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"Gheorghe Asachi" Technical University of Iasi, Romania

OPTIMIZING BIOREMEDIATION OF HYDROCARBON POLLUTED SOIL BY LIFE CYCLE ASSESSMENT (LCA) APPROACH

Giuliana D'Imporzano[1,6]*, Ilaria Re[1], Federica Spina[2], Cristina Varese[2], Edoardo Puglisi[3], Giulia Spini[3], Carla Gramellini[4], Giacomo Zaccanti[4], Fabrizio Beltrametti[5] Adriana Bava[5], Fabrizio Adani[6]

[1]Consorzio Italbiotec, Via Fantoli 16, 20100 Milano MI Italy
[2]Università di Torino, Viale Mattioli 25, 10125 Torino TO Italy
[3]Università Cattolica del Sacro Cuore, Via Emilia Parmense 84, 29122 Piacenza PC Italy
[4]Arpae Emilia Romagna, Via Po 5, 40139 Bologna BO Italy
[5]Actygea Srl, Via R. Lepetit, 34 21040 Gerenzano,VA Italy
[6]Università degli Studi di Milano, Via Celoria 2, 20100 Milano MI Italy

Abstract

In the former Carbochimica site of Fidenza, a bioremediation approach was developed using the technique of biodegradation of pollutants thanks to a selected autochthonous bacterial-fungal consortium. The soil was heavily polluted up to values of total hydrocarbon equal to 1800 mg/kg. The consortium was selected from the microorganism living in the Fidenza soil, bioaugmented and finally reinoculated in the bio-pile for soil treatment. The approach is absolutely innovative, due to the presence not only of bacterial strains but also for the use of fungal strains operating in synergy with the bacteria. The first data from the trials show an effective soil remediation performance. The LCA analysis allowed to make a global assessment of the environmental impacts of the bio-pile remediation treatment scenario compared to the no-action scenario. Impacts were assessed on 18 impact categories at the midpoint level according to the ReCiPe method. For the bio-augmented bio-pile remediation, the results showed a value in the climate change category of 10 kg CO_2 for each ton of remediated soil, and at the same time improvement in the categories relating to the toxicity at the local level.

Key words: bio-augmentation, bio-remediation, hydrocarbon, LCA

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1. Introduction

The depuration of soil in contaminated industrial areas is a crucial practice to reduce significant hazards for health and environment. The remediation of soil answers to the need of restoring the natural ecological functions: geopedological nutrient cycling, primary production of food and feedstock, water depuration and biodiversity saving (WHO, 2005). Several case studies showed that the ecological restoration of soil resulted in a significant increase in biodiversity and in the restoration of critical ecosystem functions (Benayas et al., 2009).

According to the European Environmental Agency, the EU territory counts 340,000 contaminated sites (EEA, 2014, Panagros et al., 2013) of which, at least 290,000 have never been treated. Among the soil polluted by hydrocarbons, the

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[*] Author to whom all correspondence should be addressed: e-mail: Giuliana.dimporzano@unimi.it; Phone: 39 3287573510; Fax: 39 0250316521

recurring compounds are mineral oils, polycyclic aromatic hydrocarbons and mixtures of low weight volatile hydrocarbon (EEA, 2014).

If, on the one hand, the restoration of the natural function of the soil is a social priority at the local level, on the other hand, every intervention of remediation brings environmental costs, which always have a global dimension (greenhouse gas emissions, particulate matter formation), unlike the effect of site pollution. In order to evaluate the effectiveness of a bioremediation treatment, it is necessary to make an analysis of the environmental impacts of all the steps included in the remediation process and to have an idea of the consequences of inaction (no action scenario).

Up to now, the criteria used to choose a soil remediation technology are based on technical standards or cost constraints (Cappuyns, 2013), and yet it is not common practice to perform a global analysis of the environmental consequences at the local and global level for the different technologies and in different environments. The life cycle assessment (LCA) is a widely accepted and applied method for evaluating and quantifying the environmental impacts associated with the life of a product or service, from the input of resources to end-of-life treatment.

