Remediation of a Soil Contaminated with Lindane in an Electrobiochemical Slurry Reactor

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ABSTRACT

Lindane is a chlorinated pesticide known for its toxicity and persistence in the environment. Recently, it has been proposed that soil microbial fuel cell technology (SMFC) could be applied to enhance the removal of organic matter, phenol, and petroleum hydrocarbon in contaminated soil with simultaneous electricity output. Yet, there is no information on the application to remediation of soils polluted with pesticides. The purpose of this research was to evaluate the biodegradation of lindane with simultaneous electricity generation in an electrobiochemical slurry reactor (EBCR). The EBCR was inoculated with a sulfate reducing inoculum acclimated to lindane, characterized, and further batch operated for 30 day at room temperature. No external carbon source was supplemented in the experiment 1; the substrate was the soluble natural organic matter (NOM) of the soil. In the experiment 2 the EBCR was supplemented with a stock solution of sucrose: sodium acetate: lactate to give a final concentration of 2g COD/L in the reactor. Results from electrochemical impedance spectroscopy characterization in the EBCR (Experiment 1) showed that the equivalent circuit had an anodic resistance R_1=2064Ω, cathodic resistance R_3 = 192 Ω; and electrolyte/membrane resistance R_2 = 7Ω, totalling a relatively high overall internal resistance R_{int} of 2263Ω. During the batch operation, the EBCR showed a 30% lindane removal efficiency along with a maximum volumetric power volumetric of 165 mWm^{-3}. This value compared favorably with results corresponding to sediments microbial fuel cells that are used to power weather monitoring systems. The organic matter removal was very high (72% as soluble COD, NOM) whereas the coulombic efficiency was low (5.4%). The latter, although, was higher than values reported for microbial fuel cells that degraded leachate-like effluents. In Experiment 2 of the EBCR both cell characteristics and performance significantly improved. The internal resistance as determined by polarization curve was 102Ω when the connection was in parallel. During the batch operation, the EBCR showed a 78% lindane removal and a maximum power volumetric of 634 mWm^{-3}, the organic matter removal was 76% and coulombic efficiency was 15%. Finally, it can be concluded that our EBCR showed a high lindane removal capability.

Keywords: Electrobiochemical slurry reactor, lindane, soil remediation, sulphate reducing

1. Introduction

The widespread use of pesticides has lead to pollution of soil, water bodies and aquifers, and atmosphere [1, 2]. The γ-hexachlorocyclohexane (γ-HCH; also called lindane) is a highly halogenated organic pesticide that has been used

worldwide, particularly in Mexico, in spite of its banning in first world countries [3]. Lindane has been used for crop protection and prevention of vector-borne diseases for many decades [4-7]. Negative impacts of lindane on the environment and human health have been reported worldwide [8]. Due to their hydrophobicity, lindane is tightly bound to the organic matter and clay of soils. This, in turn, decreases their bioavailability. It is commonly recognized that mass transfer of HCH from soil to liquid phase is the limiting process in biodegradation processes used for soil bioremediation [9, 10]. Bioavailability of HCH in polluted soils could be increased by using slurry bioreactors (SB). SB is an ad situ soil bioremediation technology that allows the adjustment and optimization of several process variables such as mixing and water addition, nutrient supplementation, addition of surfactants and solvents to increase pollutant desorption from soil, temperature and pH control, bioaugmentation (seeding the bioreactor with microbial strains or consortia acclimated or specialized in pollutant degradation), etc., with the purpose to increase mass transfer, foster biodegradation and decrease treatment time [11-13]. On the other hand Microbial Fuel Cell (MFC) is a promising technology for the biodegradation of several organic substrates and wastes such as glucose, acetate, xylose, cysteine, cellulose and organic pollutants with simultaneous power generation [14-19]. In this device the microorganisms oxidize different substrates at the anode producing protons and electrons, which flow through an external circuit to the cathode that is in contact with oxygen, in this part the protons are used in the reduction of oxygen producing water [20-22]. Recently, it has been proposed that soil microbial fuel cell (SMFC) technology could be applied to enhance the removal of organic matter, phenol, and petroleum hydrocarbon in contaminated soil and simultaneous electricity output [17-18]. The purpose of this research was to study the biodegradation of lindane and simultaneously electricity generation using an electrobiochemical slurry reactor (EBCR) for the remediation of a polluted, heavy soil.

2. Experimental

2.1 Chemicals

γ- HCH isomer (97 % purity) was purchased from Sigma-Aldrich. Lindane is a moderately lipophilic, organo-chlorinated substance characterized by a high partition coefficient octanol-water Kow ≈ 4*103, with low solubility in water, approx. 7 mg/L at 20ºC, and slightly polar due to the strong electronegative effects of chlorine atoms bound to the aliphatic ring. Chlorobenzene (CB), dichlorobenzene isomers (1,2-DCB, 1,3-DCB) and 1,2,4 trichlorobenzene (99–99.9% purity) , hexane and acetone were of analytical grade.

