

# **BIOPILE TO TREAT OIL-CONTAMINATED SOILS: SOME BRAZILIAN EXPERIENCE**

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## **ABSTRACT**

Remediation of soils contaminated with petroleum and its products became a major issue in all regions of the world where on-shore and off-shore exploitation, refining, transportation and storage of these products are carried out intensively. Many techniques for remediation of contaminated areas have been developed and tested during decades, being bioremediation both *in-situ* and *ex-situ* tow of the available options that require further development, which are currently capturing the attention of different sectors involved with the problem in Brazil. This paper presents the historical perspective of the increasing problem that initially appeared in the most traditional industrialized countries and currently has been intensified in countries with growing economy and technological development such as Brazil. Technological options for remediating the areas, variables relevant to the cleaning process, as well as the most recent trends in Brazil regarding the use of different techniques, with focus on biopiles are briefly presented.

## **KEYWORDS**

Bioremediation; biopile; bioaugmentation; cost-effectiveness; contaminated sites; petroleum hydrocarbons.

## **1 INTRODUCTION**

With the displacement of productive centres to developing countries and strengthening of several economic sectors, including information, knowledge and technology, remarkable changes in soil uses have occurred since the 1970's, resulting in empty industrial parks and brownfields. More than one million of contaminated or potentially contaminated industrial and commercial areas are estimated inside Europe[1]. In

Netherlands, for instance, there are about 400 thousand sites suspected of being contaminated [2]; in Germany, this number is around 362 thousands [3]; in Belgium, seven thousands and in France, more than 4 thousand of such sites exist [4]. According to the Swedish Environmental Protection Agency, 45 thousand sites were suspected of being contaminated in Sweden, being half of them with no defined responsibility as required by the Environmental Code [5]. More than 10 thousand of these sites belong to the highest risk category and required investigation. The costs of cleaning up a contaminated site averages 3.5-4.5 million Euros. It was estimated that around 4.9 billion Euros would be required to remediate the most seriously contaminated sites. With an investment of around 108 million Swedish kronor a year (of which, the Swedish State pays half), by 2050, only 1,500 contaminated sites among 45 thousands estimated will be cleaned up. In USA, among 1 569 contaminated sites classified in the priority category, one thousand had been rehabilitated in 2009 [6]. Cities such as Pittsburgh (Pennsylvania), Buffalo (Nova York), Lowell (Massachusetts) in USA, as much as Liverpool in England, Kitakyushu in Japan and many others in UK, France, Belgium, Germany, Spain and the whole Eastern Europe are examples of decommissioning of industrial areas, with reduction of 40 to 80% of the productive industrial parks, which generate and transfer to a large extent to the public sector, the economic, social and environmental problems resulting from this phenomenon [6].

## **2 THE MARKET IN BRAZIL (SAO PAULO STATE AS AN EXAMPLE)**

In Brazil, according to a preliminary evaluation carried out in 2003, it was estimated the existence of more than 15 thousand potentially contaminated areas. In this total amount, Sao Paulo is the state that has the most comprehensive database of potentially contaminated areas, with 2.9 thousand contaminated areas confirmed in different stages of investigation and remediation [7]. The main states in the southeast, south and northeast regions are currently organizing step by step their databases about contaminated sites. The expectation is that the scenario in other important states from the economic viewpoint is not far from the one found in Sao Paulo, due to similarities in trade, industry and agriculture activities. In Sao Paulo, during the years, due to intensive population growth and urbanization, the changes occurred, mostly with the use of old industrial areas for commercial and residential uses [1]. Most changes occurred during the last five years, suggesting that this trend of reusing industrial areas for commercial and residential purposes is relatively recent. For most of these areas no previous diagnosis was carried out to assess the status of the soil and groundwater. Among 2 070 areas that undergone changes in land use from industrial to other uses between 1996 and 2004, about 533 (25%) were turned into more sensitive uses with the construction of households, schools, shopping centres [1] Ayres da Silva, 2002). About 12 thousand potentially contaminated areas only in the city of Sao Paulo were produced as a result of leaking, liquid waste infiltration and illegal solid waste disposal. Similar to what happened in France during the 1970's it is likely that at least 6 thousand cases of contamination will be confirmed, so remediation measures of different types can be implemented.