Thus, LCA delivers a systemic and global perspective on the service and can be usefully applied to the evaluation of technologies that produce ecological benefits (Hauschild, 2005). LCA is now increasingly used to evaluate the environmental pros and cons of different options for the remediation of contaminated sites (Beames et al., 2015, Hauschild, 2005, Toffoletto et al., 2005).

LCA in the case of contaminated sites ideally aims to account for primary impacts, associated with the state of the site pollution, (i.e. it describes the local impacts related to the pollutants bound in the soil and released during the considered timeframe of evaluation, in addition to the pollutants left in the subsurface during and after remediation); secondary impacts, associated with resources use and emissions arising in the remediation project, (i.e. the use of fuel, electricity and chemicals for the soil clean-up) and finally when possible, LCA should account for tertiary impacts, associated with the effects of the reoccupation of the site: they cover future consequences and impacts of the clean-up process and are linked to the restoration of ecosystemic services, economic benefits and social issues of the future use of soil. In this work, primary, secondary and tertiary impacts were considered, and the work highlighted the impacts at local and global level.

This assessment, therefore, provided a global tool to consider the pros and cons of a bioremediation intervention based not only on the implementation costs or the need for treatment, but also on the consideration of impacts of intervention and non-action.

Finally, the use of LCA allowed pinpointing hotspot in the management of bio-pile that were critically discussed and represent the basis for a more sustainable approach to bioremediation and bio-pile running.

2. Materials and method

2.1. Description of the contaminated site and remediation technique

The polluted soil evaluated in this work was from the Carbochimica industrial area, a national interest site (SIN) of Fidenza municipality (PC), Italy. The area was occupied for over 50 years by petrochemical companies, and currently the soil is heavily polluted with PAH and BTEX up to a value of total hydrocarbon of 1800 mg/kg. Within the frame of LIFE BIOREST, EU life project, a bioremediation approach was developed using the technique of biodegradation of pollutants thanks to a consortium of selected autochthonous bacteria and fungi. The consortium was selected from the microorganisms living in the Fidenza soil on the base of their ability to degrade different hydrocarbon compounds and to be competitive in the contextual conditions. The selected microorganisms were bio-augmented (Jiang et al., 2016, Mrozik and Piotrowska-Seget 2010, Pino et al., 2016, Spina et al., 2018) and finally reinoculated in the soil for treatment in the dedicated bio-pile. The approach is entirely innovative, due to the presence not only of bacterial strains but also for the use of fungal strains operating in synergy with the bacteria. A detailed description of the bioaugmentation approach used is provided in Spina et al. (2017) and Spina et al. (2018).

The experimental bio-remediation trial was performed on 600 tons of soil, using the facility and the management procedure actually used in the SIN, except for the use of the selected consortia of microorganism.

Excavation of soil, the first phase, was followed by the inoculation step, i.e. the soil was supplemented with rice husk, the carrier of the fungi-bacteria inoculum, nutrients were added (nitrogen and Phosphorus) and finally mixed. The soil was then positioned in a closed vessel on a waterproof platform made by a geo-membrane of high-density polyethylene (HDPE), the bio-pile. Air was forced for a total of 12 hours a day into the pile to support the composting process. The temperature of the biomass and the oxygen concentration in the outlet flow were monitored during the process.

2.2. LCA Goal and scope

The objectives of this study are a) to evaluate, via attributional LCA methodology, the potential environmental impacts of the remediation process for hydrocarbon-contaminated soils, as developed in the BIOREST project (bio-augmentation of fungi-microbe consortium), b) to compare the effects of bioremediation to that of the no-action scenario, c) to highlight possible points for improvement of the environmental performance of the bioremediation and model an optimized scenario.

2.3. System boundaries

The boundaries considered in this work include the inputs of material and energy for all the production steps and the capital goods, i.e. the building of the bio-pile device, the production of the fungi-bacteria inoculum for the bioaugmentation, the operation of the facility (energy and fuel, nutrients and water supply), and the disposal of waste (filter, active carbon disposables). Production steps considered to list the inputs are reported in Fig. 1.

