Physicochemicalparametersmonitoringduringbioremediation of soilspolluted by hydrocarbons in Brazzaville (Congo)

Abstract: This work aims to treat soils polluted by hydrocarbons using the bioremediation technique. Samples were taken from four (04) types of garage soils chosen in some districts of Brazzaville, namely Ouenzé, Mfilou, Djiri and Talangai. Four treatments were carried out for bioremediation treatment while monitoring physicochemical parameters by bioaugmentation, biostimulation and mixture of bioaugmentation and biostimulation. Several physicochemical parameters were monitored during the different treatments: The range of physicochemical parameters values is respectively between 23.3 and 28.4°C for temperature, between 38,6 and 5266,01µS/cm for conductivity, between 6.01 and 7,5 for pH, between 0 and 70% for the maximum water retention capacity, between 1 and 10% for humidity, between 0 and 88 mg/Kg for nitrogen and between 0 and 298.93 mg/Kg for potassium. The Total Petroleum Hydrocarbons (TPH) concentrations decreased significantly throughout the treatments with a drop between 25% and 85% in the hydrocarbon concentrations in soils polluted. The greatest drop (75%-85%) in the hydrocarbon content is observed for the Bioaugmentation (Bacteria) and Biostimulation+Bioaugmentation (NPK+Bacteria) combination treatments. Thus, bioremediation by adding Bacillus genus bacteria would be an alternative way for the depollution of soils polluted by hydrocarbons.

Keywords: *Bacteria, hydrocarbons, soil, pollution, bioremediation*

1. Introduction

Congoleseoillandscape expansion, with the discovery of significanthydrocarbondeposits, constitutes an undeniableeconomicopportunity. Alongsidethis expansion, we are seeing accidentaloilspills, particularlyfrom onshore oil installations. These areas withrichecosystems, locatednear onshore oil installations, can suffer the hazards of theseoilspillswhich can pollutetheirsoils, theirrivers, their plantations as well as groundwater, causingrisks for the environment and the humanhealth. Recognized as a major environmentalproblem, oil pollution is the subject of intensive research. Indeed, the spread of hydrocarbonmolecules in soil and the real risk of theirtransfer to groundwater and intofoodchain have made the decontamination of contaminated sites a major concern[1]. Furthermore, chemical and physicalremediationmethods have showntheirlimits due to theircost and theirsecondary impact onenvironment. Also, the increasingly restrictive evolution of environmentallegislation has sparked a growinginterest in

environmental protection and sustainabledevelopment. It is for thispurposethatbioremediation or biologicaldepollution, one of the mostusedmethods for purifyingenvironmentscontaminated by hydrocarbons, has become, over recentdecades, one of the mostdevelopedresearchthemes. In addition, bioremediationis an interesting alternative to otherdepollutionprocesses (physico-chemical, thermal, etc.) due to itsreducedenvironmental impacts and itslowcost[2]. Bioremediation has the particularity of addressing the soilspolluted by hydrocarbonsremediationproblemfrom the angle of soil-microorganisms (bacteria) interactions coupledwith the optimization of physico-chemicalparameters. The biodegradation of hydrocarbons by bacteriaisundeniably one of the mostsuccessfulprocesses in the elimination of hydrocarbonpollutants[3]. Indeed, in 2005, nine (9) cyanobacteria, one hundred and three (103) fungi and fourteen (14) algaewereidentified as being capable of degradinghydrocarbons and seventy-nine (79) bacterialgenera capable of usinghydrocarbons as a sole source of carbon and energy. But, it has been establishedthatbacteria are qualitatively and

Severalbacteria have already been used in numerous applications in bioremediation of environmentspolluted by hydrocarbons. The Gram-positive bacterium M. luteus has an important role in bioremediationbecauseit has abilities to tolerate and use toxicorganicmolecules as a carbon source and combines theseactivitieswithtolerance to heavymetals[4]. It isoftenisolatedfromcontaminatedsoils, hydrocarbons and sludge. M. luteus can degradehydrocarbons and olefinic compounds [5]. Severalaerobicbacterialstrainsparticipate in the degradation of PolycyclicAromaticHydrocarbons (PAHs). The molecules of naphthene, fluorene, anthragen, pyrene and benzo(a)anthracene are degraded by bacterialstrains of pseudomonas sp, rhodococcussp or evenmycobacteriumsp[6].Severalmetabolicwaysdegradation of branchedhydrocarbonshave been demonstrated for 2-methyloctene, 3,6-dimethyloctane and 2,6 dimethyldecaneusing pseudomonas citronellolisbacterialstrains[7]. Pseudomonas aeruginosastrains have been shown to be effective in the n-alkanesdegradation, but cannotdegradeeitherbranched or aromaticalkanes[8]. Bacillus genusStrains have been used in severalstudiesshowing the biodegradationeffectivenessonsoilspolluted by hydrocarbons. On the other hand, very few bioremediationstudies have been carried out withindigenousBacillus genusstrainsobtained in Congo-Brazzaville. This work sets itself the objective of monitoringphysicochemicalparameters of soilspolluted byhydrocarbonsduringsoilbioremediationusingBacilus bacterialstrains.

2. Material and Methods

2.1. Study Site

straddling the equator between latitudes 3°30' North and 5° South and longitudes 11° and 18° East. The agglomeration of Brazzaville covers an area of nearly 265 km^2. Brazzaville is located in the southern partof Congo, between 4°6'15" and 4°22'30" of southern latitude and between 15°6'0" and 15°19'15" east longitude [9].This study was carried out in four (04) garages located in fourth differentsdistricts of Brazzaville city in Republic of Congo (Figure 1):Ewoulama Garage or Garage A in Djiri district, Dubai Garage or Garage B in Ouenzé district, Moise Garage or Garage C in Mfilou district and Prince Garage or Garage D in Talangai district.

2.2. Soil Sampling

Soilsamplespolluted by hydrocarbonsweretakenfrom the followingfourth (4) garages, namely:Ewoulama Garage (Garage A), Dubai Garage (Garage B), Moise Garage (Garage C) and Prince Garage (Garage D). Figure 2 shows an Ewoulama garage (Garage 1) picture. The geographicalcoordinates of thesedifferent garages concerned by thestudy are summarized in Table 1. The sampling methodchosenissystematicrandom. The samplestaken by garage are composite type, resultingfroma mixture of sub-samplesseries

Table1: Geographic coordinates of the 04 districts concerned by the study

Garages (codes)	Geographic coordinates		Districts
	Latitude	Longitude	
Ewoulama(Garage A)	4°11'24"S	15°15'18"E	Djiri
Dubai (Garage B)	4°14'6"S	15°18'0"E	Ouenzé
Moise (Garage C)	4°13'12"S	15°16'12"E	Mfilou
Prince (Garage D)	4°13'12"S	15°17'6"E	Talangai