In 2009 almost 3 thousand sites had already been confirmed in the contaminated category [7] as shown in Table 2. Fuel stations represent 78% of these contaminated sites, followed by industrial sites (13%), commercial sites (4%) solid waste final disposal sites (3%) and accidents or unknown contamination sources (1%). The fact that 78% are fuel stations, are due to the command and control instruments in this sector, which require remediation of sites in order to deliver installation and operation licenses. As soon as other economic activities establish the

same level of requirement followed by command and control instruments, the percentage of contaminated sites due to other activities than fuel storage will increase. According to the database of CETESB, the main contaminants groups identified during the last two decades are aromatic solvents, liquid fuels, with 65% of the total contaminants according to Figure 2, illustrating how the contaminated areas are distributed in terms of contaminants in Figure 1.

Table 1. Contaminated areas, November 2009, Sao Paulo State-Brazil [7].

Region	Activities					Total
	Trade	Industry	Residues	Fuel Stations	Accidents/ unknown	
Sao Paulo State	32	83	25	675	3	818
Sao Paulo Metr. Region	23	108	17	375	5	528
Sao Paulo inland	53	129	33	900	13	1128
Sao Paulo littoral	13	34	20	199	2	268
Paraíba Valley	2	28	1	130	1	162
Total	123	382	96	2,279	24	2,904

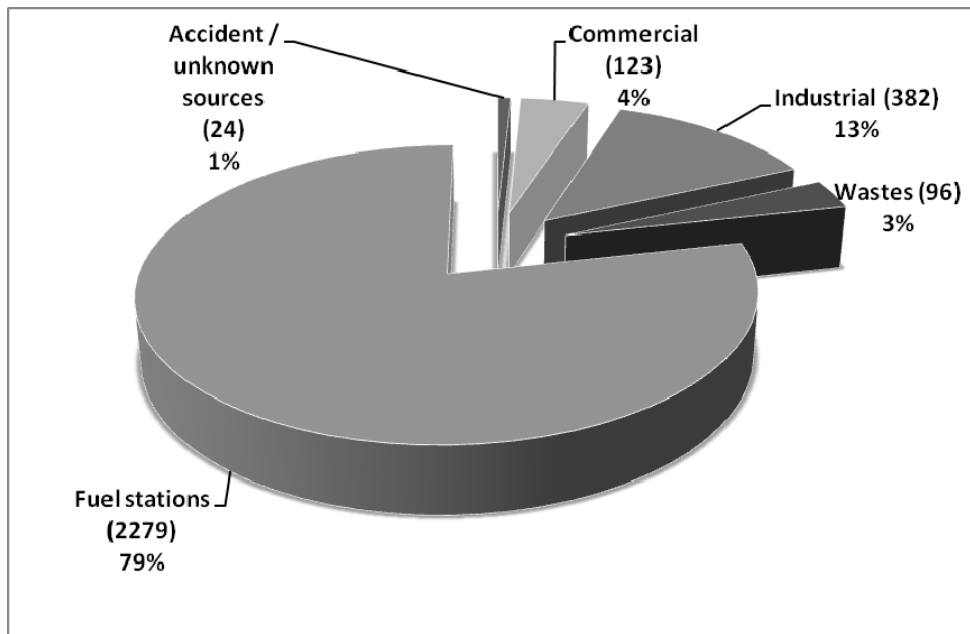


Figure 1. Distribution of contaminated areas according to activity - Nov/2009 [7].

**Most commonly used remediation techniques in Brazil:** The first contaminated sites in Brazil were identified during the 1980's. The first remediation actions occurred in 1991, when *pump-and-treat* technique was used to remediate aquifers contaminated with petroleum in underneath fuel stations. The next years were followed by a large number of environmental diagnosis and intensive technology development and transfer, particularly in Sao Paulo metropolitan area. In 1997 the technique soil vapour extraction (SVE) and air injection in saturated zone named *air sparging* (AS) were introduced in Brazil. The Industrial Area of Camaçari in Bahia State was the first area remediated with these technologies [8].