The functional unit (FU) provides the reference to normalise all the data in the assessment. The FU for remediated soil should consider not only the final quality but also the starting point of the pollution level. In this work, to take into consideration the clean-up level and the contamination of the soil at the starting point, the FU is set as the amount of soil (1 ton) coming from 0 to 3 m depth, remediated to a level of 50%, i.e. almost 800 mg $kgTS^{-1}$ of total hydrocarbons have been degraded.

2.4. Inventory

Life Cycle Inventory (LCI), is where the energy and material inputs and outputs (including products, co-products, wastes and emissions) are identified and quantified to provide the basis for impacts evaluation. It is based on the identification of system boundaries (Fig. 1) and the quantification of the inlet and outlet flows.

Primary data coming from the bio-pile were used both for inputs and outputs of the core module of the analysis (structure for bioremediation and managing, level of contaminants at the end of the process). Upstream module data, such as the manufacturing of products and goods used in the facility and produced elsewhere, transportation of raw materials, extraction and refining of raw materials, come from the database Ecoinvent 3.3.

Emissions of volatile hydrocarbons from bioremediation facilities may impact air quality or human health. In the considered process, the treatment is performed by positioning a bio-pile in a closed vessel under negative pressure, and carbon filters treat all the air before discharge. Thus, the only possible emission in the atmosphere refers to the excavation phase and is accounted in the inventory according to the findings of Ausma et al. (2011) during the landfarming.

Opposite the air emission referring to the situation as it is (soil not remediated) is estimated based on surface volatility of the compounds present in the soil and according to the amount of them likely exposed to the soil/air interface (Nishiwaki et al., 2009).

The pollution level in the soil is the primary impact. In this work, the amount of hydrocarbons in the soil in the reference scenario (no action) and the amount of the residual hydrocarbons in the remediated soil is considered. The evaluation of pollutants' transfer for the soil–groundwater pathway requires the evaluation to be based on primary local data or modelling based on laboratory leaching tests. In this work, the emission to the soil in the reference scenario (no action) and the emission to the soil of the residual content of pollutant in the remediated soil (remediated scenario) is considered. Different conservative models have been reviewed to consider the mobility of pollutants to groundwater, since that is one of the main impacts. Main models and references used tomodel the leaching into groundwater are Zand et al., 2009, Kalbe et al., 2008. The resume of primary data of the inventory of this work is reported in Table 1.

