A critical analysis of ex-situ bioremediation technologies of hydrocarbon polluted soils

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Abstract. Hydrocarbon contamination represents an important environmental issue due to the large number of polluted sites. This type of pollution is a serious threat to human health, causes economic loss and organic pollution of ground water which limits its use, environmental problems and decreases the agricultural productivity of the soil. Therefore remediation of hydrocarbon contaminated soils represents a necessity. Bioremediation of hydrocarbon contaminated soils has gained attention in recent decades mainly due to the lower costs of its application and very low environmental impact. Biological remediation technologies utilize the ability of microorganisms (bacteria, fungi) to degrade organic matter and create optimal conditions for an accelerated degradation. Ex situ bioremediation technologies such as biopile, bioreactors, composting and landfarming have been successfully used in the treatment of hydrocarbon contaminated soils. This study provides a critical perspective of the ex situ bioremediation techniques and explores strategies to improve their performances and treatment time. The principle, applicability, advantages, limitation and concerns, efficiency and costs of each technique are evaluated and discussed.
Key Words: biopiles, bioreactors, composting, ex-situ technologies, landfarming.

Introduction. Hydrocarbons are widely used as primary energy and fuel resources, due to the energy they produce, therefore a large quantity of hydrocarbons are being released into the environment, accidentally or not (Das & Chandran 2011; Panda et al 2013). The most common environmental contaminants include petroleum, gasoil, solvents (chlorinated solvents and benzene, toluene, ethylbenzene and xylene BETX), polynuclear aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) (Najirad et al 2012). These contaminants are highly persistent in the environment, toxic and present significant health risks to humans, ingestion of which can affect several body organs such as lungs, liver and kidneys (Akpur et al 2014; Alrumman et al 2015).

Soil remediation is among the most expensive treatments in the world (Agamuthu et al 2013). Biological methods have been in rapid development since the late 1980s, after the chemical and mechanical treatments of soils and water, and thermal treatment of hazardous wastes proved to be economically and environmentally unsustainable (Asha & Sandeep 2013). In the current technical systems of cleaning up hydrocarbon contaminated sites, bioremediation is an option that offers the possibility to destroy various contaminants using natural biological activity and uses relatively low-cost, low-technology techniques, which generally have a high public acceptance (Shukla et al 2010).

Soil bioremediation process may be implemented using a variety of different engineered configurations ranging from in situ subsurface (unexcavated) processes to application of completely mixed soil (slurry bioreactor) (Ward & Singh 2004). Ex situ technologies involve the transport of the polluted soil to a place where a suitable treatment system can be engineered. The main ex situ bioremediation technologies used for hydrocarbon contaminated soil treatments include biopiles, composting, landfarming and bioreactor. In certain cases, treatment can be done on the contaminated site. Technologies in this category have the advantage of efficient and rapid treatment, the downside being the increased costs involving the excavation and transportation.

Principle of bioremediation. Bioremediation can be defined as the process where contaminants in the soil, sediments, sludge or groundwater are biologically degraded into innocuous substances such as carbon dioxide, water, fatty acids and biomass, through the action of microbial metabolism (Sharma 2012; UNIDO 2014). In particular, indigenous microorganisms play an essential part as biogeochemical agents that decompose complex organic compounds into simple inorganic compounds or into their constituent elements (Adams et al 2015).

The success of bioremediation application depend on the interactions between the chemical structure of the contaminant, the number and type of microorganisms present in the contaminated soil, as well as the environmental conditions (temperature, oxygen concentration, climatological conditions, pH, moisture content, presence of alternate carbon sources, soil properties, and nutrient availability) (Akpe et al 2015; Nwogu et al 2015).

The aim of bioremediation technologies is to create the optimum conditions to facilitate biological degradation of the contaminants. This can be done through processes such as biostimulation (addition of amendments such as nutrients, organic substrates, aeration, etc) or bioaugmentation (addition of microorganisms).

In the bioremediation process, appropriate nutrient concentrations especially nitrogen and phosphorus need to be maintained in the optimal ratio to offset the imbalance caused by high carbon content of crude oil during pollution, which may retard the growth and activities of bacteria (Nwogu et al 2015). The mean of correction for this matter is addition of various forms of limiting nutrients and electron acceptors, such as phosphorus, nitrogen, oxygen, or carbon (Adams et al 2015). Table 1 presents the optimum environmental conditions for bioremediation, and the means of correction.

