration of the site upon closure.

Permit conditions including emission limit values must be based on the **Best Available Techniques (BAT)** as defined in BAT Reference Documents (BREFs). The BATs conclusions contained in the BREFs are adopted by the Commission as

Implementing Decisions. The IED requires that these BAT conclusions are the reference for setting permit conditions. For certain activities, such as large combustion plants, waste incineration and co-incineration plants and solvent using activities, the IED also sets EU wide emission limit values for selected pollutants. The revised (2024) IED, also indicates that the lowest end of BAT-AEL should be the reference point for permit conditions when BAT is applied.

The IED allows competent authorities some flexibility to set less strict emission limit values. This is possible only in specific cases where an assessment shows that achieving the emission levels associated with BAT described in the BAT conclusions would lead to disproportionately higher costs compared to the environmental benefits due to the geographical location or the local environmental conditions or the technical characteristics of the installation. Through the European Pollutant Release and Transfer Register (E-PRTR), emission data reported by Member States are made accessible in a public register. This provides environmental information on major industrial activities.

In 2022, the Commission adopted proposals to revise the IED and the E-PRTR. The proposals aim to improve the Directive by increasing the focus on energy, water and material efficiency and reuse, in addition to promoting the use of safer, less toxic or non-toxic chemicals in industrial processes.

CHAPTER IV of the Directive (Special Provisions for Waste Incineration Plants and Waste Co-Incineration Plants) applies to plants that incinerate or co-incinerate solid or liquid waste. It does not apply to gasification or pyrolysis plants, if the gases resulting from this thermal treatment of waste are purified to such an extent that they are no longer a waste prior to their incineration and they can cause emissions no higher than those resulting from the burning of natural gas. If waste co-incineration takes place in such a way that the main purpose of the plant is not the generation of energy or production of material products but rather the thermal treatment of waste, the plant is regarded as a waste incineration plant.

The Directive provides emission limits for incineration and co-incineration plants. Also, waste incineration plants shall be operated in such a way as to achieve a level of incineration such that the total organic carbon content of slag and bottom ashes is less than 3% of the dry weight of the material and if necessary, requires the use of pre-treatment techniques. Finally, if hazardous waste with a content of more than 1% of halogenated organic substances, expressed as chlorine, is incinerated or co-incinerated, the temperature required to comply shall be at least 1 100°C.

The above requirements are also included in **Directive 2000/76/EC of December 2000 on the incineration of waste.** The installation's permit shall establish emission limit values for the polluting substances referred to in Annex IV of the Directive, and monitoring should include continuous measurements of NOx, CO, total dust, TOC, HCl, HF and SO_2 and also measurements for heavy metals and dioxins and furans.

The Industrial Emissions Directive also requires operators of permitted activities to ensure that waste treatment installations do not deteriorate the quality of soil and groundwater and for this a baseline report is required. Such baseline report should allow a comparison between the state of the site before activities commenced and after definitive cessation of activities at the site. Permit conditions should, therefore, include appropriate measures to prevent emissions to soil and groundwater and regular surveillance of those measures to avoid leaks, spills, incidents or accidents occurring during the use of equipment and during storage of waste.

It is important to note that the definition of pollution included in the Directive includes not only the emission of chemical substances to the environment but also the emissions of vibrations, heat or noise into air, water or land which may be harmful to human health or the quality of the environment, result in damage to material property, or impair or interfere with amenities and other legitimate uses of the environment.

European Council Directive 1999/31/EC on the landfill of waste aims to ensure a progressive reduction of landfilling of waste, in particular of waste that is suitable for recycling or other recovery, and, by way of stringent operational and technical requirements on the waste and landfills, to provide for measures, procedures and guidance to prevent or reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment, including the greenhouse effect, as well as any resulting risk to human health, from landfilling of waste, during the whole life-cycle of the landfill. The Directive requires Member States to set up a national strategy for the implementation of the reduction of biodegradable waste going to landfills, that should include measures to achieve the targets regarding recycling, composting, biogas production or materials/energy recovery. Today, the disposal of hazardous oily sludges in landfills is severely restricted.

The **Ambient Air Quality Directive** (**2008/50/EC)** defines and establishes objectives for ambient air quality designed to avoid, prevent or reduce harmful effects on human health and the environment as a whole. The Directive also has the objective of assessing the ambient air quality in Member States on the basis of common methods and criteria; obtaining information on ambient air quality in order to help combat air pollution and nuisance; and to monitor long-term trends and improvements resulting from national and Community measures. Ultimately, the Directive seeks to maintain air quality where it is good, and improve it where is not. The focus of the Directive is on ambient concentrations of sulphur dioxide, nitrogen dioxide or, where relevant, oxides of nitrogen, particulate matter (PM_{10}, $PM_{2.5}$), lead, benzene and carbon monoxide. The Directive provides target levels and alert levels for these substances that Member States need to comply with. Where, in given areas, the levels of pollutants in ambient air exceed any limit value or target value, Member States shall ensure that air quality plans are established for those areas in order to achieve target values.

At international level, the Gothenburg Protocol, and amendments to it, sets emissions ceilings levels for various pollutants. Its aim is to control long-range transboundary pollution. It is implemented at EU level through several directives, including the National Emission Ceilings (NEC) Directive (2016/2284/EU) that replaces earlier legislation (Directive 2001/81/EC), and whose aim is to set emission reduction commitments for air pollutants.

The World Health Organization (WHO) published updated Global Air Quality Guidelines in September 2021 covering Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulphur dioxide and carbon monoxide. They provide guidance on thresholds and limits for key air pollutants that pose health risks. They are guidelines only and are not binding on any country unless that country chooses to adopt them into its own legislation. These guidelines are an update on the previous 2005 version, which have been frequently referenced in debates about air quality targets.

The Basel Convention on the control of transboundary movements of hazardous wastes and their disposal is an international treaty that aims to reduce the movements of hazardous waste between nations. The overarching objective of the Basel Convention is to protect human health and the environment against the adverse effects of hazardous wastes. Its scope of application covers a wide range of wastes defined as “hazardous wastes” based on their origin and/or composition and their characteristics. The provisions of the Convention centre around the following of principal aims such as:

- the reduction of hazardous waste generation and the promotion of environmentally sound management of hazardous wastes, wherever the place of disposal;
- the restriction of transboundary movements of hazardous wastes except where it is perceived to be in accordance with the principles of environmentally sound management; and
- a regulatory system applying to cases where transboundary movements are permissible.