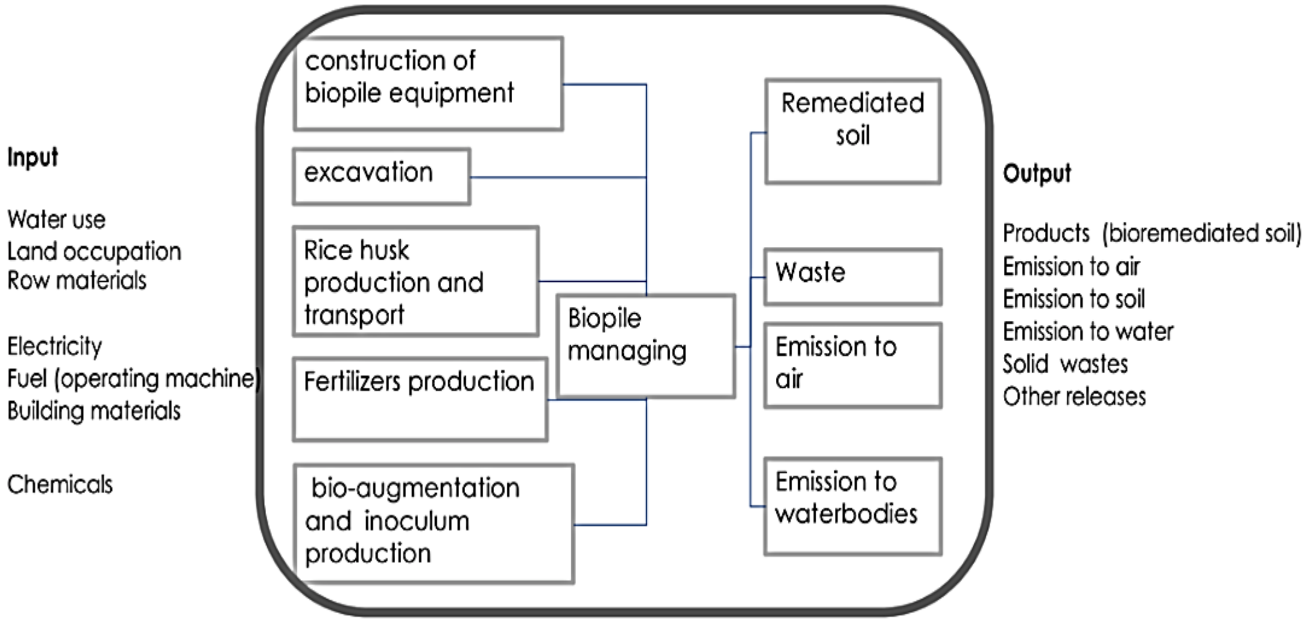

Fig. 1. System boundaries of the bio-remediation technology

Table 1. Data used for calculation of the inventory

Parameter	***Unit***	***Value***
Soil treated in a bio-pile	ton	600
Time of treatment	days	150
Average number of treatments performed in the structure (bio-pile vessel) in one year	n	3
Bio-pile equipment, lifetime	years	3
Bio-pile surface	m^2	385
Destination of soil use: urban industrial	m^2	1307
Height of bio-pile	m	1.3
Bio-pile structure		
HDPE vessel	kg	15600
HDPE pipe for water drainage	kg	900
Total HDPE	kg	16500
Steel (equipment/pumps)	kg	100
Average distance from the suppliers of building equipment	km	60
Bio-pile running		
Diesel consumed for excavation in the site and bio-pile production	litre diesel	500
Electricity consumed in bioremediation trial	kWh	10500
Electricity modelled for the optimised scenario		
Air supply	$m^3 h^{-1}$	200
Water added to bio-pile	kg	1500
Rice husk added (% of soil volume)	%	10
Urea added to the bio-pile	kg	180
Market phosphorus fertiliser added to the bio-pile	kg	36
Average distance for commercial fertilizer supplier	km	100
Amount of slurry used in the optimised scenario	ton	45
Average distance for slurry supplier	km	20
Bioaugmentation process, inoculum production (for at least 100 bio-pile)		
Lab selection		
Fuel for soil sampling operation: 600 km (return travel with a small vehicle)	km	600
Electricity for lab operation (economic allocation)	kWh $year^{-1}$	43200
Gas for lab operation (economic allocation)	$m^3 year^{-1}$	2000
Inoculum production, industrial scale		
Fermenter production capacity	litre	200
Heat needed for fermenter (gas to keep 25 degrees for three days) methane gas	m^3	2.0
Electricity	kWh	216
Amount of inoculum needed for one bio-pile	litre	1

2.5. Scenarios considered

The scenarios considered in the analysis are described below. 1) No-action Scenario: no remediation is implemented, and the primary impacts of the pollution of soil are considered to persist for 50 years (land use is prevented, and emission to waterbodies continues); 2) Bioremediation by bio-augmentation Scenario: bioremediation is performed according to the model proposed in the Biorest project and described in the section System Boundaries, data come from a full-scale trial; 3) Optimized Bioremediation Scenario: on the basis of highlighted hotspots and data recorded on-site, an optimized scenario is modelled to overcome the weak points of the process. The optimized scenario is modelled according to conservative assumptions: the key differences with respect to the trial performed in scenario 2, are the use of local fertilizers in place of commercial ones and the lower time of active aeration. Lower aeration can be safely assumed as working mode, considering the very high levels of oxygen recorded in the outlet airflow during the whole test (oxygen level of the outlet airflow always almost equal to 21%v/v).

2.6. Method for the Life Cycle Impact Assessment

In the Life Cycle Impact Assessment (LCIA), emissions and resource data identified during the Life Cycle Inventory (LCI) are translated into environmental indicators. In this work the ReCiPe 2008 method Hierarchist perspective (Goedkoop, 2009; Huijbregts et al., 2017) was used to calculate indicators at midpoint level. The software Open LCA was used for the computational implementation of the inventories.