If needed, correction is applied to modify the parameters: temperature, which affects the biochemical reaction rates, can be controlled by using plastic covering; irrigation is applied to achieve the optimal humidity level; in case the soil has a high acidity, it is possible to rinse the pH by adding lime. Soil aeration can be corrected by tilling or sparging air, in some cases, hydrogen peroxide or magnesium peroxide are amended. Gypsum or organic matter can be added to improve soil structure (Thapa et al 2012).

Table 1

Environmental conditions affecting degradation (Adapted from Vidali (2001) and Thapa et al (2012))

Parameters	*Condition required for microbial activity*	*Optimum value for an oil degradation*	*Correction*
Soil moisture	25–28% of water holding capacity	30–90%	Irrigation
Soil pH	5.5–8.8	6.5–8.0	Too much acid- adding lime
Oxygen content	Aerobic, minimum air-filled pore space of 10%	10–40%	Till or sparge air
Nutrient content	N and p for microbial growth	C:N:P = 100:10:1	Nutrient addition
Temperature (°C)	15–45	20–30	Plastic covering to enhance temperature
Contaminants	Not too toxic	Hydrocarbon 5–10% of dry weight of soil	-
Heavy metals	Total content 2000 ppm	700 ppm	-
Type of soil	Low clay or silt content	-	To improve soil structure – addition of gypsum or organic matter

This review will consider the main ex situ technologies used in the treatment of hydrocarbon contaminated soils, relevant aspects such as principle of operation, principle, applicability, advantages and limitation, efficiency and costs of each technique are discussed.

Ex situ technologies

Composting. The simplest and most common technique of ex situ bioremediation techniques used in treating hydrocarbon contaminated soil. In composting, organic wastes are degraded by microorganisms into innocuous, stabilized byproducts (UNIDO 2014). It is usually applied in the treatment of agricultural and municipal solid wastes and sewage sludge, where the organic wastes are converted into useful soil amendments, such as

humus, but more recently is also successfully applied in the treatment of hydrocarbon contaminated soils (von Fahnestock 2005; Potra & Micle 2012; Tomei & Daugulis 2013).
The principle of operation. In the composting process, organic compounds are biodegraded, bio transformed, or stabilized by mesophilic and thermophilic bacteria. It is initiated by mixing contaminated soil with organic carbon sources (organic matter from pigs, horses, cattle livestock, fruits, vegetables, wood chips, grass, hay, straw) to encourage the development of bacterial populations able to degrade the pollutants, and bulking agents - which are added to enhance the porosity of the mixture (EPA 2006; Micle & Neag 2009; Nedeef et al 2012; Tomei & Daugulis 2013). The resulted mix is arranged into 3-4 m wide trapeze stacks or in the form of parallel lines, spaced apart to avoid compaction and to facilitate biodegradation (Mihail 2000).

Contaminant degradation in composting is an aerobic process, which requires oxygen to stabilize the organic wastes, optimal moisture content and porosity of the mixture (Sayara 2010). Proper amendment selections ensure adequate porosity and provide a balance of carbon and nitrogen to promote thermophilic microbial activity (FRTR 2002). The C: N ratio is considered among the factors affecting the compost process and compost quality. Microorganisms require digestible carbon for energy and nitrogen for cell synthesis; during aerobic metabolism microbes use about 15 to 30 parts C for each part of N. The optimum C: N ratio is between 25:1 and 35:1, a higher C: N ratio reduces the rate of process and a lower ratio leads to nitrogen loss. Depending on the waste, the C: N ratio differs, for example food waste have the C: N=15:1, fruit waste has 35:1, green vegetable waste, weeds have the ration C: N from 11:1 to 20:1, sawdust 500:1. Mixing of waste is needed to obtain a proper C: N ratio (Stabnikova et al 2010).

The insulative properties of the composting pile and the production of metabolic heat produced by microorganisms during degradation of the organic material, create a self-heating environment that serves to further stimulated microbial activity (Wiliams & Keehan 1992). Report compost / contaminated soil can vary between 0.2 and 0.7 (Nedeef et al 2012).

A typical composting process takes place at temperatures from 54 to 65 °C (FRTR 2002). The elevated (thermophilic) temperatures facilitate a higher reaction rate than that generally achievable at ambient conditions, and this may also increase contaminant solubility and higher mass transfer rates, making contaminants more available for metabolism. Due to the range of alternative substrates present and the high level of metabolic activity, the opportunity for cometabolism (degradation of a recalcitrant compound while a microorganism is obtaining its carbon and energy from more utilizable compounds) increases as well (Wiliams & Keehan 1992; Bavarva 2015).