Before an export of hazardous waste may take place, the authorities of the State of export notify the authorities of the prospective States of import and transit, providing them with detailed information on the intended movement. The movement may only proceed if and when all States concerned have given their written consent.

5.1. DISCUSSION

As reported by the Concawe Member Companies, most waste treatment options are carried out offsite, by waste management contractors, which provide single treatment options or a combination of treatment options including pre-treatment (dewatering for example) as required, based on the quality of the sludge and the management options available. Therefore, permitting issues related to emissions from waste treatment activities affect primarily those waste contractors rather than the refineries themselves. Member Companies interviewed indicated some pre-treatment carried out on site primarily to reduce the volume of sludge being sent off site and therefore reduce disposal costs, or in some cases, to attend the sludge quality requirements of the waste contractor. One of the Concawe Member Companies interviewed indicated they manage most waste sludges produced on-site (by using biopile technology as described earlier). However, this is rare, given the difficulty of obtaining the required waste management permits for waste treatment within the boundaries of an operating refinery and the convenience of available specialised waste contractors benefiting from a range of available technologies and benefits of scale by treating large volumes of waste from different industries.

Some treatment options may be easier to implement within a refinery than others and one respondent indicated they were considering solvent extraction for biorefinery filter cake, and that they were in contact with a contractor to build a small treatment unit at their refinery. Refineries seeking to treat waste onsite may need to apply to the environment regulator for an environmental permit. A permit may also be required for a mobile plant that can then be used at several sites.

Some activities may qualify for a waste exemption when is exempt from needing an environmental permit. Each exemption has specific limits and conditions that need to be complied with. Typically, registering an exemption does not remove the need to apply for other permits or permissions such as the need for planning permission or a water discharge permit.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

6.1.1. Oily Sludges Production and Reported Management Options

Concawe waste surveys have identified that oily sludges are significant wastes in refinery operations. A waste survey with focus on oily sludges was carried out in 2022 for the years 2019, 2020 and 2021. This report represents the second phase of this project which aims at using the survey data to do a sustainability study on waste sludges to achieve sludge minimisation and move waste sludge management up the waste hierarchy.

In the 2019-2021 period, oily sludges in European refineries represented between 19.6 and 22.2% of total produced wastes. On a normalised basis, an average of 0.66 tonnes of oily sludges were produced per kilotonne of oil throughput. The main three types of oily sludges produced by weight were tank bottom sludges, refinery maintenance sludges and WWTP sludges. Together they represented 72% of all oily sludges produced.

Oily sludges have a highly diverse composition consisting of petroleum hydrocarbons, water and a mineral portion of clay, slit and sand. A sample of an oily sludge from an API separator in a Canadian refinery consisted of 50% water, 30% oil and 20% solids (Hue et al 2019). Tank bottom sludges can have a higher proportion of oil (up to 60%). The oily fraction consists of a wide range of saturated and aromatic hydrocarbons, resins and heavier fractions such as asphaltenes.

Considering the three main types of oily sludges produced (tank bottoms, maintenance and WWTP sludges), incineration with and without energy recovery, followed by landfill, treatment and recycling were the main management options. However, some differences exist between the three sludge types. Landfill, followed by incineration (approx. 50%) were the main management options for tank bottom sludges. Recycling and landfill (approx. 50%) were the main management options for maintenance sludges. Finally, wastewater sludges were primarily managed by incineration with and without energy recovery (some 60%).

To help visualise the relationship between pre-treatment and final management option selected for the three main oily sludges discussed, the report includes Sankey diagrams for each waste sludge type. The separation techniques used, or the lack of any separation or pre-treatment, seem to be a function of the quality of the sludge needing disposal or recovering in terms of water content and solids content and oil composition; the type of available management options in country; and costs related to these management options. This is based on the fact that the same management options accept the same type of sludge both with prior pre-treatment and without any pre-treatment. In some cases, pre-treatment is carried out by waste contractor prior to disposal or treatment.

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.

6.1.2. Selection of Oily Sludges Management Technologies for Sustainability Assessment

To inform the sustainability assessment of oily sludges management options, a literature review was carried out to describe current, conventional technologies such as those reported in Concawe waste survey, and to identify and describe emerging technologies that can provide viable alternatives for the management of sludges with less environmental impacts and that hold a higher position in the waste hierarchy. Several emerging technologies were identified representing different treatment mechanisms, resource recovery performance, energy consumption and environmental impacts. 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 sludges management technologies can be divided into those that focus on the recovery of the oil contained in the oily sludges and those more conventional disposal/treatment technologies currently used by the industry. The degree of application of the oil recovery methods to refineries vary, with some technologies only tested at laboratory or pilot scale, while others are being more routinely used, if not in refineries, in similar applications. The technologies identified are listed in **Figure 8**, earlier in the report.

Overall, information found during the literature review contained little information on technologies equipment needs, energy consumption, costs and emissions. Opinions regarding whether a technology was an emerging one or was already an established technology also differed greatly among the authors reviewed.

The selection of technologies for further sustainability analysis was based primarily on the degree of performance information available and development stage (laboratory, pilot, full scale use), and also their applicability to a refinery context defined via an assessment of their advantages and disadvantages. A combination of emerging and conventional technologies was selected for comparison. The selected technologies were landfill, incineration, cement works, biopiles, pyrolysis and solvent extraction.

6.1.3. Sustainability Assessment of Selected Waste Management Technologies

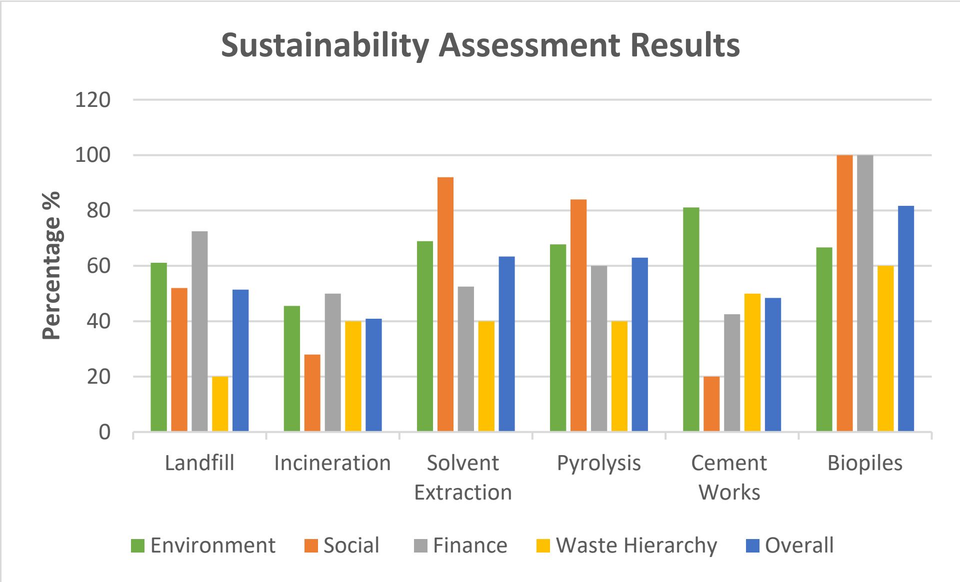
The aim of the sustainability assessment was to assess overall environmental, and more broadly, sustainability and circularity performance of emerging technologies, and to compare these with conventional oily sludges treatment approaches. A multi-criteria analysis approach was taken. This approach uses data from available sources and is a useful method to identify system boundaries and which parts of the management options are responsible for the higher impacts.