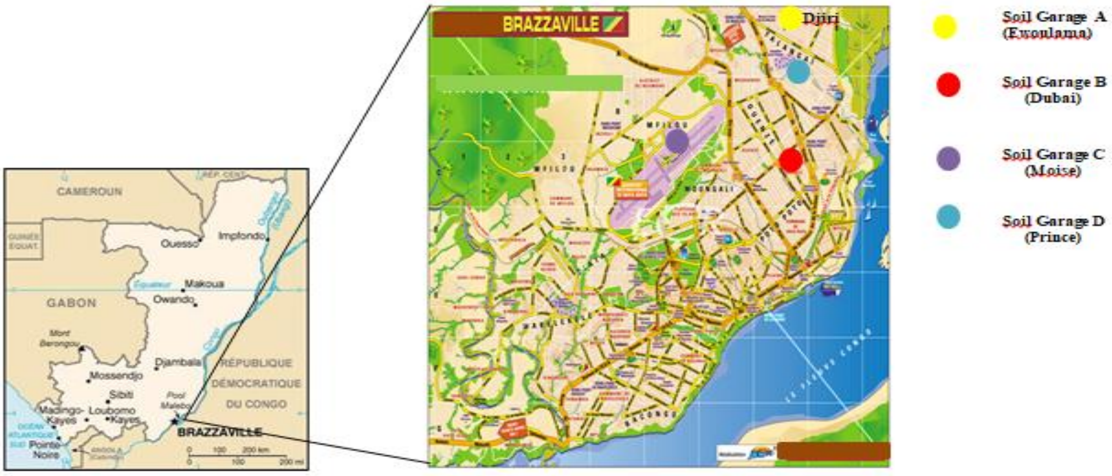


Figure 1: Brazzaville Map indicating the localisation of the four (04) garages chosen for this study [10]

Figure 2: Ewoulama Garage (Garage A)

taken in accordance with the systematicrandom sampling strategy (ISO-18400-102, 2017). For this, a rectangular area polluted by hydrocarbonswaschosen in each garage and wasdemarcated over an area of 10 to 15m^{2}with a square mesh. Ineachdemarcated area, 5 sub-sampleswere taken from the four corners of the demarcated area as well as in the center. The 5 sub-sampleswere takenfrom a depth of 20 cm using an auger. The 5 sub-sampleswere mixed equally in order to constitute the mostrepresentative composite sample. Each composite sampleis made up of 10 kg of contaminatedsoilresultingfrom the mixture of 5 sub-samples. Then, composite samplesfromeach garage wereplaced in plastic boxmeasuring 13m by 23.5m. The soilscollected are placed in sterilized glass jars and coveredwithaluminum foil (Figure 3). Then,theyweresent to the laboratorywheretheyhave beendried for three (03) days at ambient temperature of 25°C, thensieved on 2mm meshsieves (ISO-23266, 2020). Finally, thesesoilpollutedcomposite sampleswereweighed and thenpackaged in 1000mL glass bottles.

Figure 3 : Conditioning of soilsamplespolluted by hydrocarbons for transport to laboratory

2.3.Bacterial strains

Bacteriasought are thosebelonging to the Bacillus genusobtainedafter isolation. Thesebacteriawereisolated in Irsenlaboratoryin Brazzaville by using suspension dilution method[11]. Bacterialstrains are inoculatedinto a BH type mineral medium. The bacterial culture iskept in an incubator 15 days.

2.4. Inoculation tests

Four (4) plastic boxcontainingsoilpolluted by hydrocarbonsweretreated, respectively:

- Box1:Pollutedsoil + Natural attenuation (no amendment), this boxcontainsonlypollutedsoil,
- Box 2:Pollutedsoil + Consortium (Bacteria+NPK), this boxis made up of pollutedsoil and a mixture of nutrients NPK + Bacillus type bacteria,
- Box3:Pollutedsoil +Bacteria(Bioaugmentation), this boxcontainspollutedsoilwith a medium of Bacillus type bacteria,
- Box4:Pollutedsoil + nutrients NPK (Biostimulation), thisboxcontainspollutedsoilwith NKP nutrients in order to stimulatebio-stimulation.

2.5 Physicochemical parameters of soil samples

Temperature and electricalconductivity aremeasuredusing a multi-parametersuch as Water QualityMeter (EZ9908), according to ISO-11265 standard distilled water in the ratio 1/5 (w/v). The pH ismeasuredwith a Water QualityMeter type pH meter (EZ9908) according to the ISO-10390 standard whichconsists of measuring a suspension of soil in distilled water according to the ratio 1/5 (w/v). The maximum water retentioncapacity (MWRC)wasdeterminedunder the action of gravimetryaccording to a distilled water-soil ratio 1/1 (w/v) [12]. Humidity, nitrogen and potassium wereobtainedpotentiometrically by directlyimmersing the humidity tester probe or the NKP fertilizer detector soil tester of the Sonkir type multi-parameterdirectlyinto the soil.

2.6 Total petroleum hydrocarbons (TPH) concentrations in soils

The total petroleumhydrocarbons (TPH)wereextracted by Soxhletaccording to Environment Protection method 3540 Agency (EPA). EPA Method 3540 isbased on liquid-solid extraction by continuous sample. The total petroleumhydrocarbons (TPH)from the hydrocarbon-pollutedsoilswereextracted by Soxhletduring the treatments (Figure 4). 10g of soilwrapped in Wattman filterpaper are introducedinto the cartridge and hydrocarbons are extractedwithdichloromethyl at 40oC for 6 hours.

Figure 4 : Extraction of hydrocarbons by Soxhlet

The soilisdried at ambient temperature of 25°C and the mass ismeasuredevery 24 hoursuntil a stable mass isobtained. The total petroleumhydrocarbon (TPH) rate iscalculatedaccording to the followingformula:

$$\%\ \mathbf{TPH} = \frac{\boldsymbol{initial\ mass - \ final\ mass}}{\boldsymbol{initial\ mass}}\ \boldsymbol{X}\ \mathbf{100}$$

3. Results and Discussion

3.1Evolution of different garages soilstemperaturedepending on treatments and time

Figure 5 shows the evolution of the differents garages (A, B, C, D) soilstemperature as a function of treatments and time. We note thatduring the 180 days, whatever the treatments, temperature values oscillatebetween 23.3 °C and 28.0 °C for soilof Garage-A, 23.6 °C and 28.6 °C for soilof Garage-B, 23.8°C and 28.4°C for soilof Garage-C and 23.7°C and 28.4°C for soil of Garage-D. For all garages and whatever the treatments, a drop in temperatureisobserveduntil the 30th daybeforegoing back up to the 90th, then a new drop in temperatureisobserved up to 180 days. Temperaturepeaks are observedaround 28°C. The recordedtemperatures fit wellwithin the temperature range whichdetermines the conditions required for good microbialdegradation[13; 14]. Indeed, the optimal growthtemperature and temperatures range that a microorganism can toleratedetermineitssurvival and the roleitwillplay in hydrocarbonsdegradation[15]. The temperatureisproportional to bioremediation speed. In general, a decrease in temperatureisaccompanied by a decrease in biodegradation rate which can beexplained by a decrease in enzymaticactivity. In temperatures have the effect of increasing the rate ofbiodegradation[16;17]. In ourwork, hydrocarbonsdegradationis optimal around 28°C.