2.2 Lindane and metabolite analysis

Lindane was analyzed by Headspace-Solid Phase Microextraction-Gas Chromatography- Electron Capture Detector (HS-SPME-GC-ECD). The procedure for the extraction of HCH residues in the soil slurry reactor was performed according by Quintero *et al.* [23]. The intermediate metabolites in the experiment 1 were analysed in an Agilent Technologies GC/MS with an autosampler Gerstel (MPS-2 Twister), the oven temperature were programed as follows: hold time 40°C, 2 min; ramp rate at 3°C/min to 180°C; ramp rate at 8°C/min to 270°C. The injection volume was 1µl via a split-less injection at 280°C. Helium was used as a carrier at a flow rate of 1.0ml/min. The intermediate metabolites in the experiment 2 were analyzed in a Perkin Elmer gas chromatograph equipped with an electron capture detector. Selected samples of EBCR (experiment 2) were analyzed in a Perkin Elmer GC-MS, the oven temperature were programed as follows: hold time 40°C, 6 min; ramp rate at 3°C/min to 180°C; ramp rate at 10°C/min to 300°C. The injection volume was 1µl via a split-less injection at 250°C. Helium was used as a carrier at a flow rate of 1.0ml/min.

The soil pH was determined in a slurry soil/deionized water 1:2 (w/w) [10], soil texture was measured by the hydrometer method, biochemical oxygen demand (BOD) was estimated according to the Standard Methods (Method 507) and organic matter content was estimated by the method of oxidation with $K_2Cr_2O_7$ [24]. In sulphate reducing seed reactor (Table 1) were determined: pH, sulphate, organic matter content such as COD and biomass according to the Standard Methods (methods 423, 426C, 508, and 209E respectively; 25). The alkalinity was analysed according to Poggi-Varaldo and Oleszkiewicz [26].

Table 1. Performance of sulphate reducing seed reactor used for inoculation of electrobiochemical slurry reactor

Parameter	
Lindane (%)	76.36± 15.2
pH (-)	7.55 ± 0.25
COD (%)	52.87 ±18.24
Biomass (mg VSS/L)	1469.11 ± 674.269
Factor α (–)	0.17 ± 0.10
Sulpate(%)	76.81± 20.48

2.3 Soil

An agricultural soil with high contents of organic matter and clay (Table 2), contaminated with a dose of 100 mg lindane/kg dry soil.

Table 2. Main physico-chemical characteristics of mineral agricultural soil used in this work

Parameter	
Source	Huajuapán de León, Oaxaca
Type	Cambisol
pH	7.31 ± 0.06
Organic matter (%)	8 ± 0.09
COD (mg COD/kg dry soil)	5100 ± 436
BOD (mg BOD_5/kg dry soil)	3725 ± 353
Clay (%)	43 ± 0.79
Sand (%)	37 ± 2.70
Silt (%)	21 ± 3.33
Texture	Clayish
Hydraulic conductivity	Low to moderate

2.4 Electrobiochemical slurry reactor

The EBCR consisted of a Plexiglass cylinder approximately 6 cm in diameter and 8 cm in height (308 mL capacity), the anodes used in this experiment were graphite discs (5cm D x 0.5 cm) and the cathodes were of Toray carbon cloth, the cathodes were in contact with atmospheric air (Figure 1). The electrodes were separated by a cation exchange membrane (Nafion 117, coated with 0.5 mg/cm2 platinum catalyst, Pt 10wt%/C-ETEK) and was inoculated with a sulfate reducing inoculum acclimated to lindane [27].

2.5 Experimental design

2.5.1 Experiment 1

The EBCR was batch operated for 30 day at room temperature. The concentration of soil was 66%. No external carbon source was supplemented; the substrate was the soluble natural organic matter of the soil (NOM). Measurements of the power output were performed using a Multimeter ESCORT 3146A.

2.5.2 Experiment 2

The EBCR was batch-operated for 30 day at room temperature. The concentration of soil was 33% w/v. The EBCR was fed a solution stock of sucrose: sodium acetate: lactate to give a final concentration of 2g COD/L in the EBCR at 15 y 25d. The mix was with nitrogen the first 15 days, afterwards mixing was performed in a shaker at 100 rpm. Measurements of the power output were done using a Multimeter ESCORT 3146A. The process controls were EBCR under open-circuit and non-EBCR conditions as the biotic control and abiotic control respectively.

2.6 Determination of internal resistence of the electrobiochemical slurry reactor

2.6.1 Electrochemical impedance spectroscopy in the experiment 1

The internal resistance (R_{int}) of EBCR was calculated as a function of cell voltage using electrochemical impedance spectroscopy (EIS). The electrochemical impedance spectra were recorded over a frequency range of 1 mHz to 100 kHz [28-30], equivalent circuit models were fitted to the data using the program of ZView2.

2.6.2 Polarization curve method in the experiment 2

The internal resistance of was determined using the polarization curve method, by varying the external resistance ($100\text{-}10^5\Omega$) according to procedures suggested by Logan *et al*. [20], Poggi-Varaldo *et al*. [21], Vázquez-Larios *et al*. [22], Sathish-Kumar *et al*. [31], this was carried out 0d y 7d of operation.