3. Results and discussion

3.1. Soil characterization

The soil considered in this work was a silty clay soil (45% clay, 23% silt), rather low in carbon content. The soil texture data suggest that it is a severe soil to treat: the macroporosity is low, the movement of oxygen and water is hampered, and pollutants are firmly bound to the soil colloids (De Andrade Lima, 2018). Typically clay soil is less aerated and more prone to the conservation of carbon (Hassink, 1997, Jagadamma et al., 2010); thus, the remediation action is very challenging and demanding in time and energy. The characterization of samples collected at the start and at the end of the remediation process are reported in Table 2

The addition of nutrients to the bio-pile supplies large availability of nitrogen so that no limiting conditions are experienced by the selected consortia to start the degradation of pollutants. The Carbon to Nitrogen ratio (C/N) is equal to 5 at the starting of the activity of the bio-pile and reaches 6.5 at the end of the treatment. The total carbon of soil is coming mainly from the hydrocarbons present in soil (50%, i.e. 1.6 g kgTS^{-1}) and from the addition of rice husk as inoculum carrier. During the process, almost 0.8 g kgTS^{-1} of total hydrocarbon were degraded, corresponding roughly to 0.31 g kgTS^{-1} of carbon, i.e. a large amount of the overall decrease of organic carbon in the soil of the bio-pile (0.5 g kgTS^{-1}). These values prove that remediation activity was effective and specific for pollutant degradation.

3.2. Impact assessment

In the no-action scenario (Table 3), the only impact categories listed are the ones related to toxicity (for human and ecosystem), due to the pollutants that are released year by year in water bodies and air, affecting the quality of the environment for years to come (primary impacts). All these categories describe the persistence and accumulation of hazardous chemicals and are all expressed as the amount of 1 kg of 1,4-dichlorobenzene (1,4-DB) equivalent. Photochemical oxidant formation describes the air pollution consequent to the reaction of sunlight with emissions from the contaminated soil (or combustion of fuel) as it is formed by the NOx and Non-Methane Volatile Organic Compounds (NMVOCs); it is expressed as non-methane volatile organic compounds equivalent. In the no-action scenario, the emission of NMVOCs due to the soil pollution exceeded the emission caused by the remediation activity (fuel combustion for remediation activity).

LCA categories dealing with toxicity are complex to be described and resumed in one number. The toxicity indicators are related to many compounds that may disperse into different environmental compartments, with different kinetics: thus, they are finally very difficult to model. Research on these categories is still at an initial stage, so these are no categories as robust as the categories related to climate change, fossil depletion or eutrophication. ERA, Environmental Risk Assessment is the tool to specifically address the evaluation of the potential damage to humans and the ecosystem at the local level, while LCA by now, studies the system as a whole and aggregates a large number of impacts on different geographical and temporal scales altogether; it allows to draw the big picture but at the same time lessens the focus on the local scale of the problems, thus may underestimate the local and specific impact of toxicity.

Table 2. Characterisation of the soil used in the bio-pile tests

		Start of bio-pile running	*End of bio-pile running*
pH		6.82±0.05	6.83±0.03
Hydrocarbon (sum of C<12 and >C12 compounds)	mg kgTS^{-1}	1615±248	843±150
Carbon content in soil	g kgTS^{-1}	3.24±0.09	2.74±0.12
Nitrogen	g kgTS^{-1}	0.67±0.04	0.42±0.06

Table 3. Characterisation at the midpoint level according to Recipe (H) method of the scenario no-action and remediation by bioaugmentation