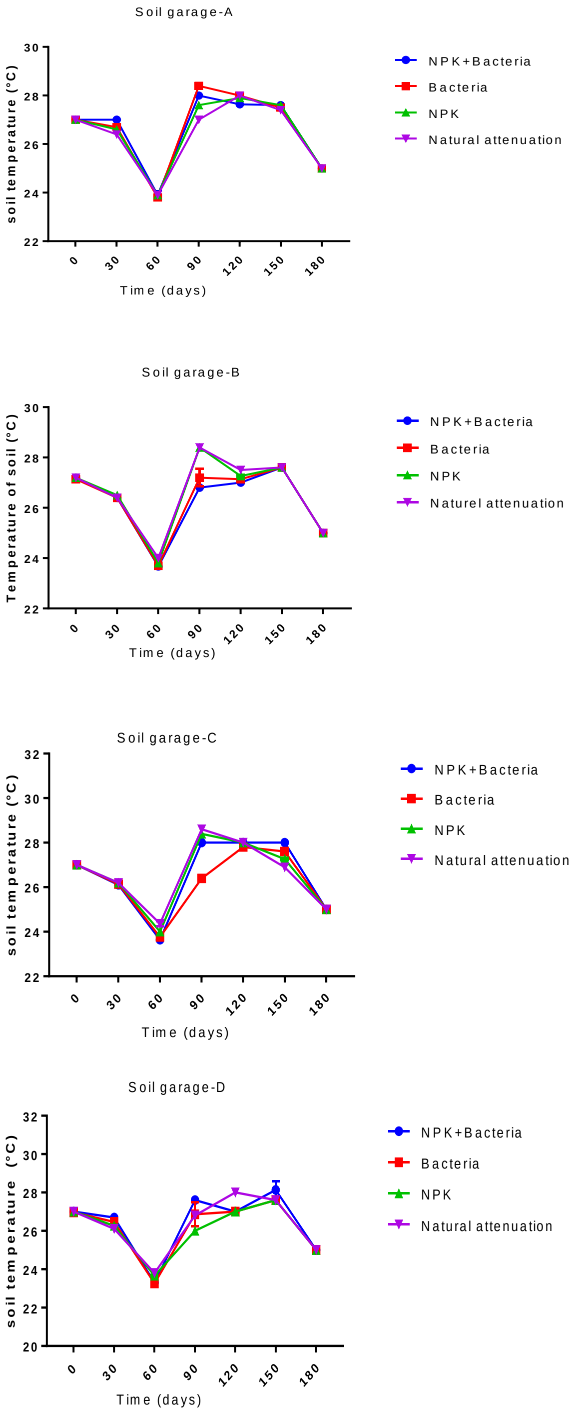


Figure 5 : Evolution of garage (A, B, C, D) soils temperaturedepending on treatments and time

3.2 Evolution of different garages soilselectricalconductivitydepending on treatments and time

Figure 6 shows the evolution of the differents garages of time. We can note a variation in soilelectricalconductivitybetween 66.41 and 2600.01 µS/cm for soilof Garage A; 38.6 and 5266.01 µS/cm for soilof Garage B; 110 and 3633.67 µS/cm for soilof Garage C and 144.26 and 4162 µS/cm for soilof Garage D. All curvesevolve in a similarwaywithmuchhigherconductivitieswith the NPK and NPK+Bacteriatreatments. The increase in conductivityis due to the overdose of nutrients in the NPK and NPK+Bacteriatreatments. The lowconductivities of soilstreatedonlywithbacteria or undernaturalattenuation can beexplained by the factthatsoilssampled are ferraliticsoilswhich are naturallypoor in mineralelements[18].

The depth ofsampling is a factor alsocontributing to the drop in conductivity values becausesoilcollectedbeyond 15 cm depthreducesexcesssalts to 80% [19]. Furthermore, thesesoilelectricalconductivity values are in accordance with the AgronomyMomento in whichitisdemonstratedthatlimit values for degradation of hydrocarbons insoil are between 0 and 6000 µS/cm [20]. Althoughafter 180 days, wesee a drop in electricalconductivity in all treatments. Theseelectricalconductivity values are wellwithin the recommended range for the degradation of hydrocarbons.

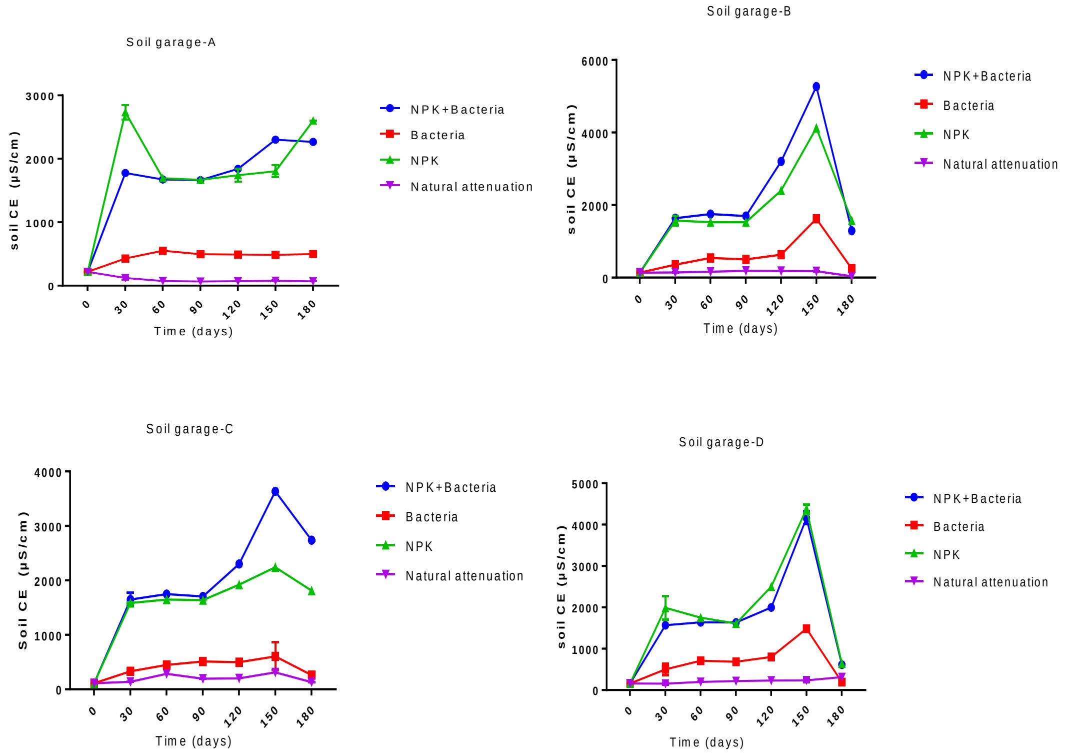


Figure 6 : Evolution of garage (A, B, C, D) soilselectricalconductivitydepending on treatments and time

3.3 Evolution of different garages soils pH depending on treatments and time

Figure 7 illustrates the variation of garages (A, B, C, D) soils pH duringthe differenttreatments as a function of time. We note that at start of all treatments, pH values are neutral around 7.50 in soil of Garage A, 7.10 in soil of Garage B, 7.15 in soilof Garage C and 7.15 in soilof Garage D. Forsoilshavingundergonenaturalalteration, a slightincrease in pH isobserved up to 90 dayswith values of up to 7.5. Then, we observe a drop up to 180 dayswithpH values oscillatingbetween 6.5 and 7. For soils (A, B, C, D) treatedonlywithbacteria, we observe a sawtoothevolution, with successive pH increases anddecreases in ranges of 7 to 7.5. At 180 days, the pH values of all soils are around 7. The soilcurves (A, B, C, D) treatedwith NPK and NPK+Bacteriaevolve in a similarway and are almost superposable. The general trend of thesecurves shows a drop in pH up to 6. Thus, unlikesoils (A, B, C, D) havingundergonenaturalattenuation or treatedonlywithbacteriawhose pH values remainaround the neutralitywhatever the soilsandtreatments duration. pH of the soils (A, B, C, D) treatedwith NPK and NPK+Bacteria tend towards acidification the furtherweadvance intreatments. This aciditycouldbeexplained by the degradation of hydrocarbons by microorganisms due to the accumulation of organicsacidsproducedduring the elimination of hydrocarbons and macromolecular as CO_2 and H_2O [21; 22]. Thus, soilspolluted by hydrocarbonsbecomeslightlyacidic due to the appearance of acidssmallquantityresultingeitherfrom the n-alkanesoxidation or fromcompounds resultingfrom the breakdown of aromaticnuclei[23]. It shouldbeemphasizedthatthese pH values are in the optimal range favorable to hydrocarbonsbiodegradation.