Maximum remedial efficacy is achieved by maintaining the key parameters in optimal levels, oxygen (10–15 %), moisture (50–55 %), C: N ratio (30:1), pH (6–9), and porosity (1–5 cm) (Kuppusamy et al 2016).

There are three designs commonly applied for composting technology, each of them can be successfully used to biologically convert organic waste materials into compost under aerobic conditions, the difference being the level of process control.

In windrow method, the compost is placed in long, low, narrow piles, which are periodically turned with mobile equipment to improve aeration and porosity of the mix by exposing new surfaces and redistribute the mass; is usually considered to be the most cost-effective composting alternative but offers the lowest level of aeration and temperature control by generally relying on passive airflow and may also have the highest fugitive emissions (Figures 1 and 2).

	
Figure 1. Composting in windrows (Source: Gomez 2014).	Figure 2. Aeration equipment used in composting (Source: Fafard et Frères 2013).

In *static pile method* the aeration is provided by using forced aeration system, made of perforated pipes underlying the compost pile attached to a mechanical blower or vacuum pumps(which help maintaining the proper temperature).

Mechanically agitated in-vessel composting combines the periodic mixing provided by the windrow technology and the actively managed aeration associated with aerated static piles. This method is the most expensive but also provides the highest level of process control (FRTR 2002; von Fahnestock 2005; EPA 2006).

Aplicability: This technique is effective in treating contaminated soil with the compounds such as mono-aromatics (BTEX), phenols, PAH (the lightest type naphthalene and phenanthrene), petroleum hydrocarbons (gasoline, diesel, lubricating oil), herbicides / pesticides (such as atrazine) and PCB, PCP, chlorobenzene and some explosives (trinitrotoluene, RDX, and HMX etc.) (EPA 2006; Nedeef et al 2012).

Advantages and limitations: Composting is a sustainable and simple technique which reduces pathogens, stabilizes the waste, reduces the mass of the waste and also improves the soil structure, nutrient status and microbial activity in the soil. Compared to biopile technique, the biodegradation process is slower and less efficient. A limiting factor is the odor and leachates management generated in biodegradation process (Megharaj et al 2011; Kuppusamy et al 2016).

Efficiency: Composting bioremediation efficiency is influenced by environmental conditions. In some cases, it can reach more than 95%. The kinetics of degradation is the most constraining limiting factor (Nedeef et al 2012).

Treatment time: The time required for the treatment process ranges from 2 to 12 months (Mihail 2000; Nedeef et al 2012).

Costs: The costs are determined by the amount of soil to be treated, the soil fraction in the compost, availability of amendments, the type of contaminant, and the type of process design employed (FRTR 2002). Costs vary from 15-40 € per ton, averaging € 25 per ton (Nedeef et al 2012).

Landfarming. Land treatment, also called landfarming or land application (EPA 2006) is a simple technique that has been applied commercially in large scale with relative success. It has been used for over 25 years in the oil industry but has been known worldwide for more than 100 years (Khan et al 2004).

Landfarming is an engineered bioremediation system particularly useful for remote sites due to minimal equipment requirement, which generally uses passive aeration by tilling or ploughing the contaminated soil in order to reduce contaminant levels (EPA 2014).

The principle of operation: after excavation, the material is deposited on a large flat impermeable surface to increase interaction between polluted soil and atmosphere in order to improve the aerobic microbial activity in the soil (Zisu 2008; Nedeef et al 2012). In general, polluted soil is placed in layers no more than 0.4 meters thick so it can be worked with agricultural machines (Figures 3 and 4) (Wiliams 2006; Micle & Neag 2009).

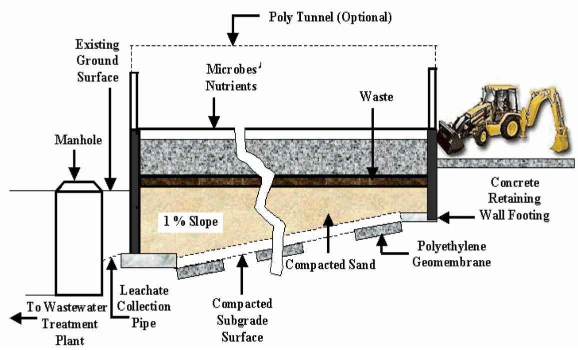

Figure 3. Land Treatment Schematic (Source: FRTR 2002).