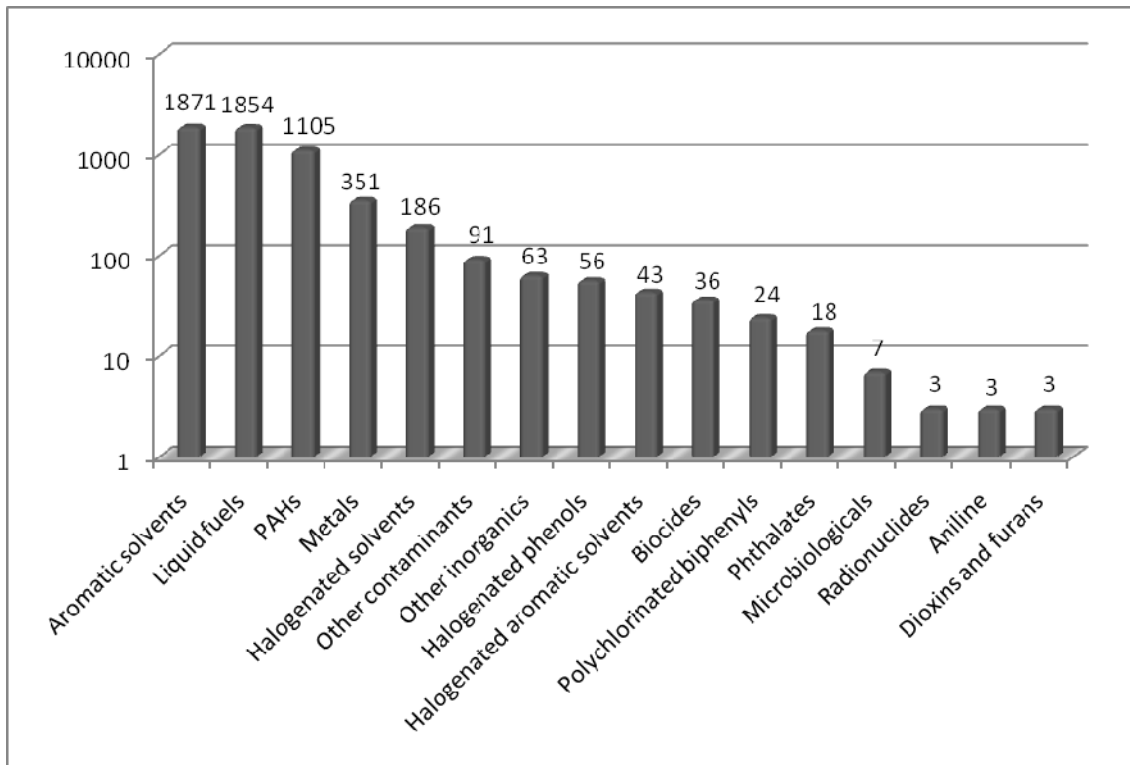


Figure 2: Registration of contaminants responsible for contaminated areas Nov/2009 [7].

Between 1999 and 2000 the first multiphase extraction (MPE) combining the benefits of pumping and soil vapour extraction were used, being this strategy the one applied to areas contaminated with hydrocarbons less dense than water, as it is the case of fuel stations, rail terminals for fuel distribution and the petrochemical industries. During the first years of the 21<sup>st</sup> century, companies coming from Canada, USA, Germany and France brought new equipment and technologies to Brazil through cooperation with well-established local companies to implement remediation systems based on Advanced Oxidative Processes (AOPs), reactive barriers, and *in situ* bioremediation. According to [7], in 1.275 areas undergoing remediation or already remediated by 2009, pump and treat (P&T), recovery of free phase and multiphase extraction had been the techniques chosen in 68% of the cases (Figure 3), which reflected two aspects: (a) the large number of fuel stations undergoing remediation due to leaking from storage tanks; (b) reduced technological knowledge particularly found in small and medium size companies, which give service to the fuel distribution network, since these techniques are simple to apply and the investments required are relatively low, compared to more advanced techniques. In 2009, the next two most commonly used techniques were vapour extraction and soil and waste removal, which together represented 20% of the remediation projects. The other technological options brought from abroad still require further adaptation to the local conditions in order to produce efficiency and effective results. Figure 4 shows the evolution during the years of different remediation techniques in USA, which is currently one of the most advanced and mature markets in the world. During the 1980's the prevalence of pump and treat (P&T) was progressively replaced by monitored natural attenuation-MNA and bioremediation. As previously mentioned (Figure 3), in Brazil the stage is still the prevalence of P&T, suggesting the juvenile nature of the remediation market.