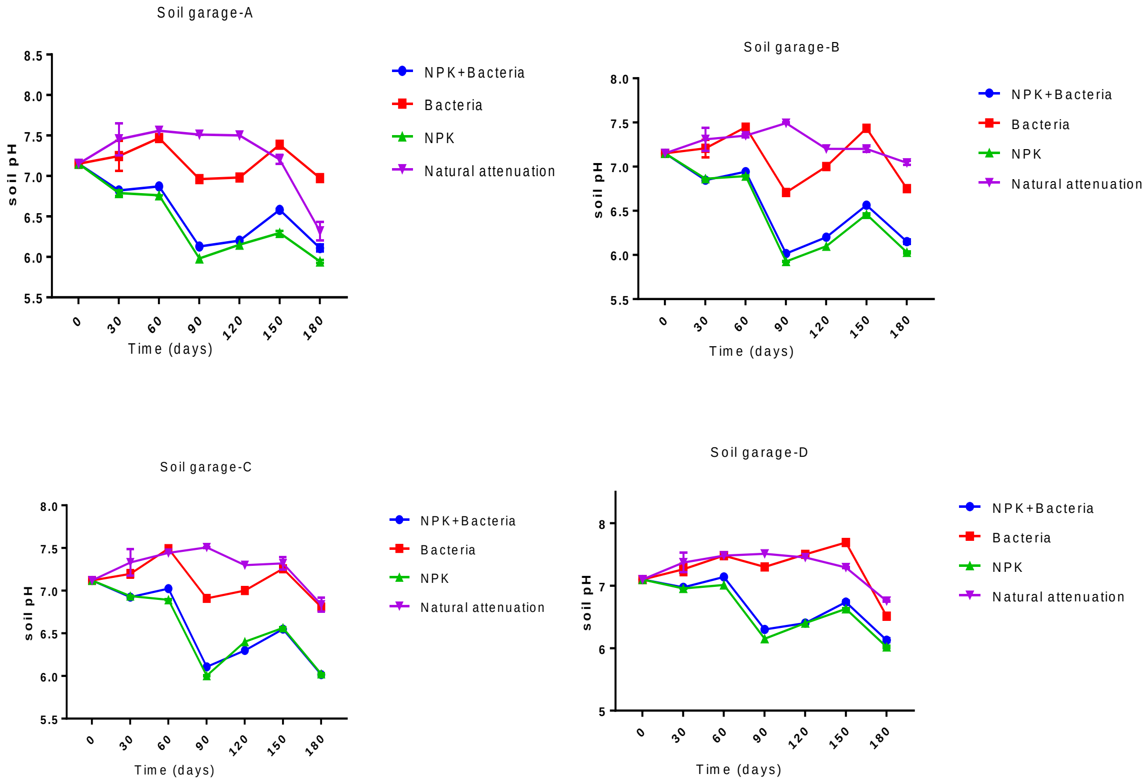


Figure 7 : Evolution of garage (A, B, C, D) soilspHdepending on treatments and time

3.4 Evolution of different garages soils maximum waterretentioncapacity (MWRC) depending ontreatments and time

Figure 8 shows the evolution of the maximum water retentioncapacity (MWCR) of garage soilsduring the differenttreatments as a function of time. The initial values ofMWCR are around 35%. We note a progressive decrease in the maximum retentioncapacity for all soilsduring the first 150 days, with values oscillatingbetween 0 and 20% whatever the treatment. On the other hand, from 180 daysonwards, the MWCR of all soilsincreasesverysharply, reaching values between 50% and 70%. At 180 days:

- thesoilof garage A has betterMWCR (around 60%) withtreatmentsbased on bacteria and NPK,
- thesoils of garages B and C have betterMWCR (around 50%) with the NPK and NPK+bacteriatreatments,
- soil D presentsbetter MWCR (around 65-70%) withtreatmentsbased on bacteria, NPK and NPK+bacteria.

This sharpdecrease in MWCR over the first 150 daysis due to soil pollution degreebecause the more polluted the soil, the more hydrocarbonswillprevent water frombeingretained in the soil[12]. In fact, the water retentioncapacityissignificantlyreduced by hydrocarbons, whichhinders the circulation of air and water in soil matrix and thereforereduces water infiltration into the soil[24]. However, the sharpincreasebetween 150 and 180 days in all designatedtreatmentsissynonymouswith the reduction in pollution and therefore a progressive degradation of hydrocarbons.Indeed, the reduction of hydrocarbons in the soilfreessoil pores and allows, under the effect of gravity, waterinfiltration intosoil intersites [25]. Between 50 and 85% of the retentioncapacity(maximum quantitythatsoil can activityis maximum; itdecreasesfrom 85% due to local anaerobiosis (reduction of oxidativeprocesses) and below 50% due to lack of water [26]. All MWCR values obtainedfrom 180 days are between 50% and 70% whilethosebetween 0 and 150 days are between 0 and20%. The optimal MWCR values for hydrocarbondegradation are from 180 days.