Figure 4. Landfarming technology (Source: ETEC 2016).

Amendments or fillers can significantly increase remediation efficiency, nutrients, pH buffers and bulking agents may be applied to stimulate aeration of co-substrates, microbial metabolism or bacterial inoculations (Gomez 2014; Camenzuli & Freidman 2015). The biodegradation process is stimulated aerobically by tilling, ploughing or trough other mechanical mixing methods the soils which help by enhancing contact between contaminants and microorganisms, ensuring aeration and increase mixing and distribution of soil amendments (EPA 2014; Kumar et al 2011). Treatment strategies can be tailored according to the site-specific characteristics such as climate, location, soil type and temperature (Camenzuli & Freidman 2015). The process performance can be enhanced by adequate control of the influencing parameters: temperature needs to be maintained between of 20–40 °C, pH of 6.5–7.5, moisture up to 12-30% by weight or between 40-85% of the field capacity, and C:N ratio of 9:1 (Khan et al 2004; Kuppusamy et al 2016). Treatment is achieved through biodegradation and possibly photo oxidation in sunlight (Rockne & Reddy 2003). This technique can be applied in situ in cases of shallow contamination (less than 1 meter below ground surface) while in cases of deep contamination (deeper than 1.5 meters), the soils should be excavated and treated in special facilities (Kuppusamy et al 2016; UNIDO 2014).

Advantages and limitations: Landfarming is a popular technique due to the use of simple equipment and operability that makes the technology highly cost competitive; however there are some limiting factors that may be considered before employing this technology, such as a large area for treatment, the production of leachate and the volatilization of the compounds. Volatile constituents tend to evaporate rather than biodegrade in the treatment process and can result in air pollution problems. Prevention of groundwater and air pollution increase treatment cost, thereby reducing the main advantage of the technology. Landfarming may not be effective in treating heavier hydrocarbons and concentration reduction >95% are difficult to achieve also the effectiveness of the technology at high constituent concentration (more than 50.000 ppm) in severely diminished (EPA 2004; Mphekgo & Thomas 2004; Tomei & Daugulis 2013).

Aplicability: Landfarming is suitable for the treatment of a variety of organic chemicals including: BTEX, total petroleum hydrocarbons (TPH), such as diesels, light lubricating oils, crude oil, PAHs, particularly the lower ringed aromatic lighter compounds, such as naphthalene, phenanthrene and phenolic compounds (EPA 2014). Lighter petroleum hydrocarbons, including the constituents of gasoline, tend to be removed by evaporation during aeration processes and less degraded by microbial respiration and higher molecular weight petroleum constituents, such as those found in heating and lubricating oils and to a lesser extent in diesel fuel and kerosene, require long periods of time to degrade (Khan et al 2004; EPA 2004).

Efficiency: The best yields are obtained during summer, in warm, moist, sunny conditions; the biological processes are significantly diminished in intensity or even completely arrested in case of frost. In favorable conditions the yield could reach 90% (Rockne & Reddy 2003; Micle & Neag 2009).

Treatment time: The landfarming treatment period depends on the nature and concentration of contamination, clean-up criteria, soil type and volume, and varies between 3-24 months (Khan et al 2004; EPA 2014).

Costs: Treatment cost is relatively low, ranging from 30-70 €/ton (Wang et al 2016).

Biopile. Biocells, bioheaps, biomounds, compost cells, all different terms for biopiles, have been extensively used for remediating a wide range of petrochemical contaminants in soils and sediments (Germaine et al 2014). Biopile technique is a combination between landfarming and composting that provides a favorable environment for indigenous aerobic and anaerobic microorganisms and also controls physical losses of the contaminants by leaching and volatilization (Kumar et al 2011; Mani & Kumar 2014).

The principle of operation: the mixture of contaminated soil, nutrients and water is piled in a contained, covered and lined installation similar to a modern landfill (Camenzuli & Freidman 2015). Generally, the biopile system includes a treatment bed, an aeration system, irrigation/nutrient system and a leachate collection system (Shukla et al 2010). The regular biopiles are 2–3 meters high. In certain cases, plastic covers are used to prevent volatilization, evaporation and potential runoff (Figures 5 and 6) (FRTR 2002; EPA 2006; Sardrood et al 2013). In order to enhance the degradation process by creating optimum growth conditions within the pile, moisture, heat, nutrients, oxygen, and pH are carefully controlled and maintained (EPA 2014; Germaine et al 2014).