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 (ECME June 2006) and complemented with indicators from US EPA’s “Tool for the Reduction and Assessment of Chemical and other environmental Impacts”. 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, commercial availability, and operational costs.

The results of the assessment are shown in **Figure 16** below. 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 conventional options such as landfilling, cement works and incineration with energy recovery.

Figure 16 Sustainability Assessment Results



While cement works scored low on criteria associated with air emissions (GWP, AP and ECT), its overall environmental score was high due to the lack of water emissions and solids requiring further treatment/disposal and its high degree of energy recovery. Alternatively, it scored low in social pillar due to high overall emissions of NOx and SOx affecting human health and the environment. Together with incineration, cement works scored lowest in the economic pillar. Landfill scored high in the economic pillar together with biopiles while the opposite is true in the hierarchy pillar.

The assessment demonstrated that options with a higher degree of circularity may present higher environmental and social impacts than disposal options. Also, while the assessment provides a rapid method to compare impacts and benefits of different technologies, cross-media effects and other operational considerations are not clearly demonstrated.

6.1.4. Other Operational Considerations

The pre-treatment of oily sludges onsite was primarily driven by the need to reduce sludges water volumes and to comply with waste management contractors' requirements. When pre-treatment was required, their selection was dictated primarily by operational cost and degree of dewatering required. In some cases, when pre-treatment was required, this was undertaken at the waste management contractor's facilities.

Oil retained in sludges or other types of waste represents a loss of product and, where possible, efforts should be made to recover the oil. There are several ways to reduce the generation of oily sludges or to reuse/destroy them on site as outlined in the REF BREF BAT conclusions. They include measures such as the destruction of oily sludges in a coker, if the refinery has one; maximising the removal of solids from the desalter; preventing solids entering the refinery sewer system; and segregating relatively clean rainwater run-off from process streams.

6.1.5. Waste Management Regulations

There are several European Directives that are relevant to waste management activities. The most relevant to this assessment are the Industrial Emissions Directive and the Waste Framework Directive.

The **Industrial Emissions Directive (Directive 2010/75/EU, amended in 2024)** is currently the main EU instrument regulating pollutant emissions from industrial installations/activities and livestock farms in an integrated manner, on a sector-by-sector basis, through Best Available Techniques (BAT) conclusions and Reference document (BREF). The sectors include waste management activities such as biological and physico-chemical treatment; recycling/reclamation; oil re-refining; disposal or recovery of waste in waste incineration plants or in waste co-incineration plants, landfills and temporary storage; and pre-treatment of waste for incineration or co-incineration. The IED states that permits must take the whole environmental performance of a plant into account. This covers emissions to air, water and land, generation of waste, use of raw materials, energy efficiency, noise, prevention of accidents, and restoration of the site upon closure. Most refineries operate under the Refining of Mineral Oil and Gas BREF which cover all these activities.

The Waste Framework Directive (Directive 2018/851 of the European Parliament and the Council on amending Directive 2008/98/EC on waste), sets out the basic concepts and definitions related to waste management, such as definitions of waste or recycling. It introduces the waste hierarchy, the Polluter Pays principle and the Extended Producer Responsibility. It objective is to protect the environment and human health by preventing or reducing the generation of waste and the adverse impacts of the generation and management of waste.

The regulatory review and interviews with Concawe Member Companies indicated that some treatment options may be easier to implement within a refinery than others. Refineries seeking to treat waste onsite may need to apply to the environment regulator for an environmental permit. A permit may also be required for a mobile plant, but this can be used at several sites. In addition, the Refining BREF explicitly prohibit the use of off-site waste as feedstocks, restricting any pre-processing offsite and further treatment onsite as this would require a new permit. The same limitation applies for coprocessing biowaste in a refinery.

Some activities may qualify for a waste exemption when is exempt from needing an environmental permit. Typically, registering an exemption does not remove the need to apply for other permits or permissions such as the need for planning permission or a water discharge permit.

6.2. RECOMMENDATIONS

The generation of oily sludges in the refining industry is inevitable and its proper treatment and management is a challenge for the industry. Wherever possible, the reduction in oily sludge generation is recommended. As stated earlier in the document and as recommended in the Best Available Techniques (BAT) Reference

Document for the Refining of Mineral Oil and Gas, 2015, oily sludges can be sent to a coking unit where it becomes part of the refinery products. Reducing the amount of solids entering the refinery sewer system, segregation of clean water from process water, and reducing solids generated in the desalter are additional practices that help reduce overall oily sludges production. The use of efficient dewatering/thickening techniques as those described in previous sections can significantly reduce the volumes of oily sludges to final treatment or disposal. The next Refining BREF could give legislators an opportunity to simplify waste processing onsite as the refineries contribute to the circular economy.

Several emerging oily sludge treatment technologies have been developed in recent years. Some of these focus on the separation and recovery of the oil fraction and not all have been proven in the field. While multi-criteria analysis is a rapid semi-quantitative tool to evaluate difference in environmental and social impacts of waste management technologies, they rely on available information not always applicable to specific refinery conditions or sludge quality.

Moreover, emerging techniques and their degree of application to refineries varies, with some technologies only tested at laboratory or pilot scale. Therefore, a conclusion can only be drawn once their performance and cross-media effects are determined at the operational scale.

Quantitative sustainability appraisal tools, such as LCA tools, are widely used to evaluate environmental impacts of various waste management practices, although significant knowledge gaps exist regarding the difference in environmental load or energy consumption between conventional and emerging oily sludge treatment approaches. Their use can be beneficial in the understanding of impacts and benefits from emerging technologies in comparison to conventional approaches. They can also help quantify possible cross-media effects and to avoid unintended consequences of improving one or more of the evaluated pillars in detriment of others.