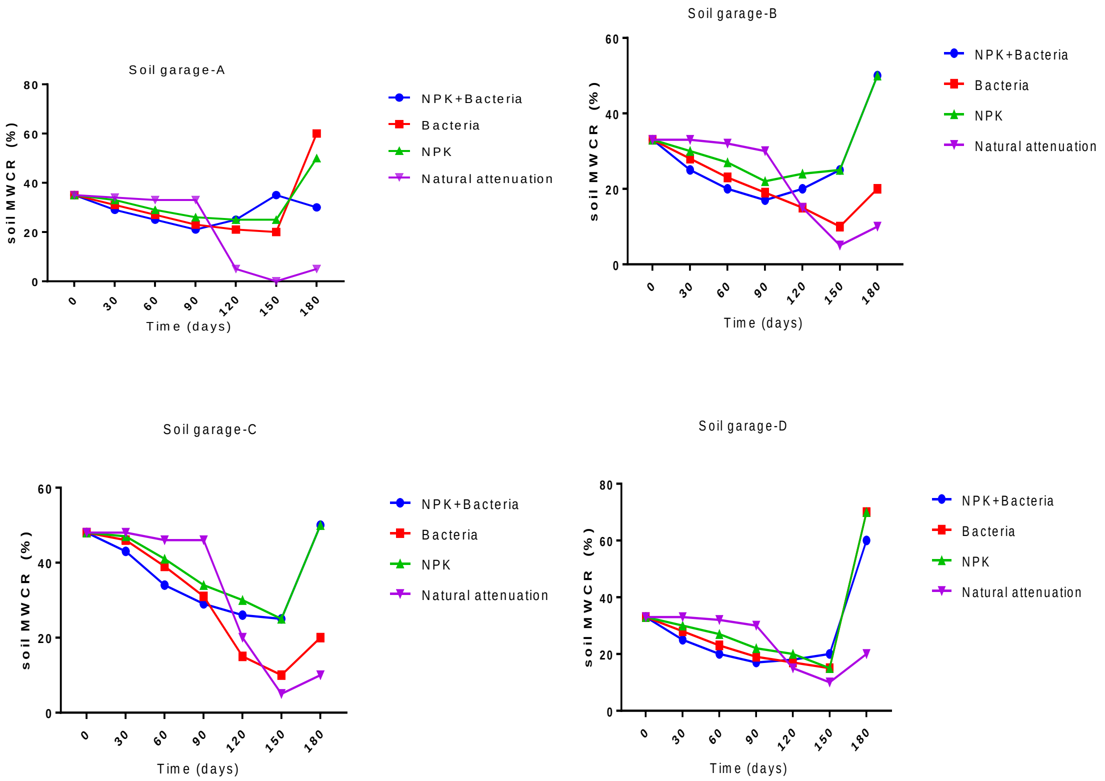


Figure 8 : Evolution of garage (A, B, C, D) soilsMWCR (maximal water capacityretention) depending on treatments and time

3.5Evolution of different garages humidity depending on treatments and time

Figure 9 shows the evolution of soils garages (A, B, C, D) humidityduring the differenttreatments as a function of time. In general, the resultsobtained show thathumidity varies between 1 and 10% for all soils. An increase in humidityisobserved in the differenttreatmentsduring the 180 days due to optimization by adding water into the medium. This increase can beexplained by the reduction water evaporation and permeabilitycaused by hydrocarbonshydrophobicity[27], whichwouldincreasesoil water retention. The reduced transpiration and reduced rate of water absorption intosoilresult in increasedsoilhumidity.These values remain in favorable conditions for hydrocarbonsdegradation[14]even if humiditybelow 2% wouldlimit good bacterialgrowth for hydrocarbonsdegradation[28]. The low value in naturalattenuationtreatmentscouldbeexplained by the climatic conditions of the sampling site or the texture and the effect of oil pollution as highlighted by the workcarriedout[29]. However, soilhumidityishigher (close to 10%) for soilstreatedwith NKP and NKP+Bacteria.

3.6Evolution of different garages nitrogen concentrationdepending on treatments and time

Figure 10 shows the evolutionof soils garages (A, B, C, D) nitrogen concentrationsduring the differenttreatments as a function of time. We can seethat at the start of all treatments, the nitrogen concentrations are verylow and almostzero for all soils. Theselow values show the poverty of soilnitrogen in environmentspolluted by hydrocarbons. This nitrogendeficit in hydrocarbon-pollutedsoilsis due to organiccarbonincrease, thuscausing high biologicalactivitywhiledecreasing the nitrogen concentration [30; 31]. During the first 30 days of NPK+Bacteria and NPK treatments, nitrogen concentrations weresignificantly high, varyingfrom 0 to 88 mg/kg for soilof Garage A;from 0 to 59.68 mg/kg for soilof Garage B; from 0 to 87.68 mg/kg for soil of Garage C and from 0 to 30.67 mg/Kg for soil of Garage D. The nitrogen concentrations increaseisonlyobserved in soilstreatedwithNPK+Bacteria and NPK.

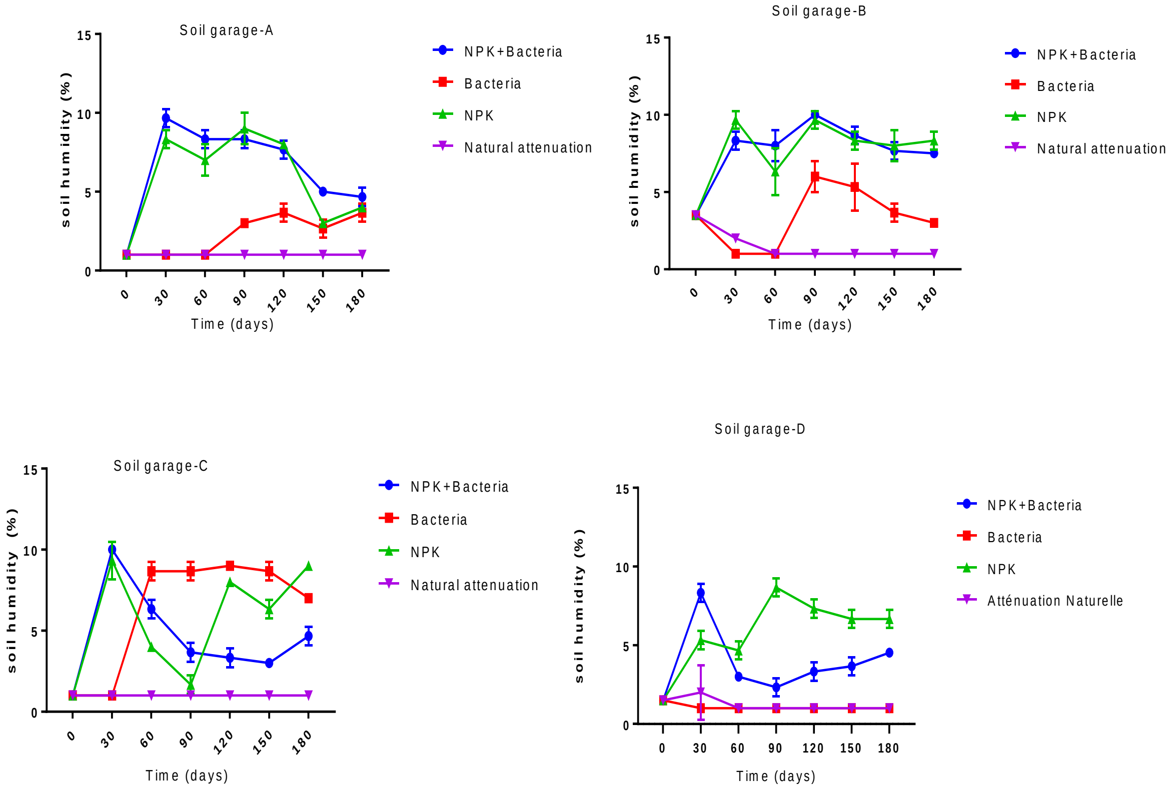


Figure 9: Evolution of garage (A, B, C, D) soilshumiditydepending on treatments and time