Similar to the composting technique, in biopile treatment, aeration occurs either passively or forced by air injection through a perforated piping system placed throughout the pile. The air distribution system can also be used to provide heat in order to optimize temperature when conditions are limiting. However, excess air injection can cause soil drying, which may inhibit microbial activity and accelerate the volatilization of the hydrocarbon contaminants rather than their biodegradation (Naseri et al 2014).

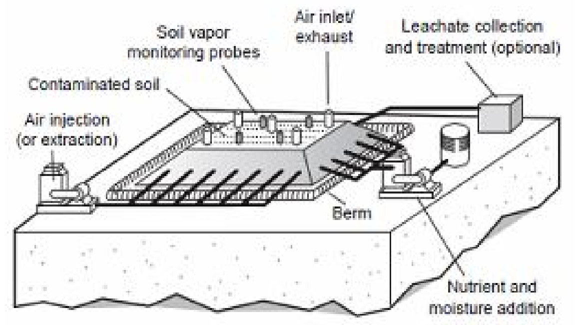

Figure 5. Typical Biopile Setup (Source: EPA 2004).

Figure 6. Ex-Situ Biopile Treatment (Source: Biogenie Corp. 2016).

In biopile system, biodegradation is preferred over volatilization (Sanscartier et al 2009; Sardrood et al 2013). The degradation of heavier petroleum products such as heating oil and lubricating oil generally takes more time compared to the lighter ones (Kuppusamy et al 2016). Surface drainage and moisture from the leachate collection system are collected, treated and recycled to the contaminated soil. The leachate is loaded with microorganisms which, by being reused, eliminate the acclimatization time. Nutrients (nitrogen and phosphorus) are often added to the recycled water (EPA 2006; Zisu 2008).

Biopile has a higher efficiency compared to composting and landfarming in terms of mass transfer of air, nutrients and water, thus providing a better pollutant removal strategy (Kuppusamy et al 2016). This technique has been successfully applied in extreme environment conditions. For this purpose, several strategies such as heating, biostimulation and bioaugmentation were used to increase the biomass of degrading microorganisms and shorten the bioremediation process (Gomez 2014).

Applicability: This technique has been subjected for numerous studies and research from laboratory to field scale applications, successful application have been demonstrated for most petroleum contaminants. Also pesticides, halogenated and non-halogenated VOCs (volatile organic compounds), nonhalogenated SVOCs (semivolatile organic compounds) can be treated (Khan et al 2004; Germaine et al 2014).

Advantages and limitations: advantages by comparison to landfarming, it requires a smaller area for the treatment of a similar volume of soil. However, it requires more complex technology, thus increasing the costs (Sanscartier et al 2009). Treatment in biopile isn't very effective for contaminant concentrations higher than 50.000 mg kg^{-1}, even more in cases of heavy metal concentration higher than 2500 mg kg^{-1}, which inhibits microbial growth (Kuppusamy et al 2016).

Efficiency: The yield of this process varies widely depending on the environment, reaching much more than 90% if the treatment time is sufficiently long (Nedeef et al 2012)

Treatment time: Biopile treatment lasts from a few weeks to a few months, depending on the contaminants present and the design and operational parameters selected for the biopile (EPA 2006).

Costs: Costs of treatment depend on the location where bioremediation process takes place, the costs vary from 30-70 €/ton when treatment is done on site, and 40-80 €/ton when treatment is done ex situ (Nedeef et al 2012).

Bioreactors. Bioreactor technique is an ex-situ biochemical processing system designed to remove pollutants from wastewater or pumped groundwater using microbes, treatment of contaminated soils in solid and liquid (slurry) phases. Regardless of the medium subjected to bioremediation, the principle is the same, only the biodegradation equipment defers (Neag 1997). Slurry bioreactors are the most highly engineered bioremediation systems and one of the most efficient ex situ technologies used in treatment of contaminated soils by recalcitrant pollutants under controlled environmental conditions. Slurry bioreactors have been employed as full-scale devices, and have been also extensively utilized for feasibility studies in a variety of bioremediation applications (Robles-González et al 2008; Tomei & Daugulis 2013; Kuppusamy et al 2016).