Impact category	*Unit*	*No- action scenario*	*Remediation by bioaugmentation*
Climate change	kg CO_2 eq	0	9.69
Ozone depletion	kg CFC-11 eq	0	7.72E-07
Terrestrial acidification	kg SO_2 eq	0	4.49E-02
Freshwater eutrophication	kg P eq	0	1.64E-03
Marine eutrophication	kg N eq	0	3.74E-03
Human toxicity	kg 1,4-DB eq	1.27	1.69
Photochemical oxidant formation	kg NMVOC	0.04	0.03
Particulate matter formation	kg PM10 eq	0	0.02
Terrestrial ecotoxicity	kg 1,4-DB eq	0.30	4.87E-03
Freshwater ecotoxicity	kg 1,4-DB eq	0.16	0.12
Marine ecotoxicity	kg 1,4-DB eq	0.01	0.07
Ionising radiation	kBq U235 eq	0	0.68
Agricultural land occupation	m^2a	0	0.49
Urban land occupation	m^2a	17.9	0.07
Natural land transformation	m^2	0	1.15E-03
Water depletion	m^3	0	0.24
Metal depletion	kg Fe eq	0	0.38
Fossil depletion	kg oil eq	0	4.60

Bioremediation scenario, on the contrary, displays impacts in the categories related to the operation of bio-pile venting and equipment construction, belonging to the secondary impacts. The emission of CO_2 equivalent (Climate Change), that is a widespread indicator of environmental performance, is equal to 9.69 kg for each ton of treated material (FU).

It is difficult to compare the performance of the remediation implemented in this work with other reference data, as most of the published LCA studies on bioremediation express the impacts as aggregate indicators at endpoint level (Cadotte et al., 2007, Suer et al., 2011; Toffoletto et al., 2005). In this work for clarity and simplicity, we chose to use only indicators at the midpoint level, i.e. numbers that have a stronger relation to the real quantity of the environmental flows. The endpoint indicators describe the effect of damage produced, i.e. provide sharper information on the environmental relevance, but they bring more uncertainty than the midpoint indicators (Hauschild and Huijbregts, 2015). Anyhow, to better frame the relevance of the impact of remediation, we can compare CO_2 emission to numbers more comfortable to manage: 1100 tons of remediated soil cause the same CO_2 emission of only one inhabitant equivalent for one year according to ReCiPe normalization factor. The emission of CO_2 for remediation is mainly due to the use of electricity for bio-pile venting (23%) and to the construction of the device (HDPE for the containment of bio-pile in a closed vessel) that accounts for another 21%. The excavation phase, in which the soil is excavated from the site (up to 3 meters depth) and is positioned into the bio-pile, contributes for 17% of the CO_2 emissions, including the fuel used and all the emission caused by the engine. Finally, 16% of the total CO_2 equivalent is caused by the production of chemical fertilizers (N addition) used in the bioremediation.

The same four categories are, as expected, the main contributors to the category of fossil depletion, that quantifies the total use of fossil fuel; in this category the higher contribution is due to the use of HDPE for the bio-pile equipment.

Terrestrial acidification quantifies the deposition of nitrogen oxides (NOx), ammonia (NH_3), and sulphur dioxide (SO_2) to the soil in acidifying forms. (Huijbregts et al., 2017). Terrestrial acidification, in the remediation scenario, depends mainly on the use of nitrogen fertilizers supplied to the bio-pile and on the use of rice husk, that is related to agricultural activity (and to nutrients management). Finally, also the use of electricity and fuel brings a smaller contribution to these categories. The category of freshwater eutrophication quantifies the increase of phosphorus in the freshwater environment, where phosphorus is the limiting factor for biomass production, leading to increased biomass productivity and biodiversity reduction. In this remediation activity, the category of freshwater eutrophication is mainly fed, once again, by the combustion of fossil fuel and the deposition of P contained in the fuel (Wang et al., 2014).