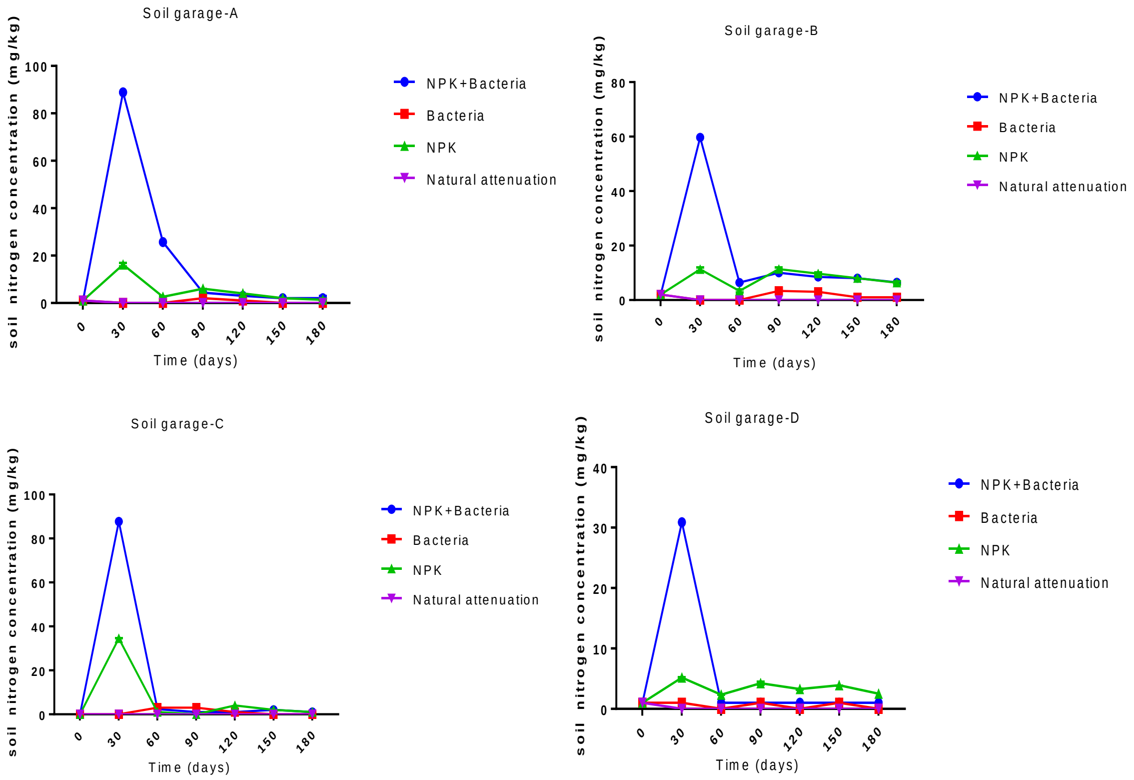
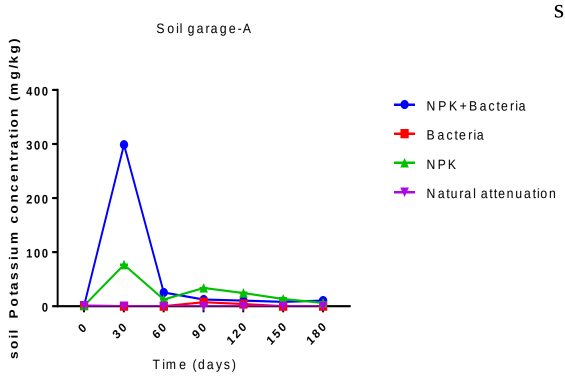


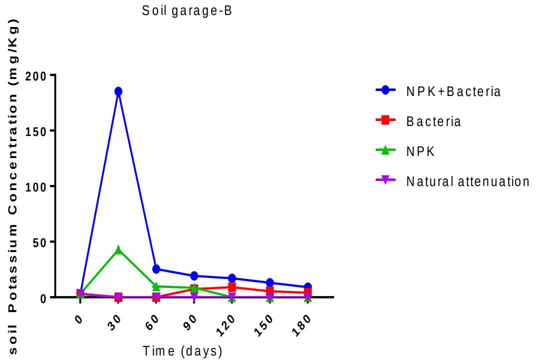
Figure 10: Evolution of garage (A, B, C, D) soilsnitrogen concentration depending on treatments and time

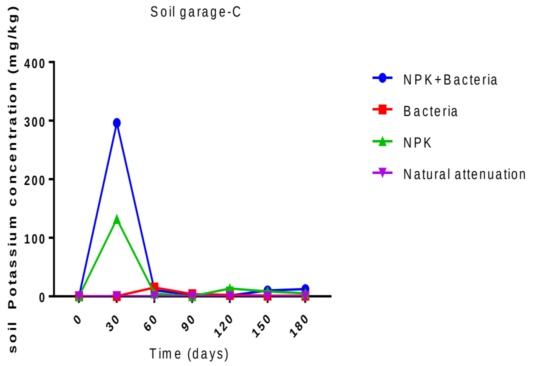
This increaseiscaused by the supply of nutrients in the twotreatments (NPK+Bacteria and NPK). However, after 30 days of treatments (NPK+Bacteria and NPK), the nitrogen concentrations graduallydecreased, signaling the consumption of nutrients by the microorganisms. However, soilstreatedwithNPK+Bacteria and NPK have nitrogen contents suitable for soilbioremediation[31].

3.7Evolution of different garages potassium depending on treatments and time

Figure 11 shows the evolutionof soils garages (A, B, C, D) potassium concentrations during the differenttreatments as a function of time. At the start of all treatments, potassium concentrations are verylow and almostzero. Potassium levels in undergonenaturalattenuation and treatmentwithonlybacteriaremainverylow. In soilstreatedwithNPK+Bacteria and NPK, the potassium concentration increases up to 30 daysonlyvaryingfrom 0 to 300 mg/kg for soilof Garage A;from 0 to 200 mg/kg for soilof Garage B; from 0 to 300 mg/kg for soilof Garage C and from 0 to 150 mg/Kg for soilof Garage D. Between 30 and 180 days, the potassium concentrations in soilstreatedwithNPK+Bacteria and NPK graduallydecreaseuntiltheyreachcloser to zero. For soilstreatedwithNPK+Bacteria and NPK, the increase in potassium concentrations between 0 and 30 daysis due to the addition of nutrients in the treatments. The drop in potassium levelsfrom 30 daysis due to the factthatit has been consumed by the bacteria for theirgrowth and survival[32]. SoilstreatedwithNPK+Bacteria and NPK have potassium concentrationssuitable for soilbioremediation[31].







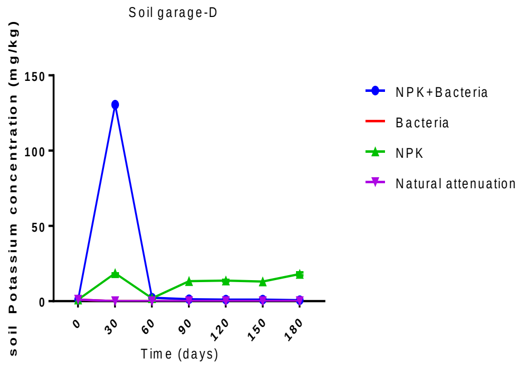


Figure 11 : Evolution of garage (A, B, C, D) soilspotassium

3.8Evolution of different garages total petroleum hydrocarbon(TPH) concentration depending ontreatments and time

Figure 12 shows the evolutionof soils garages (A, B, C, D) total petroleumhydrocarbon (TPH) concentrations during the differenttreatments as a function of time. The initial content of total hydrocarbons in soils of garages A, B, C and D are respectively 8.19%, 8.29%, 10.76% and 7.07%.