7. GLOSSARY

AP	Acidification Potential
API	American Petroleum Institute
BAT	Best Available Technology
BTEX	Benzene, Toluene, Ethylbenzene and Xylenes
CAR	Carcinogenic Effects
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAF	Dissolved Air Flotation
ECT	Ecotoxicity Effects
EN	European Standard
EU	European Union
EU28	Abbreviation of European Union (EU) which consists of a group of 28 countries
EP	Eutrophication Potential
EWC	European Waste Catalogue
GWP	Global Warming Potential
H_2	Hydrogen
HCl	Hydrogen Chloride (Hydrochloric Acid)
HF	Hydrogen Fluoride (Hydrofluoric Acid)
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
LPGC	Liquified Petroleum Gas Condensate
MEK	Methyl Ethyl Ketone
NCAR	Non carcinogenic Effects
NH_3	Ammonia
NO_x	Nitrogen Oxides
ODP	Ozone Depleting Potential
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorinated Biphenyls
PCDDs	Polychlorinated Dibenzodioxins
PCDFs	Polychlorinated Dibenzo Furans
RE	Respiratory Effects
SM	Smog Formation
SO_2	Sulphur Dioxide
SO_x	Sulphur Oxides

SuRF-UK	United Kingdom Sustainable Remediation Forum
TOC	Total Organic Carbon
TS	Total Solids
US	United States
VOC	Volatile Organic Compound
WDF	Water Framework Directive
WWTP	Waste Water Treatment Plant

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ANNEX A: TREATMENT/DISPOSAL TECHNOLOGIES

Oil Recovery Methods
Solvent Extraction
Solvent extraction involves the mixing of oily sludge with suitable organic solvents, 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. Different solvents have been tried at different solvent/oily sludge ratios such as methyl ethyl ketone (MEK), liquified petroleum gas condensate (LPGC), hexane, xylene, toluene, turpentine and others. Extraction experiments with MEK and LPGC, reported by Abouelnasr and Zubaidy (2008), achieved oil recoveries of 39% and 32% for MEK and LPGC respectively using a 4:1 solvent to sludge ratio. MEK and LPGC are commonly available at many petroleum refineries and therefore provide a viable option. Taiwo and Otolorin (2009) reported a recovery of petroleum hydrocarbons of approximately 67% using hexane and xylene, mainly in the range of C9 to C25. A large proportion of the oil recovered using solvent extraction is in the range of diesel oil that can be used for energy recovery, while up to 93% of the recovered solvent can be reused for the next solvent extraction cycle (Hu et al, 2019). It has been reported that recovered oil may need further treatment due to its sulfur content. Extraction performance is affected by temperature, pressure, solvent type, solvent to oily sludge ratio and degree of mixing. The solvent extraction process typically involves the mixing of the oily sludge with the solvent in a vessel. Mechanical agitation is commonly used to aid the extraction process. After mixing, the mixture is transferred to a decanter centrifuge to separate the solids, and a liquid mixture of water, oil and solvent is recovered. This mixture requires further separation to remove the water from the oil/solvent phase which is then sent to a vacuum distillation unit to separate the oil from the solvent. Hu et al (2016) reported that roughly 300 kg of recovered oil can be generated from 1000 kg of oily sludge using MEK as the solvent, with a quality similar to a heavy fuel oil and having approximately 3% of asphaltenes impurities. The solids recovered from the process may require further treatment before final disposal such as incineration or landfilling.
Pyrolysis
The term pyrolysis refers to the thermal decomposition of organic materials at high temperatures (400-600^{0}C) in an inert environment (Johnson et al 2018). 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 (Hu, 2020). 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. Since pyrolysis is an endothermic reaction, the products from this process have a higher total heating value than the original sludge. According to Hu et al, 2017, approximately 33 w.t.% of pyrolysis oil, 14 w.t.% of solid char and 53 w.t.% of gaseous products can be produced from oily sludge pyrolysis between 450-500^{o}C. 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 (Li et al 2021). Major gaseous products include H_2, CO_2, CO, water and approximately 25 w.t.% of non-condensable hydrocarbons such as methane, ethane and hydrogen sulfide (Hu et al 2019). 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.

The pyrolysis process is affected by a number of factors such as temperature, heating rate, and the properties of the oily sludge. Liu et al. (2009) found that the faster the pyrolysis heating rate, the higher the proportions of carbon and sulfur in the solid residue of the oily sludge and that the recovery rate of petroleum hydrocarbons changed significantly under the influence of the heating rate, with nearly 80% of the total organic carbon in the oily sludge converted into petroleum hydrocarbons. Ma et al. (2014), when conducting a pyrolysis experiment of oily sludge in a rotary kiln reactor, found that when the pyrolysis temperature was 550ºC, the recovery rate of pyrolysis oil reached 87.9%. Its components were found to be mostly linear alkanes with a low molecular weight.

In recent years, the addition of catalysts (catalytic pyrolysis) and biomass (co-pyrolysis) have shown to increase the efficiency of oil recovery and the quality of the pyrolytic oil, while other improvements such as sulfur stabilisation, increased gas production with less H_2 and more methane were also observed. Calcium based compounds have been used as catalysts such as CaO, $CaCO_3$, $CaCl_2$, as neutralising and solidification agents and sulfur binders. Others (Shie et al, 2002) has reported the use of iron and aluminium compounds as catalysts to improve oil quality and reaction rates. Inorganic matter such as fly ash from power plants mixed with oily sludge has also been used resulting in oil with more saturates content and gas production, although the concentration of heavy metals can be a problem.

Rice husks, walnut shells, sawdust, apricot shells have been used as feedstock for co-pyrolysis (Lin et al, 2018) to increase oil recovery efficiency and gas yield. Industrial organic wastes such as coal, polyethylene and waste scrap tyres are also common feedstocks for co-pyrolysis. Kositsov et al 2015 found that co-pyrolysis of peat and oily waste decreased pyrolysis temperature and increased yield of liquid and gas products. Co-pyrolysis of oily sludges with inorganic solid wastes (such as steel slag) has also been reported to improve oil yield and flue gases.

Much of the work to understand pyrolysis plant efficiencies to recover pyrolysis oil and gas, and its impacts to the environment was undertaken in laboratory-scale and pilot-scale plants using tube furnaces, tank reactors with stirring and rotary reactors among others. Wang et al, 2011 reported that a rotary furnace with a capacity of 10 t/d attained more than 80% w.t.% oil recovery and resulted in a solid residue with less than 0.3 wt% of oil. At industrial scale, chain-slap conveyor, rotor and stator and rotary kiln reactors have all been mentioned in the literature (Li, et al 2021). The pyrolysis reactor is the core of the pyrolysis plant. Pre-processing, drying and a py-gas combustion unit are typical components of a pyrolysis plant.