Marine eutrophication refers to the amount of N that will end up in coastal water, causing an increase in primary productivity, as N is the limiting factor for eutrophication in the marine environment. For nitrogen release, in the remediation option, the main contribution is provided by the rice husk added as inoculum carrier. The production of rice husk is related to nitrogen management in soil, leaching and final release to the coastal water bodies. The bioremediation scenario, as the no action, shows an effect on the category of human toxicity, linked to the burning of fuel for the production of electricity and the production of fertilizers (N and P): the impact is almost equally due to the three activities. It is anyhow to highlight that, even if the category of human toxicity is the same as the no-action scenario, the geographical location of pollution is entirely different. The impact of hydrocarbon emission is concentrated explicitly on-site and close to the site, opposite to the pollution and the effect on human health due to the production of electricity and fertilizers that is somewhere at the national level, where the energy production occurs and even further in the case of urea and phosphate fertilizers production. Again, the weights of the impacts for stakeholders are different. Particulate matter formation refers to the emission of NOx, NH_3, SO_2, or PM2.5 to the atmosphere, followed by an atmospheric transformation in the air. It is expressed as PM10 equivalent. Particulate matter formation, as in previous categories, is due to the combustion of fuel for electricity and fertilizers production. The specific bioaugmentation approach used in the trials linked to the specific activity of isolating and producing fungi-microbial inoculum contributed only for 0.03% to the category of Climate change, and the contribution was even lower in the other impact categories.

Finally, LCA can partially model tertiary impacts and then provide some quantification. In the case of no-action scenario, there is an estimation of how many square meters of soil for a year will not be available for use and for the eco-systemic services, such as water depuration and biodiversity reservoir. It is more difficult in this case to provide an explicit "positive" quantification of the eco-systemic services that the soil will provide once the restoration occurs. In this work, it is assumed that the remediated soil will be transformed from an industrial area with no vegetation (low eco-systemic services) to a higher quality ranking area with vegetation.

Comparisons of scenarios highlight the topic of the weighting between primary (local) impacts and secondary impacts, that are often global or far from site impacts (CO_2 emission or ozone depletion). To address this point, somehow lacking in LCA, Diamond et al., (2009) suggested to include in the LCA evaluation, some impact categories that are specific for the effect and damage at local level, such as changes in soil quality parameters, changes in aquifer and changes in the level and quality of ecosystem regeneration.

3.3. Modelling an optimized scenario

In this work, the results showed, for the remediation option, an impact at the global level (global impact categories such as Climate change), due to the energy demand for soil treatment, but at the same time a definite improvement in the categories relating to the local toxicity, i.e. pollution of the air and water sectors. At the same time, hotspots and possible enhancements are clearly outlined: treatment in bio-augmented bio-pile has its primary source of impacts in the consumption of electricity for aeration and in the use of chemical fertilizers. The amount of oxygen in the exhausted air was always in the range of 21%; thus, excessive ventilation was performed in the bio-pile. If we consider the total carbon amount in soil (Table. 2) and the oxygen consumption related to this degradation, we find the average oxygen rate demand (Table 4) for the complete degradation of all the compounds present in the soil, considering an average value of 3.4 g of oxygen for the complete biodegradation of 1 g of hydrocarbon (Huesemann and Truex, 1996). On the other hand, we can consider the average range of soil respiration rate, when the optimal condition of temperature and nutrients level is assured (Curiel Yuste et al., 2007; Huesemann and Truex, 1996). Considering these numbers (Table 4) it appears that the aeration provided to the bio-pile is 700 times higher than the average soil respiration rate, and 7 times higher than the oxygen supply rate needed to consume all the organic carbon in the soil in 150 days, carbon from soil organic matter, form rice husk and from pollutants. If we then consider the real amount of oxygen needed for the biodegradation that actually occurred in soil, we find a value quite close to the respiration of well-amended soil, and again the oxygen supplied is significantly in excess compared to what needed. Based on the data discussed, it is possible to model an alternative precautionary scenario, where an on-off aeration system based on O_2 concentration feedback could reduce by one third the electricity consumption all around the lifecycle of the treatment, assuring a more than suitable oxygen concentration for biodegradation process. The opportunity of this reduction is also confirmed by the fact that the setup of aeration of high rate composting facility for waste stabilization is set to assure concentration of oxygen not below 16%, a ceiling that is considered suitable to support the activity of aerobic microorganism (Petric et al., 2012).