The total petroleumhydrocarbon concentrations varies as follows:

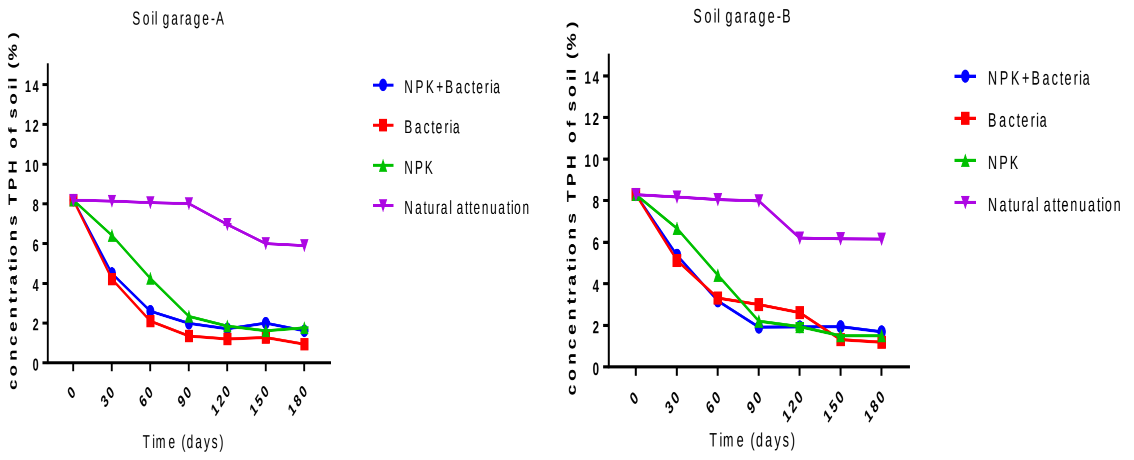
- forsoilshavingundergonenaturalattenuation: we observe a slight drop in total petroleumhydrocarbon content from 8.19% (soilof Garage A) or 8.29% (soilof Garage B) to 6%, i.e. ayield of 25% for the soils of garages A and B. No drop in total petroleumhydrocarbon concentrationsisobserved for soil of Garage C the concentrattion in TPH insoilremains stable at 10.76%. For the soil of Garage Da drop the hydrocarbon concentrationsisobserved, goingfrom 7.07% to 4%, i.e. ayieldof 43.4%,
- for soilshavingundergone the 3 treatments (Bacteria, NPK, NPK+Bacteria), we observe a drastic drop in the hydrocarbon content of 8.19% (soil of Garage A) or 8.29% (soil of Garage B) or 10, 76% (soil of Garage C) to less than 2%, i.e. a yield greater than 75% for the soils of Garages A, B and greater than 81% for the soil of Garage C. For the soil of Garage D, we observe a drastic drop in the total petroleum hydrocarbon concentrations up to 1% only in soils treated with bacteria alone and with NPK+Bacteria, i.e. a yield greater than 85%, while a drop in the total petroleum hydrocarbon concentrationsup to 4% is recorded only in soils treated with NPK with a yield of only 43%.

Thus, we note yields between:

- 75% and 85% for soils treated with Bacteria alone and with NPK+Bacteria,
- 43% and 75% for soils treated with NPK alone,
- 25% and 43% for soils having undergone natural attenuation.

Treatments with the addition of bacteria showed strong degradation compared to other treatments. The decrease intotal petroleum hydrocarbons (TPH) is due to good optimization of the physicochemical and microbiological parameters, the supply of distilled water and aeration by turning the soil, thus promoting good degradation of hydrocarbons by bacteria. Considerable decrease in total petroleum hydrocarbons (TPH)in soil would be caused by the assimilation of microorganisms and the good maintenance of conditions based on physicochemical and microbiological parameters optimization[33]. Several studies corroborate with our work presenthydrocarbon rates after 30 days at reduction rates between 56% and 85% by using bacterial strains of the genus Bacillus[11; 34]

concentration depending on treatments and time



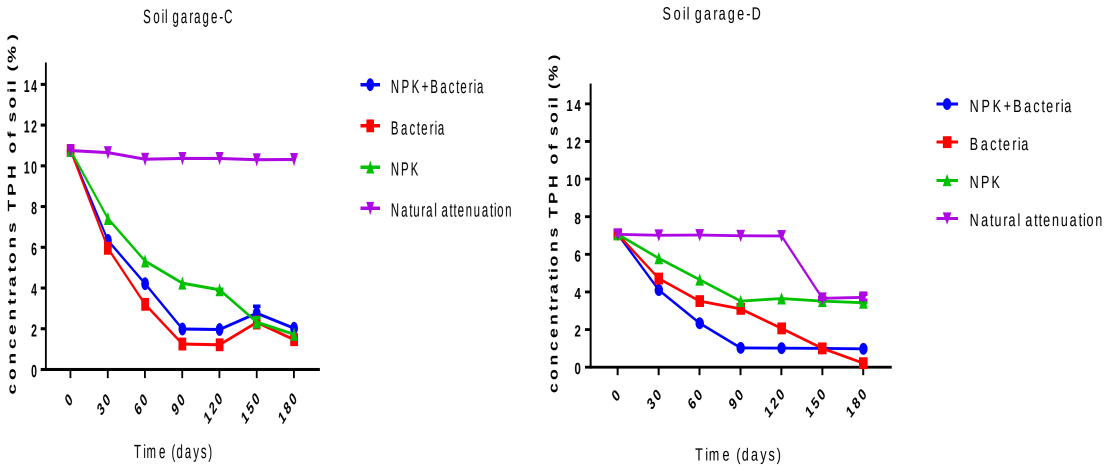


Figure 12: Evolution of garage (A, B, C, D) soilshydrocarbon(TPH) concentrationsdepending on treatments and time

4. Conclusion

The aim of thisworkwas to decontaminatesoilspolluted by hydrocarbonsusing the bioremediation technique. For this, four treatmentswereapplied to soilsamplestakenfromdifferent garages in the city of Brazzaville whilemonitoring the physico-chemicalparameters by bioaugmentation, biostimulation and mixture of bioaugmentationand biostimulation. Physicochemicalparametersstudywascarried out to betterunderstand the factorsthatcould influence microbialmetabolismduring the degradation of total petroleumhydrocarbons in the soil. The resultsobtainedshowedthat the physicochemicalparameters are optimal duringorganicdegradationprocesses. Indeed, the temperaturesrecorded, oscillatingbetween 23.3 and 28.4°C, fit wellwithin the range of temperaturesrequired for good microbialdegradation. The values ofelectricalconductivity of soils, between 38.6 and 5266.01 µS/cm, are wellwithin the range of optimum degradation of hydrocarbons. Likewise, we note that pH values oscillatingbetween 6.01 and 7.5 arewellwithin the range favorable to the biodegradation of hydrocarbons. On the other hand, maximal water retentioncapacities(MWRC) are optimal for the degradation of hydrocarbonsonlyfrom 180 dayswith values between 50% and 70%. The values relating to humidityremain in favorable conditions for the degradation of hydrocarbons, even if the most favorable conditions (close to 10%) are attributed to soilstreatedwith NKP and NKP+Bacteria. SoilstreatedwithNPK+Bacteria and NPK have the most optimal nitrogen and potassium concentrations for bioremediation of soilspolluted by hydrocarbons. We observe a drop between 25% and 85% in the hydrocarbonconcentrations in soilspolluted by hydrocarbons. The greatest drop (75%-85%) in the hydrocarbon concentrationsisobserved for the Bioaugmentationtreatments (Bacteriaalone) and the Biostimulation and Bioaugmentation combination (NPK+Bacteria). The smallest drop (25%-43%) in hydrocarbon concentrationsisobserved for soilsthat have undergonenaturalattenuation. Consequently, bioremediation by adding Bacillus genusbacteriawouldbea good alternative way for the depollution of soilspolluted by hydrocarbons.

DATA AVAILABILITY

The experimental data used to support the findingsisincludedwithin the article.