The principle of operation: contaminated soils are combined with water or wastewater and other additives and mixed in the bioreactor engineered system in form of closed vats, tanks or columns) in order to maintain contact between microorganisms and pollutants present in the soil, and do so in optimum environmental conditions for biodegradation (Latha & Reddy 2013; Bhardwaj & Kapley 2015). Soil treatment in the bioreactor requires mechanical preparation, which includes mixing, grinding and volumetric classification before the start of the biological process of degradation of pollutants (Volf 2007). In order to form the slurry, the soil is mixed with a specific water amount depending on the concentration of pollutants, the rate of biodegradation, and the soil type (Pavel & Gavrilescu 2008). Typical slurries contain 10-30% solids by weight (EPA 2006; Micle 2009). For the slurry to be maintained in optimum conditions, oxygen is provided through mechanical aeration, nutrients are also added as required, this until the pollutants are mineralized (UNIDO 2014). Addition of nutrient is based on the total amount of pollutant present in the soil in order to ensure an optimal ratio between carbon, phosphorus and nitrogen (Micle 2009). After the treatment, the slurry must be drained using pressure filters, vacuum filters or centrifuges. Resulting fluids also need further treatment with standard wastewater techniques (Williams 2006; Pavel & Gavrilescu 2008).

The regular slurry bioreactor components include the bioreactor (tank), installations for polluted soil handling and conditioning and also additional equipment such as gas emissions system, tanks for nutrient and pH conditioning of slurry (Figures 7 and 8) (Robles-González et al 2008).

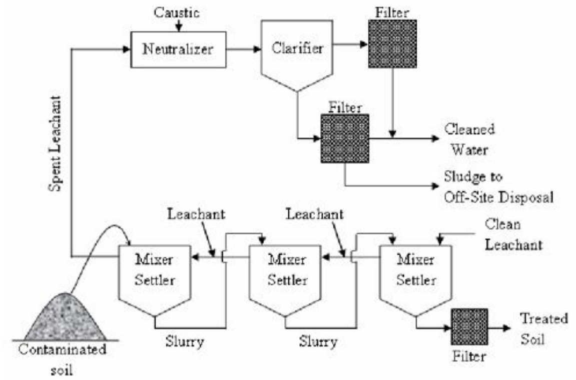

Figure 7. Bioreactor system (Source: Pavel & Gavrilescu 2008).

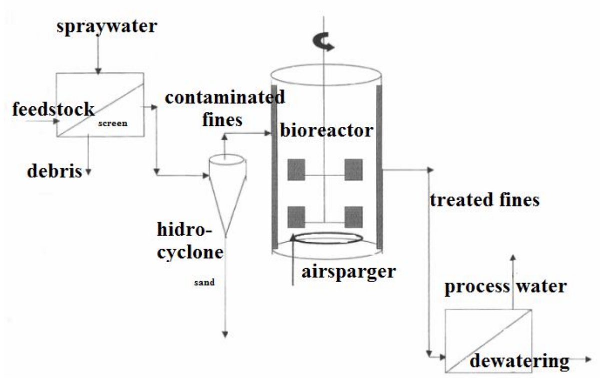

Figure 8. Typical Slurry Bioreactor (Source: Williams 2006).

As closed systems, slurry bioreactors can accelerate and enhance the treatment rate by creating better control, manipulation and oversight conditions for several environmental parameters, such as temperature, pH, aeration, nutrients, emissions and reactions (Bhardwaj & Kapley 2015; Kuppusamy et al 2016). The proper function of a slurry bioreactor depends on the balanced conditions of suspension, aeration and mixing. The important parameters that are part of the process are distribution of size particles, viscosity and density of slurry, oxygen needs of biomass, reactor scale etc. (Kleijntjens & Luyben 2001).

Slurry bioreactor technology can be operated in batch, continuous and semi-continuous models, under aerobic, anoxic and anaerobic conditions. Best control is provided by batch operation. The dimensions at full scale for low cost bioreactor are (24 m x 15 m) and the manufactured bioreactors can reach 25 meters in diameter and 8 meters in hight. It can have a capacity between 60-1000cost can reach m^3 (Robles-González et al 2008; Tomei & Daugulis 2013).

Applicability*:* Slurry bioreactor technology has been successfully applied in laboratory scale and commercial scale in the treatment of aerobically degradable compounds such as SVOCs, recalcitrant pesticides, explosive substances, aromatic hydrocarbons and chlorinated organic compounds, PAHs (Bhardwaj & Kapley 2015; Robles-González et al 2008). This technique is applied for soils that are difficult to treat by other processes, such as soils with high contents of clay (> 40%), or when more rapid treatment is required (Micle 2009; UNIDO 2014).