Finally, the use of recovered nutrients (slurry and manure) in place of fertilizers, when they are available on-site as it occurs in Fidenza district, could as well decrease the total impacts on the category of GHG and acidification. In this case, the production of slurry is considered burden-free, while it is considered the transport and the emission during use. Values of impacts of the new optimized scenario are reported as comparisons in Fig. 2. The optimized scenario, thanks to the saving of fossil fuel consumption for electricity and fertilizers, allows to decrease the values of the toxicity categories such as human, terrestrial and freshwater, of 68, 99 and 61% with respect to that of the remediation scenario and the CO_2 eq emission drops to values of 5.8 FU^{-1}.

Table 4. comparisons of the oxygen supplied in the bio-pile to the rate of oxygen consumption of soil and to the rate of oxygen consumption needed to consume all the organic compounds in the bio-pile in 150 days

Air supply	m^3h^{-1} Mg $soil^{-1}$	0.29
Oxygen rate supplied in the biopile	mg O_2 kg $soil^{-1}$ s^{-1}	0.024242
Average oxygen rate consumed by soil respiration (Huesemann and Truex, 1996, Yuste et al., 2007)	mg O_2 kg $soil^{-1}$ s^{-1}	0.000035
Average oxygen rate needed to biodegrade all the carbon in the soil in 150 day	mg O_2 kg $soil^{-1}$ s^{-1}	0.003498
Average oxygen rate needed to degrade the carbon actually degraded during the trial	mg O_2 kg $soil^{-1}$ s^{-1}	0.000035

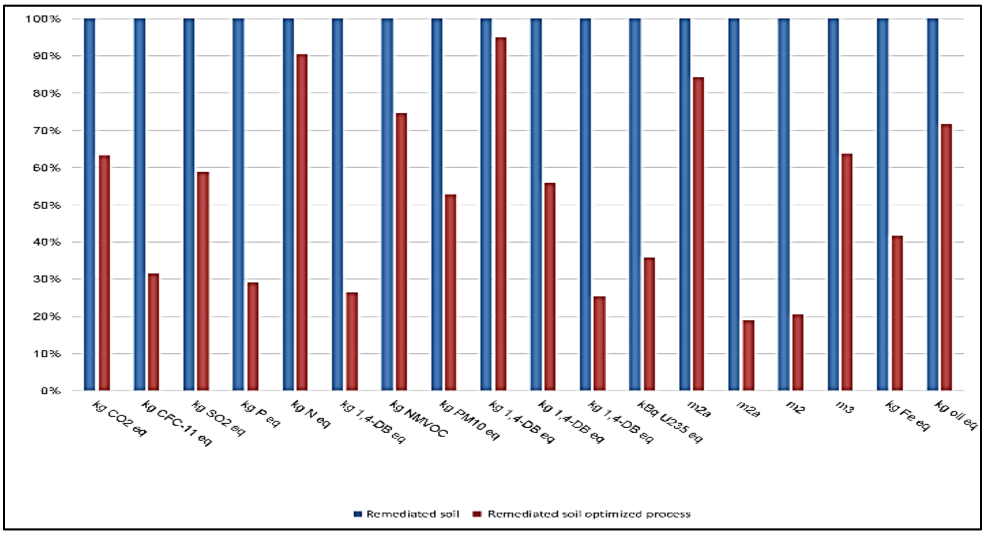

Fig. 2. Comparison between the bio-remediation scenario and the optimized bio-remediation scenario Impacts assessment calculated according to ReCiPe midpoint (H) V 1.12 method

4. Conclusions

Bio-remediation by bioaugmentation model proved to be effective in remediation, as it costed only 9.69 kg CO_2 eq per ton of soil, i.e. 1100 tons of remediated soil cause the same CO_2 emission of 1 inhabitant equivalent for one year according to ReCiPe normalization factor. The use of bioaugmentation technique contributes only to 0.003% of the total CO_2 emission. The management of oxygen supply for biodegradation should be carefully dimensioned, as the electricity used for ventilation is the main contributor to the environmental impacts of the bio-remediation treatment. Bio-remediation by bioaugmentation can be optimized, by LCA perspective, thanks to a more efficient management of air pumping and the use of recovered nutrients, to drastically reduce the value of toxicity categories and achieve a CO_2 eq emission values of 5.8 FU^{-1}.

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