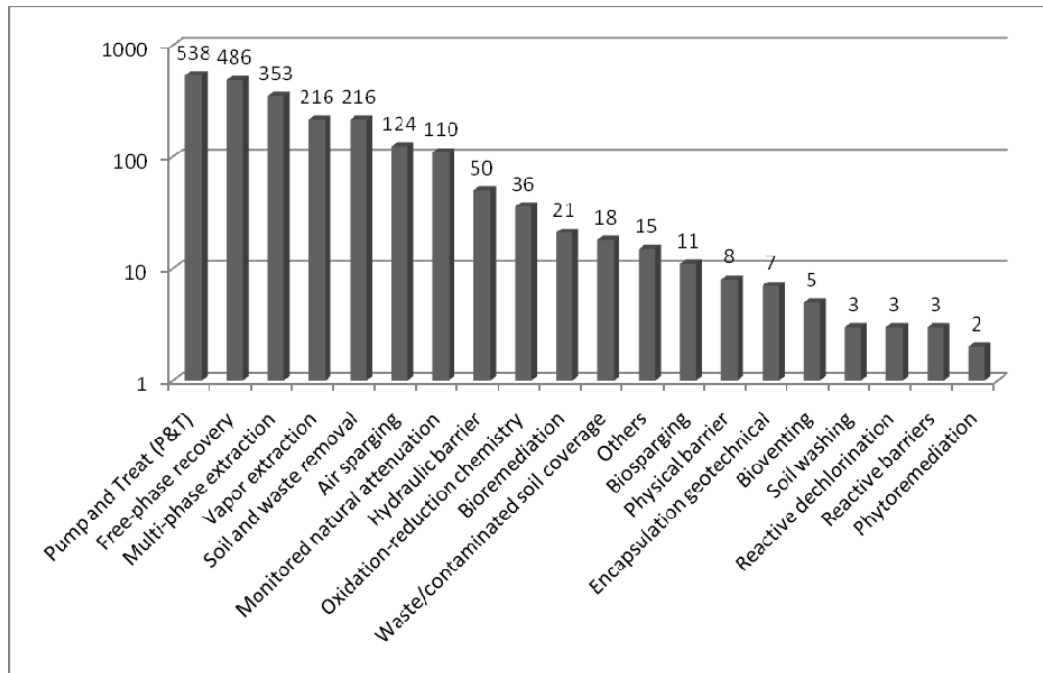


Figure 3. Frequency of use of different remediation techniques in Brazil by Nov 2009 [7].

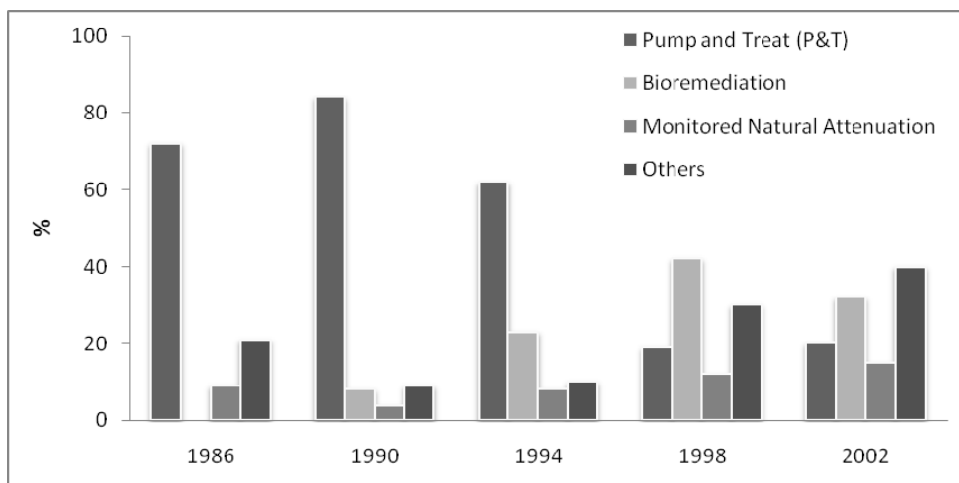


Figure 4. Evolution of remediation techniques in USA market [6].