REFERENCES

[1] GabetA. (2004). Remobilization of polycyclic aromatic hydrocarbons (PAHs) present in contaminated soils using a surfactant of biological origin. Doctoral thesis n°12-2004 from the University of Limoges, specializing in water chemistry and microbiology. 177.

[2] Daverey A., Pakshirajan K. (2011). Pretreatement of synthetic dairy wastewater using the sophorolipid producing yeast candida bombicola. Appl. Biochem. Biotechnol. 163:720-728.

[3] Sauret C. (2011). Ecology of marine bacterial communities subjected to oil pollution. Doctoral thesis from Pierre and Marie Curie University.

[4] Sandrin T.R., Maier R.M. (2003). Impact of metals on the biodegradation of organics pollutants. Environment Health Perspect: 1093-1101.

[5] Zhuang W.Q., Tay J.H., Maszenan A.M., Krumholz L. R., Tay S. T-L.(2003). Importance of Gram-positive naphtalene-degrading bacteria in oil-contaminated tropical marine sediments. Lett. Appl. Microbiol : 251-270.

[6] Sutherland J.B., Raffi F., Khan A. A., Cerniglia C.E. (1995). Mechanisms of polycyclic aromatic hydrocarbon degradation. In microbial transformation and degradation of toxic organic chemicals. Edited by young. L. L. and C.E Cerniglia. Wiley-Liss. New-york.

[7] Alvarez H.M. (2003). Relation ship between β-oxidation pathway and the hydrocarbon-degrading profile in actionmycetes bacteria. International Biodeterioration and biodegradation 52, 35-42.

[8] Bekenniche N. (2014). Cracterization of hydrocarbon biodegradation activities by different microbial genera isolated from contaminated sites. Doctoral thesis of University of Oran, Algiers.

[9] Kimbatsa F.G., Mahoungou E., Berton Ofouemé Y. 2018. The importance of horticulture in the fight against food insecurity, poverty and environmental protection in Brazzaville (Republic of Congo). OpenEdition Journals Caribbean Studies. 38-40, pp. 1-47

[10] Brazzaville map. (2018). Holidays-Arts-Guides-Travels.

[11] Elenga Wilson P. S., Okeni-Boba J. G., Kayath A. C, Mbemba K .M, Nguimbi E., Ahombo G. (2022). Qualitative and Quantitative Assesment of a surfactin biosurfactant in the Bioaugmentation of crude-oilContaminatedSoil in Garages in the Republic of Congo. *10*, 1-11.

[12] Kaboré-Ouédraogo P., Savadogo P., Cheik A., Savadogo A., Alfred S. (2010). Study of the bioremediation of soilscontaminated by hydrocarbons in Burkina Faso. 10 p.

[13] Rad S.N., Ghavidel A., Alikhani, H-A. 2015. Bioremediation of Gasoil by Indigenous Bacterial Strains Isolated from Oil Contaminated Soils. Journal of Soil Environment 1, 45-50.

[14] Sims J.L., Sims R.C., Matthews J.E. (1990). Hazard. Waste & Hazard. Mat : Approach to bioremediation of contaminatedsoil. Slater. Vol.7(n02), 117 -149.

[15] Atlas R.M., Bartha R.B., Menlo Park C.A. (1998). Microbial Ecology : Fundamentals and Applications. Benjamin/Cummings Publishing, Menlo Park, CA.

[16] Sandvik S., Lode A., Pedersen T.A. 1986.Biodegradation of oily sludge in Norwegian soils. Appl MicrobiolBiotechnol 23, 297–301.

[17] Song D., Arata Katayama A. 2010. Approach for estimatingmicrobialgrowth and biodegradation of hydrocarbon contaminants in the subsoilfromfieldmeasurements: 1. Development and verification of the model
Environmental Sciences and Technologies, 44 (2), 767-773.

[18] Nzila J-D. (2013). State, Needs and Priorities for Sustainable Land Management in Congo-Brazzaville. pp.5-14.

[19] Bauder T.A., Waskom R. M., Davis J.G.(2007), Irrigation water quality criteria, Crop Series Irrigation, no.0.506.

[20] Aumar N., Sediri D. (2018). Study of the physicochemical properties of the soils of two service stations Idjeur and Fréha. Master memory. Mouloud Mammeri Tizi-Ouzou University, Biology, Specialty: Biodiversity and Environment. Algeria: Faculty of Biological Sciences and Agronomic Sciences. 71p.

[21] Bergue J-M. (1986). Soil pollution by

[22] Sakata, T., Kojima, T., Fujieda, M., Takahashi, M., Michibata, T. (2003). Influences of probiotic bacteria on the production of organic acids by porcine cecal bacteria in vitro. Proceedings of the Nutrition Society, 62(1), 73-80.

[23] Meriem S., Benkhebcheche D.E. (2016). Contribution to the study of the biodegradation of hydrocarbons in drilling muds by bacteria producing biosurfactants. Memory, University of the Mentouri Constantine Brothers, 77p.

[24] Onojake M.C., Osuji L. C.(2015).Assesstment of the physico chemical properties of hydrocarbon contamined soil. Archives of applied science research. pp.48-58.

[25] Coulomb C. (1992). Study of water circulation in drained clay soil. Thesis, Paris-Sud, n° 2154, 245 pp.

[26] Langenhoff A. (2007).In situ bioremediation technologies – experiences in the Netherlands and future European challenges, TNO, Complementary report for EURODEMO to the "Status report on technologicalreliability for demonstratedsoil and groundwater management technologies withspecial focus on the situation in Europe (D6.2) part 2", 21 pp.

[27] Chalghmi H. (2015). Study of marine pollution by hydrocarbons and characterization of their biochemical and molecular effects on the clam Ruditapes sp. Geochemistry. University of Bordeaux; University of Monastir (Tunisia).

[28] Belmenai M., Benhafed N. E. (2015). Isolation and characterization of hydrocarbonoclasticbacteria. Memory, University of the Mentouri Constantine Brothers, 66pp.

[29] Degranges P., Gugalski. T., Leleu M., Greffard J. (1977). Fate of hydrocarbons in the soil. BRGM report.77 SGN 114 MGA. 31pp.

[30] Amadi A., Dickson A. A., Maate G. O. (1993). Remediation of oil-pollutedsoils 1. Effect of organic and inorganicnutrientsupplements on the performance of maize (Zeamays L). Water, Air and Soil Pollution n° 66. pp. 59-76.

[31] Devatha C. P., Vishal A. V., Rao J. P. 2019. Investigation of physical and chemicalcharacteristics on soil due to

[32] Louati H. (2013). Study of the bioremediation of sediments contaminated by polycyclic aromatic hydrocarbons: Ecological impact on the microflora and miofauna of the Bizerte lagoon. Doctoral thesis. Biological science. University of Carthage and Montpellier II. 180p.

[33] Devinny, J. and S. H. Chang. (2000). Bioaugmentation for soil bioremediation, In: Wise, D. L., Trantolo, D. J. (eds) Bioremediation of contaminated soils, Marcel Dekker, New York, pp. 465-488.

[34] Rhbal H., Souabi S., Safi M., Terta M., AradM., Anouzla A., Hafidi, M. (2020). Decontamination of soilspolluted by hydrocarbons. Journal Scientific studies and research: Chemistry and chemical engineering, Biotechnology, Industry food ISSN: 1582-540X 21 (1), pp. 001 – 016.