Although fast pyrolysis technologies for the production of liquid fuel have been successfully demonstrated on a small scale, and several large pilot plants or demonstration projects are in operation or at an advanced stage of construction, they are still relatively expensive compared with fossil-based energy, and thus face economic and other non-technical barriers when trying to penetrate the energy markets (EUBIA. 2021). Commercial plants were identified in several countries primarily 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. The author could identify one pyrolysis plant for the treatment of mixed industrial oily sludges (not refinery sludges) in Hubai, China, with a capacity of 115,000 tonnes per year. In fact, Chinese industries seem to be dominant in the market with companies, who advertise the manufacturing of pyrolysis plants for a variety of uses including oily sludges, of different capacities. The company has delivered several plants to different countries for the uses listed above. Pyrolysis plants for the treatment of oily sludges solid phase after separation is known to be used in the Netherlands.

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 (Martinez-Palou et al., 2013; Abdurahman et al., 2017), and it also decomposes large molecules of petroleum hydrocarbons into smaller ones. Da Silva (2014), further reported that this microwave pyrolysis also promotes the transfer of solid particles in the oil phase to the water phase therefore improving the quality of the resultant pyrolysis oil. While in conventional thermal heating, heat is transferred to the material through convection, conduction, and radiation of heat from the surfaces of the material, microwave energy is reached directly to the materials through molecular interaction with the electromagnetic field so that heat energy can be generated throughout the volume of the material therefore achieving rapid and uniform heating across the material. Johnson et al (2019) indicated that one pilot study resulted in the recovery of 146 barrels of oil and 42 barrels of water from 188 barrels of oil-water emulsion, while Lin et al (2017) used microwave heating to treat oily sludge from refinery wastewater that accelerated the conversion of sludge biogas, increased the yield of gas products and reduced solid impurities, while achieving a yield of recovered oil of 33%. When compared with other oil recovery techniques, microwave irradiation showed reduced treatment times, higher viscosity lowering and efficiency and little or no pollution. However, the application of this technology at an industrial scale may be limited due to requiring sophisticated equipment which in turn may imply higher costs.
Ultrasonic Irradiation
Ultrasonic treatment uses the vibration collision, cavitation effect, and heat action of the sound field to break the oil and water in the oily sludge to realize the three-phase separation of oil, water, and solids (Check and Mowla 2013; Check 2014; Mao et al. 2016). These processes mainly rely on cavitation, especially at the solid-liquid boundary (Hamdaoui and Naffrechoux, 2007; Xu et al., 2009). Under the continuous irradiation of ultrasonic waves, the viscosity of oil-water emulsions decreases continuously. The small droplets in the emulsion mixture accelerate, collide and coalesce, ultimately achieving the purpose of separating the aqueous phase and the oil phase to recover the crude oil (Hamida and Babadagli, 2008; Xie et al., 2015). The method efficiency was found to be sensitive to the ultrasonic irradiation time, with increased irradiation time resulting in decrease dewatering of the sludge. To solve this problem, a two-stage ultrasonic irradiation process with equal irradiation time (Check, 2014) was developed. Experimental results demonstrated that the process can effectively reduce the settling time, and the dehydration rate of heavy oil was found to reach 96%. Pilot tests have found crude oil recoverability in the range of 46% to 60%. The addition of a surfactant was found to further increase the recovery rate of crude oil to 82–90% (Gao et al., 2018b). The ultrasonic irradiation method has the advantages of short treatment time, good viscosity reduction effect and no secondary pollution. However, although this method has entered the pilot scale application stage, with a few reports of its use in oilfield or refinery applications, the need of large ultrasonic emission equipment and high cost of use and maintenance, are the biggest obstacle to this technology’s use in the future.

Surfactant Enhanced Oil Recovery
The use of surfactants for the recovery of oil from oily sludges, 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 (Seo et al., 2018). The ratio of the surfactant to the oily sludge, and the type of surfactant(s) used are very important for the efficiency of the recovery rate of crude oil. In fact, surfactants are extensively used in the pre-treatment stages of other recovery technologies, such as mechanical centrifugation or flotation methods to increase the recovery efficiency of crude oil. Researchers have also found that the de-oiling process of oily sludge via chemical agents is also controlled by the solid concentration and temperature. Different surfactants have been tested or are used commercially such as sodium dodecyl benzenesulfonate, polyoxyethylated alkyl phenol esters and sodium ethoxylated alkyl sulfate. A solution of sodium ethoxylated alkyl sulfate was found to be highly effective resulting in a residual oil content in the solid residue of 1.25% (Hui et al 2020). In selecting a surfactant for extracting the crude oil, its effectiveness, cost, biodegradability, toxicity, and the possibility of re-use are important factors. The use of biosurfactants have increased in recent years, due to their generally good surface activity, low biological toxicity, good demulsification performance, and strong selectivity, such as rhamnose tallow which is widely used (Yan et al (2012). Yan et al. (2012) used rhamnose tallow to recover crude oil from refinery sludge, which was found to directly recover 91.5% of crude oil from sludge under optimal conditions. Compared with mechanical centrifugation, solvent extraction, and other methods, the process is much simpler, does not require large and complex machinery and equipment, and is characterized by a large treatment capacity and high efficiency.

Freeze/Thaw
Another method of oil recovery from oily sludge is the freezing/thawing method. Given the different compositions of petroleum hydrocarbons in oily sludge produced in refineries, two main situations arise during the separation of the water-phase and the oil-phase by this method depending on whether the water-phase or the oil-phase freeze first. When the water-phase freezes ahead of the oil-phase the volume expansion of the frozen water droplets causes the coalescence of the water with the break-up of the emulsion mixture. During thawing, gravity and surface tension stratify the oil-water emulsion ultimately achieving separation and recovery of oil (Hui, et al 2020). The other situation is when the oil-phase freezes first. In this case, ice formed by the freezing of the less dense oil will cover the water-phase. During the thawing process, the oil-phase and water-phase gradually stratify and separated due to gravity and the oil can be recovered. Jean et al (1999) was one of the first to verify the feasibility of the method obtaining 50% of oil from an oil-water mixture. Other have been able to remove more than 90% of the water contained in petroleum sludge (Johnson, et al, 2019). 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.