In Brazil, among 200 companies that offered services for pollution control and abatement with focus on remediation of contaminated sites, 100 has the headquarter in Sao Paulo [9]. Among them, 2% are large-size companies with annual income of US\$ 30 million, 7% are medium-size companies with annual income between 4.5 and 30 US\$ million. The remaining 91% are small-size companies with annual income below US\$ 4.5 million.

### 3 BIOREMEDIATION OPTION

Bioremediation can be regarded as an attractive technology that results in the partial or complete biotransformation of organic contaminants to microbial biomass and stable innocuous end-products such as CO<sub>2</sub> and water. Moreover, this technology seems to be

cost effective and environmentally accepted [10]. In situ bioremediation includes bioventing, biosparging, bioaugmentation and intrinsic bioremediation or natural attenuation. An *ex situ* bioremediation can be carried out through landfarming, static biopiles and bioreactors. The main advantages of *in situ* bioremediation are: (a) the fact that there is no need for removal of soil or groundwater; (b) the fact that an effective transformation of contaminants occurs, instead of contaminants removal or immobilization, which might not be a permanent solution. An *ex situ* bioremediation has the advantage of allowing major intervention and better control of variables, being also faster and less dependent on the hydraulic conductivity, as it is the case of in situ bioremediation. The last property is particularly important when remediating clayey soils. Its main disadvantage is the need for excavation/removal of soil or groundwater. Many environmental variables can affect the biodegradation process in different levels affecting the microorganism's growth and metabolism and/or the physical and chemical properties of the contaminants [11]. Such variables are:

- **Microbial population:** Microorganisms must be in sufficient number [12] and resist to the toxic effect of contaminants, which in turn depends on concentration. When the population of indigenous microorganisms capable of degrading the target contaminant is less than  $10^5$  colony-forming units (CFU) per gram of soil, bioremediation will not occur at a significant rate. Too low concentration of contaminants might also limit biodegradation [13]. Different factors in the soil might affect the microorganism's metabolism.
- **Hydraulic conductivity (*k*):** It must be sufficiently high to allow transportation of nutrients and electron's acceptor through the soil and/or aquifer and it is particularly relevant for in situ bioremediation. Soils with  $k > 10^{-4}$  cm s<sup>-1</sup> are considered the most suitable ones to be treated by *in situ* bioremediation [12].
- **Temperature:** According to Atlas *et al.* (1998), the enzymatic degradation and the microbial metabolism, double every 10 °C until a temperature around 40 °C is reached; from this point, temperature has the opposite effect (inhibition) to most microorganisms. In high temperatures, proteins might be damaged. Thermophile microorganisms can also bioremediate [14]. Under very low temperatures, the kinetics slows down due to increasing viscosity and reduced water solubility of contaminants, promoting the volatilization of toxic alkanes of low molecular weight.
- **Moisture:** The most suitable range depends on the field capacity and it is important for nutrients diffusion and microbial mobility [13]. The optimum moisture range goes from 25 to 85% of the field capacity.
- **Electron acceptors:** The petroleum hydrocarbons biodegradation occurs due to oxidation-reduction reactions, where the hydrocarbon is oxidized (electron donor) and a compound which play the role of electron acceptor is reduced. Compounds that act as electron acceptors include O<sub>2</sub>, nitrates, iron oxides, sulphates, water and CO<sub>2</sub>, being this the decreasing preferential order. Acceptors with higher oxidation potential result in faster oxidation of hydrocarbons [15]. Dissolved O<sub>2</sub> is a limiting factor, since besides acting as final electron acceptor in the aerobic metabolism, it also works as substrate in the initial stages of petroleum bioremediation processes due to catabolism of aliphatic, cyclic and aromatic hydrocarbons by microorganisms that only initiate reactions catalyzed by enzymes such as mono- and dioxygenases [16]. Under anoxic or anaerobic conditions other electron acceptors are activated.
- **pH:** Soil pH has a direct action on the microbial metabolism; for instance, under acidic pH, metals availability in solution increases, which makes the environment

toxic to most microorganisms. The optimum range is around neutrality between 6 and 8.