Advantages and limitations: Slurry phase bioremediation is a highly effective and expeditious process in comparison with the other analyzed processes. This technology offers a great advantage - precise control over the entire process; allowing control and maintenance of the influencing parameters best yields are achieved (Tomei & Daugulis 2013). While highly effective and rapid, the technique presents important disadvantages such as costs of the technology and pretreatment. Before entering this process, the contaminant can be extracted from the soil through physical extraction or through a soil washing process, which may severely increase the costs of this technique (Vidali 2001; Latha & Reddy 2013; Bhardwaj & Kapley 2015). Other factors that may increase the costs and therefore limit the applicability of this method (FRTR 2000):

- the requirement for excavation of the contaminated soil;
- nonhomogeneous soils or clayey soils cause serious difficulty in material handling;
- the increased cost of dewatering the soil fines;
- requirement of a unrecycled wastewater disposal method.

Efficiency: Decontamination using bioreactors is an efficient process; yields over 90% are easily achieved (Micle & Neag 2009).

Treatment time: A complete treatment is achieved in a few months and the biodegradation rate is rapid. (Kuppusamy et al 2016). Depending on the desired level of removal, nature and concentration of contaminant, treatment time varies in the slurry reactors between 5 days for PCP, 14 days for a pesticide-contaminated soil, and 60 days for refinery sludge (FRTR 2002)

Costs: Treatment using slurry-phase reactors cost vary 130-200 €/ton. Further treatment of volatile compounds enhance the costs, to approximately 160-210 €/ton (FRTR 2000; Kuppusamy et al 2016).

Numerous studies and research for ex situ bioremediation techniques have been conducted worldwide, from laboratory scale to full-scale application, in order to enhance the efficiency of bioremediation. Table 2 presents some examples of these technologies and their performances in treating hydrocarbon contaminated soils.

Table 2

Application of ex situ bioremediation technologies

Method	*Contaminant*	*Time*	*Yield*	*Reference*
		Composting		
Laboratory-scale in-vessel composting reactors	PAHs	98 days	-	Antizar-Ladislao et al (2006)
Enhanced laboratory-scale composting reactors	PAH	30 days	89%	Sayara et al (2011)
		Landfarming		
Field-scale enhanced landfarming	TPH	39 month landfarming	68.48%-90.04%	Wang et al (2016)
Laboratory-scale landfarming -batch applications	Diesel	300 days landfarming	59-73%	Liu et al (2012)
		Biopile		
Enhanced biopile pilot experiment	BTEX	15 days	90%	Genovese et al (2008)
Enhanced laboratory scale biopile	Diesel	40 days biopile	70 %	Chemal et al (2012)
Field-scale enhaced biopile	TPH	220 days	49.62%	Wang et al (2012)
		Bioreactor		
Enhanced slurry phase bioreactor	PAHs	-	85.5 - 92.8%	Nasseri et al (2010)
Enhanced slurry phase bioreactor	PAHs	3 days	99%	Moscoso et al (2012)

Conclusions. Each of the methods presented in this paper possess a number of advantages and disadvantages. Compared to in situ, ex situ technologies usually need less time for treatment and also provide a better control of the bioremediation process. Nonetheless, ex situ treatment requires the removal of contaminated soils from site, leading to a raise in costs and necessary equipment. Solid-phase systems (composting, landfarming, biopile) require a large amount of space, and cleanup requires more time to complete than slurry-phase processes (bioreactor). Also, considerable distinctions are observed between the technological levels used in ex situ methods, from the simple excavation and pile placement of contaminated soils in landfarming, to controlled systems such as bioreactors whose complexity is comparable to that of industrial reactors. The costs of ex situ bioremediation technologies depend on a number of factors, including the nature and concentration of contaminants, the amount of soil in need of treatment, time scales and the remediation goals. In terms of efficiency, none of these technologies are suitable for all types of contaminants or for all specific local conditions that exist at contaminated sites. Treatment processes are usually combined for better efficiency of contaminants removal.

Bioremediation is a sustainable solution and has been validated as a suitable and cost effective alternative for the remediation of hydrocarbon contaminated soils. Further studies must be undertaken to improve the efficiency of ex situ biological technologies and more research is needed to reduce the cost of implementing the techniques.

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