Sand Attrition
No research papers were found on this technique which was mentioned by Member Companies. However, some information exists in contractors' websites. 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 cleanly separates into the oil water and solid phases. Some of the advantages of this technique include a reduction on disposed waste, water recovery with TPH concentrations of less than 15 ppm, and residual solids that are typically classified as non-hazardous. Up to 98% oil recovery efficiency has been stated by contractors which can be return to clients for further reuse. The method can process volumes of up to 120m3 and the equipment can be mobilised to the client location minimising transport needs. Sand attrition equipment has a small footprint making their transport and setting up on client's locations easy to achieve.
Froth Flotation/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. As the bubbles move to the surface of the slurry, they collide with oil droplets which spread and attached to the surface of the bubble film. Because the density of the oil phase is less than that of the water phase, the bubbles attached to the oil phase droplets quickly float to the surface. After a time, the oil droplets floating on the surface of the slurry can be scrapped off, collected and further purified. Laboratory tests found crude oil recovery rates of 55% and rates can be increased with increasing amounts of foaming agents (such as dodecylbenzene sulfonate), and lower pH, which facilitates the solubilisation of the oily sludge. Compared with the surfactant method, this method has the disadvantage of requiring additional air flotation equipment and is sensitive to the viscosity of the oily sludge with increasing need of surfactants and water as the viscosity of the sludge increases. This can produce excess wastewater and increase the cost of subsequent treatment with associated environmental risks which could hinder large scale application of this technique (Hui et al 2020).
High Temperature Reforming
High Temperature Reforming (HTR) is a process in which influent emulsion or sludge is heated above the boiling point of water and then allowed to flash in a separation tower where steam and light hydrocarbons are subsequently extracted (DrillingFluid.Org). Heavier hydrocarbons and inorganic material are removed from the separation tower as a slurry phase and can be recovered after liquid/solids separation. Light hydrocarbons and water can be recovered by condensation. This process is similar to conventional oil and gas production dehydration processes but functions at much higher temperatures. Operating at high temperatures (300-350ºC), the rate of mass transfer of hydrocarbons from the solid, inorganic phase, increases as the viscosities of hydrocarbons decrease. It also increases the molecular movement of droplets increasing coalescence. Hydrocarbons desorbed from the solid phase can then be recovered and sold/re-used.

HTR has been applied to sludges from oil exploration and production activities and has been tested with various types of oil sludges including tank bottoms sludges. It is more commonly deployed in the US and has a small footprint, which makes it suitable for a variety of industrial and field settings. Contractors offering this technology recommend piloting HTR to ensure it is applicable to the type of oily sludge that requires treatment.

Oily Sludges Management Options

Incineration and Incineration with Energy Recovery

Incineration is the process of complete combustion of oily sludge in a controlled environment with excess air and auxiliary fuels (Hu et al 2019). The combustion temperature is often >1000 C. Different types of incinerators are available. Fluidized incinerators tend to have lower pollutant emissions and higher combustion efficiency compared to rotary kiln incinerators. On the other hand, the rotary kiln incinerator is highly adaptable and can burn wastes with higher moisture content and larger incineration space, but typically requires higher maintenance.

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.

In general, two major types of incineration are used: conventional and other types that incorporate energy-recovery procedures. In the latter type of incineration, the incinerator is coupled with basic mechanisms to recover heat and energy and more sophisticated mechanisms to clean flue gas (UNEP 2020). Incineration with energy recovery offers the added benefit of using waste as a resource to produce energy. This form of incineration also decreases carbon emissions by offsetting the need for energy from fossil fuel sources and reduces methane generated from landfills if used as an alternative to landfilling (IPCC, 2007).

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. Tests of oily sludges mixed with sludges from a wastewater treatment facility, in an anaerobic environment, showed a maximum amount of biogas produced when the ratio was 60% oily sludge to 40% wastewater treatment sludge at 35ºC (Janajreh et al 2020).

Final products of anaerobic co-digestion are compounds of nitrogen and phosphorous that can be added to soil as fertilizers. According to some researches, issues with this technology remain due to high cost, long reaction time and low conversion efficiency (Murungi et al, (2021).

Co-Processing in Cement Works

The industrial process for the fabrication of cement comprises the calcination and fusion of materials comprising calcareous materials, clays and iron and aluminium oxides in a rotating furnace operated at a temperature of 1450 °C where the flame temperature oscillates at approximately 2000°C. This furnace produces clinker (Rocha et al., 2011). Wastes can be processed in such furnaces because the specific conditions of the process, such as high temperatures, an alkaline environment, an oxidizing atmosphere, an optimal mixture of gases and products and a long residence time, are usually sufficient to destroy hazardous wastes.

Co-processing is the use of alternative fuel and/or raw materials for the purpose of energy and/or resource recovery. This differs from co-incineration, the production of materials while using wastes as fuel or the plant in which waste is thermally treated for the purpose of disposal. Co-processing of wastes in properly controlled cement kilns provides energy and materials recovery while cement is being produced, offering an environmentally sound recovery option for many waste materials.

The numerous potential benefits possible through the use of hazardous and other wastes in cement manufacturing processes by the recovery of their material and energy content include: the recovery of the energy content of waste, conservation of non-renewable fossil fuels and natural resources, reduction of CO_2 emissions, reduction in production costs, and use of an existing technology to treat hazardous wastes (WBCSD, 2005).

However, the use of these alternative fuels in the cement industry has limitations. A Concawe member company indicated that cement works demand large quantities of waste, and the provision of constant volumes of waste and on a regular basis, something that is difficult for refineries to comply with. Cement works also have restrictions on some hazardous pollutants. Finally, the cost to send oily sludges to cement works was similar to incineration but with transportation to generally further away cement works this management option may be more expensive for some refineries.

Landfilling

Landfill is the oldest and 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. As stated in the Waste Survey Report (ref.) landfilling was a more frequent disposal option for non-hazardous sludges and general non-hazardous refinery wastes, with small quantities of hazardous oily sludges disposed in this way.

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.