- **Nutrients:** Contaminated soil is normally deficient in nutrients, which are necessary to support the microorganisms' growth. Different C:N:P rates have been suggested, being the rate 100:10:1, the most frequently mentioned [17]. However, other rates have been considered appropriate studies with Brazilian soils, such as 100:1.25:1. Excessive nitrogen can inhibit some microorganisms, such as the lignin-degrading system of white-rot fungi (WRF) that has been described as a degrader of a wide range of organic pollutants, particularly in liquid phase.
- **Contaminant bioavailability:** Contaminants can adsorb to soil particles, rendering some contaminants unavailable to microorganisms for biodegradation. Thus, in some circumstances, bioavailability of contaminants depends not only on the nature of the contaminant but also on soil type. Hydrophobic contaminants, like petroleum hydrocarbons, have low solubility in water and tend to adsorb strongly in soil with high organic matter content

### 3.1 Biopiles in Brazil: Transpetro

Differently from windrows that require frequent turning (usually, once a week), biopiles which is also an ex-situ strategy require forced aeration and often use complementary suction of soil gas to feed air to the microbial community. It can be conducted on site but it requires careful waste management for optimization of the degradation rate. The contaminants removal efficiency achieved with biopiles depends first of all, on the type of contaminant and the type of soil and second, on how much is done to optimize the processes and how long the biopile is operated, being the level of optimization and treatment time directly related with the final cost per treated tonne of soil. Therefore, cost-benefit analysis as well as some level of risk assessment is usually necessary in order to define the level of remediation that is required. Table 2 presents a number of experiences with *ex-situ* bioremediation of sites contaminated with petroleum hydrocarbons in lab, pilot and full-scales. In Brazil, the Norm N-2622B created by Petrobrás (2006) with the objective of establishing the criteria for waste management and final disposal by the company suggests some treatment technologies, emphasizing that the choice must consider among other aspects, the smallest environmental impact, reduction of use of natural resources and evaluation of costs with transportation as well as the impact of the final costs. The BATNEEC concept (*Best Available Techniques Not Exceeding Excessive Costs*) must be applied when choosing the remediation technique. According to the survey carried out in August 2009 in the Corporate Waste System (Petrobrás-SCR), in a 36 month-period (from August 2006 to August 2009), Transpetro - the largest oil and gas transportation company of Brazil that works with transportation and storage activities of oil and byproducts, such as ethanol, bio-fuels and natural gas – generated 258 746 tonnes of soils contaminated with oil, meanwhile in the same period, 259 233 tonnes of soil contaminated with oil, taken from contaminated areas were treated by the company. Data obtained from Petrobrás-SCR also showed that 225.898 tonnes (87%) from the total were treated with biopile technology, giving a clear picture of the current importance of this technique in the country (Figure 5). Per tonne of treated soil, the average cost varied as following, according to the technology: biopile remediation ( $233.3 \pm 128.8$  USD); Thermal desorption ( $316.7 \pm 52.9$  USD); Cement co-processing ( $758.6 \pm 309.3$  USD) and; Incineration (1.400 USD).

Table 2. Investigations about ex situ bioremediation of soils contaminated with petroleum hydrocarbons (BTEX, HTPs, HPAs).

Scale: 1. Lab-scale, microcosm; 2. Pilot scale; 3 Full-scale/ Contaminant(s) in the soil	Biological process applied (aerobic or anaerobic)	Microorganisms identified (yes/no) If yes, give the specie	Soil origin or soil type	Region (climate)	Treatment period and % removal	Reference
1 TPH	Aerobic (Oxygen reducing)	No identified	Tyrol, Austria	Tyrol, Austria	88 days; 88%	18
1 n-alkanes	Aerobic (Oxygen-reducing)	<i>Pseudomonas</i> sp. BS2201, BS2203 and <i>Brevibacillus</i> sp. BS2202	Moscow	Temperate Continental	10days; 90-95%	19
1 n-alkanes	Anaerobic (Nitrate-reducing)	<i>Pseudomonas</i> sp. BS2201, BS2203 and <i>Brevibacillus</i> sp. BS2202	Moscow	Temperate Continental	50 days; 20-25%	19
1 PAHs	Anaerobic (Nitrate-reducing)	<i>Pseudomonas</i> sp. BS2201, BS2203 and <i>Brevibacillus</i> sp. BS2202	Moscow	Temperate Continental	50 days; 15-18%	19
1 Benzene microcosms	Anaerobic (Nitrogen-reducing)	<i>Marinobacter</i>	Okahoma	Temperate	12 weeks; 10%	20
1 Benzene microcosms	Aerobic (oxigen-reducing)	<i>Marinobacter</i>	Okahoma	Temperate	4 weeks	20
1 PAHs	Aerobic (oxigen-reducing)	<i>Acidovanax</i> , <i>Bordella</i> , <i>Pseudomonas</i> , <i>Sphingomonas</i> e <i>Variovorax</i>	Canada	Low temperate	90 days; 52-88%	21
1 PAHs	Anaerobic (Nitrate-reducing)	<i>Acidovanax</i> , <i>Bordella</i> , <i>Pseudomonas</i> , <i>Sphingomonas</i> e <i>Variovorax</i>	Canada	Low temperate	90 days; 39%	21
1 PAHs	Aerobic (Oxygen reducing)	No identified	silt-clay type	Temperate	75%	22
1 TPH	Aerobic (Oxygen reducing)	No identified	Brazil (Clay soil))	Tropical	24 weeks; 86.2%	13



1	TPH	Aerobic (Oxygen reducing)	No identified	Brazil (clay soil)	Tropical	12 weeks; 70%	13
1	TPH	Aerobic (Oxygen reducing)	No identified	Calcareous sandy soil Burgan, Kuwait desert	Desert	43 weeks; 15-33%	23
1	TPH as diesel (C14-C20)	Aerobic (Oxygen reducing)	No identified	( sub solo aloino)		155 days; 65%	18
1	TPH as aviation kerosene (C11-C14)	Aerobic (Oxygen reducing)	<i>Pseudomonas aeruginosa</i> Inoculum from four contaminated sites	Brazil	Tropical	Period? 67-75 %	16
2	TPH as diesel (C14-C20)	Aerobic (oxygen-reducing) switching Anaerobic (xx-reducing)	No identified	Germany	Temperate	27 day; 50%	24
2	PAHs (naphthalene, phenantherene, metihyl-naphthalene, fluorine e fluoranthene)	Anaerobic (sulfat reducing)	No identified	San Diego Bay	Mediterranean	20 days 60-120%	25
2	TPH	Aerobic (Oxygen reducing)	No identified	Paulinea - SP	Tropical	14 days; 55-89%	26
2	PAH	Aerobic (Oxygen reducing)	No identified	Paulinea - SP	Tropical	14 dias; 70-88%	26
2	TPH	Aerobic (Oxygen reducing)	No identified	Germany	Temperate	85%	27
2	TPH, n-alkanes, PAH (dibenzo-thiophenes and phenan-threnes)	Aerobic (Oxygen reducing)	No identified	-	-	11 dias; 50-62%	28
2	TPH	Aerobic (Oxygen reducing)	No identified	Clay soil, Duque de Caixias - RJ	Tropical	120 dias; 81%	29