Landfarming is a bioremediation involves the scattering and mixing of oily sludges in the topsoil layer, in a controlled manner, for the microbiota in the ground to act as a degrading agent (Da Silva). The oily sludges are applied to large areas where they undergo biodegradation and volatilization. At the beginning of the 1950s, this treatment process attracted the interest of petroleum-refining companies in the United States, which were the first to develop and apply treatment in the soil for their waste. However, the direct application to land of refinery and other petroleum sludges are not acceptable environmentally and are banned in many jurisdictions. The construction of lateral barriers and an underlying impermeabilization layer made of high-density polyethylene or compacted clay prevents or minimises the transference of contaminants to neighbouring areas and underlying soil. Operational techniques involve the addition of nutrients, humidification, aeration and pH correction of the soil. (Harmsen et al., 2007; Maila and Cloete, 2004). Da Silva (2009) evaluated the treatment of oily wastes in a 1000 m2 area in a landfarming site at a Brazilian refinery. Biostimulation included humidification, fertilization and aeration. In parallel, a control cell was used. Results obtained after 225 days of treatment showed the TPH content decreased by 89.6% in the treated soil, with a degradation rate of 25.8 mg kg−1 day−1, whereas the control soil exhibited 22.4% degradation (6.5 mg kg−1 day−1). **Tillage** is an intensive biological treatment technique that mixes oily sludge with the soil and periodically plows the soil to degrade the organic components using soil microorganisms. The method of tillage is low-cost and easy to operate but can take long time to completely eliminate the harmful substances in the sludge.

Biopile technology involves the construction of soil mixed with oily sludges in cells or piles to stimulate internal aerobic microbial activity by efficient aeration (Da Silva). Biopiles of petroleum wastes have received increased attention as a substitute technology for landfarming which often requires a large land area. Biopiles are constructed by agglomerating the waste materials into piles or windrows, usually to a height of 2-4 m. The bio-treatment efficiency can be improved with moisture adjustment, air blowing, and the addition of bulking agent and nutrients. Bulking agents usually include straw, saw dust, bark and wood chips, or some other organic materials. Addition of bulking agents results in increased porosity in soil-sludge piles, which leads to better air and moisture distribution in the matrix. In biopiles, the temperature can increase up to 70 °C or more, due to the heat generated by intense microbial activity, so that this technique can be used in cold climates. Biopiles are easy to design and implement and can be engineered to fit different site conditions. While they require much less available area than landfarming, they still require a large area of land.

The use of biopiles for the treatment of oily sludges is not common in the industry. However, one Concawe member company stated they use biopiles to treat refinery and wastewater oily sludges and some tank bottom sludges produced at their refinery, with little if any oily sludges being disposed offsite. The method has been successful in treating this type of sludges and they are building a second biopile to treat heavier sludges. The process starts with a separation pond after which there is dewatering of the sludge by centrifugal dewatering and, increasingly, with Geobags® that have the advantage of not necessitating energy. The sludges are mixed with woodchips to provide bulking material and facilitate aeration and bacteria growing. The biopile is underlying by landfill liner, and air is injected so that odour generation is not a problem. Nitrogen and water are constantly monitored. Oil and water draining from the biopile is collected and the oil is further separated. The Concawe member company estimated that from 9000 tons of sludge approximately 10 tons of oil is recovered. Treatment time ranges between 9 and 12 weeks depending on the degree of oil contamination. The remediated sludge (soil) is used for landscaping, seeded and restored with low plants/flower that attract pollinators.

In **slurry-phase bio-treatment** oily sludges are mixed with water resulting in an aqueous phase with a larger amount of solubilized pollutants. The microbial degradation can then transform the pollutants into less toxic intermediates (e.g., organic acids and aldehydes) or end products such as carbon dioxide and water. Slurry-phase biodegradation usually occurs in designed slurry bioreactors where the contact between microorganisms, petroleum hydrocarbons, nutrients, and oxygen can be maximised. Several types of bioreactor designs are available, such as the rotating drum equipped with lifters to provide internal mixing, and the vertical tank equipped with an impeller for mixing. Bio-slurry treatment has been successfully applied to oily sludges. For example, Maga et al. reported that a 10,000-gallon sequencing batch reactor (SBR) was used for the on-site biodegradation of oily sludge, where micro-organisms degraded the petroleum substances from 20,000 ppm to less than 100 ppm within two weeks of treatment. According to Ward and Singh, a large-scale bio-slurry reactor system with a 4.55 × 106 L capacity was designed to treat oily sludge at a Gulf Coast refinery, while air sparging and mechanical agitation system were incorporated to improve the homogenization of oily sludge slurry, with 50% of oil and grease removal being achieved after 80 to 90 days of treatment.

Physico -Chemical Treatment
Stabilization/Immobilisation/Solidification
Stabilization/solidification (S/S) is a quick and inexpensive waste treatment technique aimed at immobilizing contaminants by converting them into a less soluble or a less toxic form (i.e. **stabilization**), and encapsulating them by the creation of a durable matrix with high structural integrity (i.e. solidification) (Hu et al 2013). The use of this disposal method for inorganic wastes has been widely reported. However, it is considered less compatible with organic wastes since organic compound may inhibit cement-based binder hydration and result in the release of pollutants (leachate). A possible method for improving the effectiveness of S/S treatment for organic wastes is to use binders that increase sorption of organic compounds (e.g., combined use of cement and activated carbon), thereby improving their immobilization and preventing their detrimental effects on binder hydration. In general, a Portland cement only binder system has been shown to be not effective for the immobilization of several common organic contaminants. Caldwell et al. [178] reported that activated carbon used with Portand cement was effective in the S/S treatment of a range of organic contaminants. Leonard and Stegemann found that Portland cement with the addition of high-carbon power plant fly ash (HCFA) significantly reduced the leaching of PHCs. In addition to the immobilization of organic contaminants, an advantage of applying S/S method is that some hazardous heavy metals in oily sludge can be immobilized into the cement matrix.
Oxidation/Reduction
Oxidation treatment is a useful method to degrade organic contaminants in oily sludges through chemical or other oxidation processes. 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 (Badrul Islam, 2016). The oxidation can be carried out by Fenton's reagent, hypochlorite, ozone, permanganate and persulphate, that generate a sufficient amount of radicals such as hydroxyl radicals (OH*), which can quickly react with most organic and many inorganic compounds. Many studies have proven that chemical oxidation can effectively degrade petroleum hydrocarbons and PAHs in soils, and this method has recently been applied to oily sludge treatment (Hu et al 2013). Mater et al. found that a Fenton type reagent (i.e., 12 wt% of H_2O_2 and 10 mM of Fe_2+) at a low pH (i.e. pH = 3.0) can significantly reduce the concentrations of PAHs, phenols and BTEXs in oily sludge contaminated soil.

ANNEX B: ASSESSMENT PROCESS

A maximum weighting of 5 was given to each criterion. Each option is then scored from 1 to 5, 1 being the least favourable, 5 being the most favourable. The Financial Pillar is used as an example. This Pillar has two criteria: commercial availability with an assigned weighting of 3, and cost with an assigned weighting of 5.