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3	Oily sludge from flare bunker	Aerobic (Oxygen reducing)	No identified	Alberta, Canada	Temperate	8 weeks; 62-86%	30
3	TPH as diesel (C14-C20)	Aerobic (Oxygen reducing)	No identified	Nebraska, USA	Temperate	52 weeks; 38,9%	31
3	TPH as diesel (C14-C20) and aviation kerosene (C11-C14)	Aerobic (Oxygen reducing)	No identified	Marine Corps, Hawai, USA	Temperate	7 weeks, 57,1%	32
3	Intemperic hydrocarbons	Aerobic (Oxygen reducing)	No identified	USA	Temperate	45 weeks, 55%	33
3	TPH as lubricating oil (C20-C40)	Aerobic (Oxygen reducing)	No identified	Serdp, USA	Temperate	47 weeks, 70,4%	34
3	TPH as Diesel (C14-C20)	Aerobic (Oxygen reducing)	No identified	Serdp, USA	Temperate	47 weeks, 87,6%	34
3	TPH as lubricating oil (C20-C40) and TVOC	Aerobic (Oxygen reducing)	No identified	Helsinki, Finland	Temperate	21 weeks, 70%	35
1	TPH (microcosm)	Aerobic	No identified	Clay loam, China	Temperate, continental-type monsoon climate	12 weeks, 61%	36
1	PAH (fluorene, phenanthrene, anthracene, flouranthene, pyrene and benzoanthracene) (Lab-scale reactor)	Aerobic	No identified	Sandy loam, Spain	Mediterranean	30 days, 96.53%	37
3	TPH, (windrow)	Aerobic	No identified	Scotland	Temperate	28 weeks, 98%	38
3	TPH, (Biopiles)	Aerobic	No identified	Scotland	Temperate	28 weeks, 78%	38
1	TPH, n-alkanes (Lab-scale reactor)	Aerobic	<i>Glomus caledonium</i> NW03 and <i>Bacillus subtilis</i> NW08	China	Temperate	60 days, 92.6%	39
1	TPH (bench-scale bioreactor)	Aerobic	No identified	Coarse grained, Canada	Polar desert	313 days, 66%	40

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3	TPH (landfarming experiment)	Aerobic	No identified	Coarse grained, Canada	Polar desert	3 years, 50%	40
1	TPH (bench-scale bioreactor)	Aerobic	No identified	Sandy loam soil, Brazil	Tropical	42 days, 19.6%	41
2	TPH (pilot-scale bioreactor)	Aerobic	No identified	Sandy loam soil, Brazil	Tropical	42 days, 35.1%	41
3	TPH (pilot-scale bioreactor)	Aerobic	No identified	Milan, Italy	Temperate	9 weeks, 60%	42
1	Hydrocarbons (n- hexadecane, n-octane; n- dodecane, xylene)	Aerobic	<i>Pseudomonas aerugenona</i> and <i>Rhodococcus</i> sp.	Faridabad and Ratnagiri, India	-	6 weeks, 90%	43
1	Fuel oil (aliphatic and aromatic hydrocarbons) (lab-scale reactor)	Aerobic	No identified	Aridisol Atacama Region, Chile	Desert	56 days, 59%	44

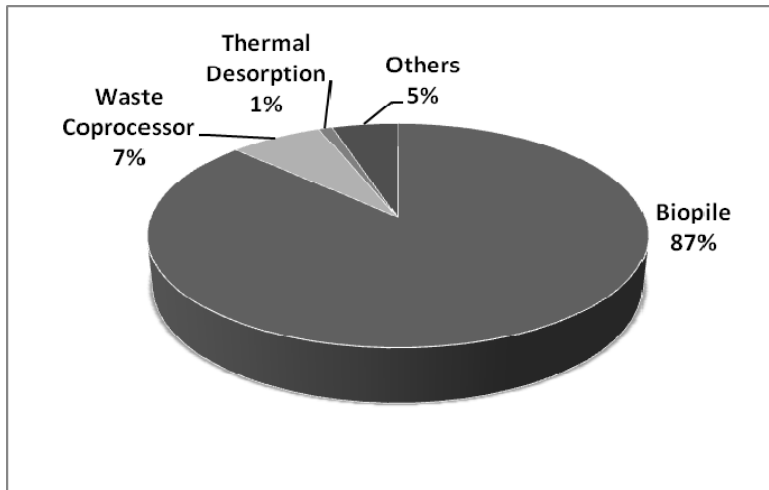


Figure 5. Remediation technologies used from August 2006 to August 2009 to treat 258 746 tons of soil contaminated with petroleum hydrocarbons (Petrobrás SCR, 2009).

#### 4 FINAL REMARKS

Bioremediation is clearly increasing in the world and particularly in Brazil, as a cost-effective alternative to treat soil contaminated with petroleum and its products. However, more investigation and process control, followed by equipment and technique development is required. On the other hand, the end-point of remediation needs to be better defined relative to the receptor that requires protection. Often, soil that shows significant recovery regarding removal of target contaminants might be still impaired with respect to human and/or ecological risk.

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