Multiplying the assigned weighting by the score given to each option results in the following maximum scores:

	Maximum score Commercial availability	Maximum score costs	Total scores
Landfill	9	20	29
Incineration	15	5	20
Solvent Extraction	6	15	21
Pyrolysis	9	15	24
Cement Works	12	5	17
Biopiles	15	25	40

This process is repeated for each relevant assessment criteria within the four pillars.

For each Pillar, the percentage of the maximum score is then calculated as follows:

- The total number of assessment criteria scored within the pillar is identified (i.e., those that received a weighting between 1 and 5). For the Financial Pillar this is 2 (i.e., two criteria). For the for the Environmental Pillar is 6 (i.e., six criteria), for the Social Pillar is 3, and for the Waste Hierarchy is 1.

- The maximum possible unweighted score for each option within the pillar is then calculated. As each assessment criteria could have scored a maximum of 5, the maximum possible unweighted score for the Financial Pillar is 10 (two criteria), for the Environmental pillar is 30 (6 criteria), for the Social pillar is 15 (3 criteria) and for the Waste Hierarchy is 5 (1 criterion).

- The maximum possible weighted score for each option is then calculated by multiplying the maximum unweighted score by the total weight and divided by the number of criteria. For the Financial criteria the maximum possible weighted score is (10*8)/2= 40. The overall score is normalised for the differing numbers of assessment criteria within each pillar. For the Environmental Pillar is (30*18)/6 = 90; for the Social Pillar is (15*5)/3 = 25; For the Waste Hierarchy Pillar this is (5*5)/1 = 25.

- The actual score for each option is then calculated as a percentage of the maximum possible weighted score in each Pillar. This meant that the overall score was normalised to account for the differing numbers of assessment criteria within each pillar. For example, the landfill option in the Financial Pillar is (29/40)*100 = 73% while for the Waste Hierarchy Pillar would be (5/25)*100 = 20%.

This process was repeated for all the pillars and the scores for each pillar are then combined and divided by 4 (i.e., 4 pillars), each representing 25% of the total score.

The percentage scores for each management options and each pillar are shown in Table below:

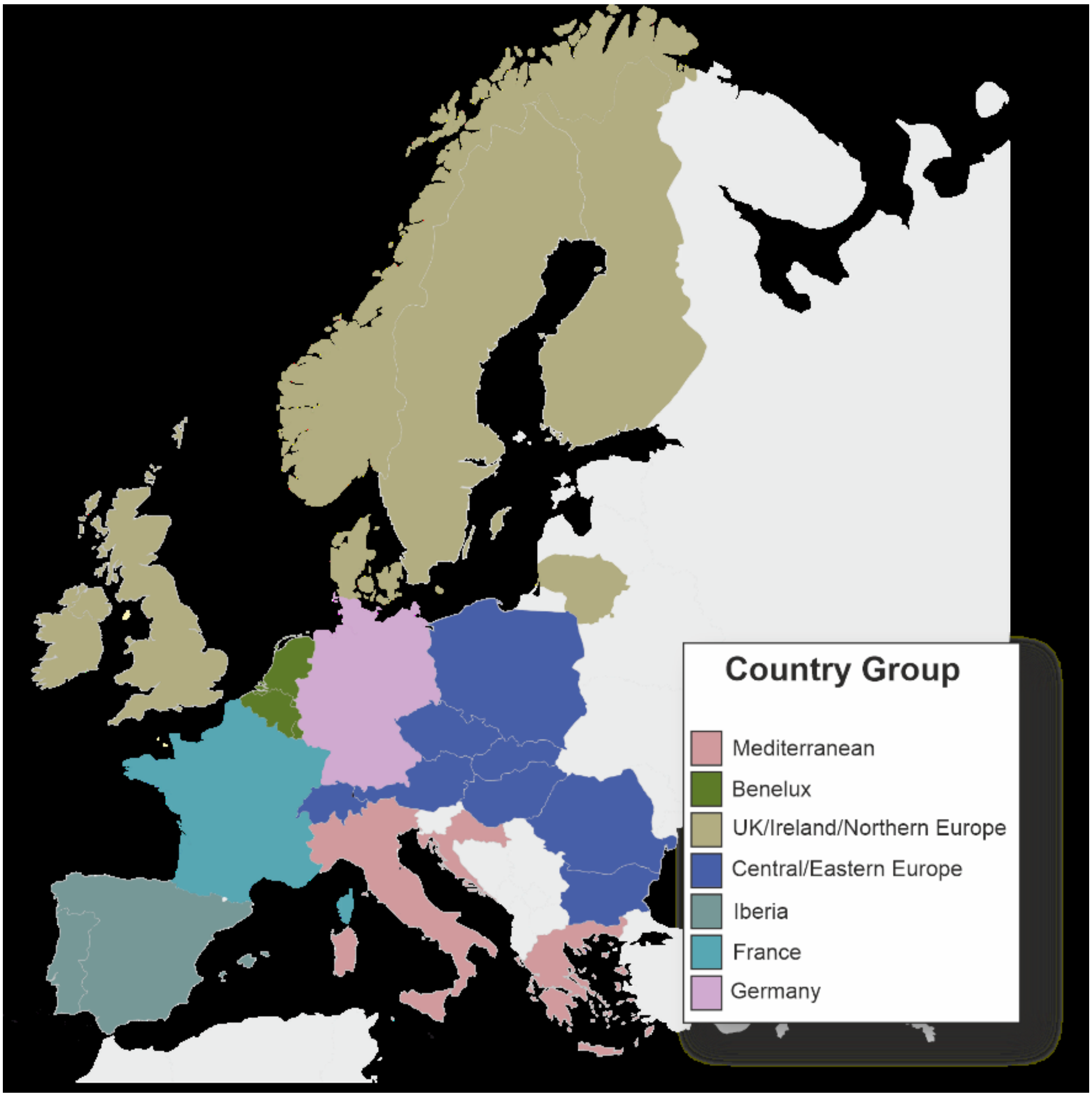
Management Options Scores in Percentages (%)

	Landfill	Incineration	Solvent Extraction	Pyrolysis	Cement Works	Biopiles
Environment	61%	46%	69%	68%	81%	67%
Social	52%	28%	92%	84%	20%	100%
Finance	73%	50%	53%	60%	43%	100%
Waste Hierarchy	20%	40%	40%	40%	50%	60%
Overall	**51%**	**41%**	**63%**	**63%**	**48%**	**82%**

ANNEX C: ASSESSMENT INPUT DATA

		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

ANNEX D: GEOGRAPHIC EXTENT OF COUNTRY GROUPINGS



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