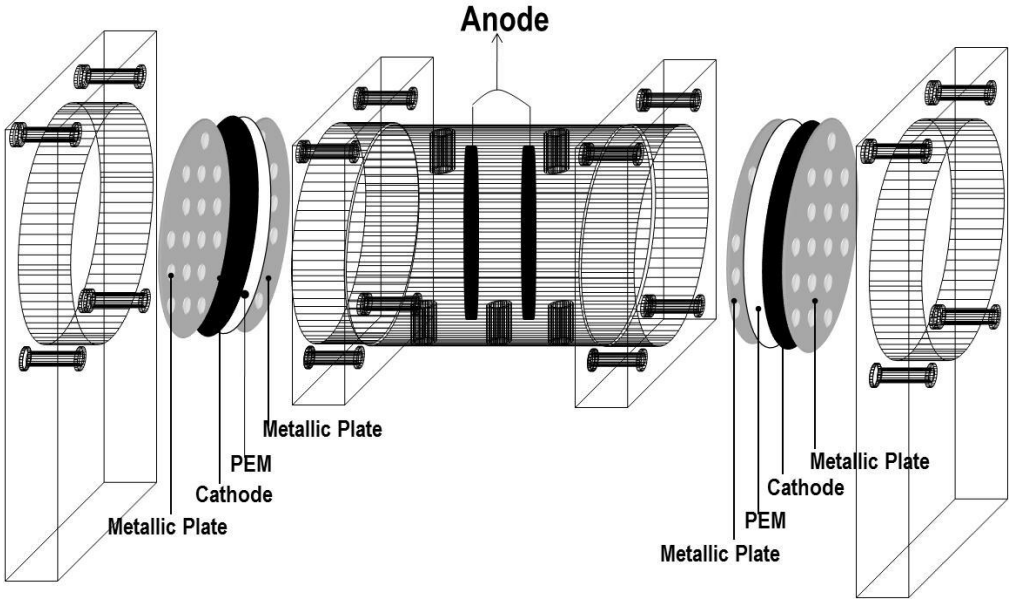

Figure 1. Schematic diagrams of electrobiochemical slurry reactor

3. Results and discussion

3.1 Experiment 1

3.1.1 Determination of internal resistance

Internal resistance is an important factor in the characterization of MFCs, because when an MFC is operated with an external resistance under an external resistance equal to its internal resistance will result a maximum value of power. Results from experiment showed that the equivalent circuit obtained from the Nyquist plot (Fig. 2) had anodic resistance R_1=2064 Ω, cathodic resistance R_3 = 192 Ω; and electrolyte/membrane resistance R_2 = 7 Ω; so the total internal resistance was 2263 Ω. Compared with microbial cell with matrix of soil, this value is lower than 10 kΩ reported by Ringelberg *et al*. [32]. They [32] worked with a cylinder (2.2cm X 10cm, D X h) as the reactor, a non-contaminated soil with texture silt loam with organic content of 11.1%, whereas the anode was carbon cloth with 16 cm^2 of surface area and the cathode was carbon cloth coated on one side with 0.5 mg Pt/cm^2. On the other hand, our internal resistance was higher than that reported by Wang *et al*. [18] and Huang et al. [17]. The former worked with a U-tube air-cathode soil MFC and a soil with texture was silt loam, the anode and cathode (connected in parallel) where carbon mesh, the cathode was coated with 0.1 mg/cm^2Pt. They reported an internal resistance of 1 000 Ω. Their soil had 28.3 3 g total petroleum hydrocarbon/kg of soil. They also observed a pollutant removal of 15% in 25 days of batch operation. On the other hand Huang *et al.* [17] found an internal resistance of 100 Ω in a system used to phenol from waterlogged soil. The paddy soil (phenol, 80mg/L) was covered with 3.0 cm of water, the anode was a layer of carbon felt (15.0cm ×12.5cm × 0.5cm) and cathode was GORE-TEX cloth (15.0cm × 12.5cm), coated with Ni-based paint (7.0g) and Pt/C solution mixed with Nafion (0.094g). Phenol removal was 90.1% in 10 days. This relatively high result could be ascribed to the fact that phenol is not strongly sorbed on to soils and can be degraded by a great variety of microorganisms and its toxicity is quite relative. In contrast, lindane is known to be very recalcitrant, toxic, and hydrophobic [7, 10].

3.1.2 Perfomance of the electrobiochemical slurry reactor

The electricity generation reached a voltage output of approximately 330 mV at 7 days (Fig. 3, table 3), power density normalized with the anode 6.6 mW/m^2 and volumetric power 165 mW/m^3. The voltage remained constant until day 20, it is low at 240mV. The organic matter removal was very high (72% as soluble COD, NOM) whereas the coulombic efficiency was low (5.4%).

3.1.3 Lindane removal and intermediate metabolites

The EBCR showed lindane removal efficiency 30%; after 30 d operation metabolites from lindane degradation/transformation were not detected (Figure 4)

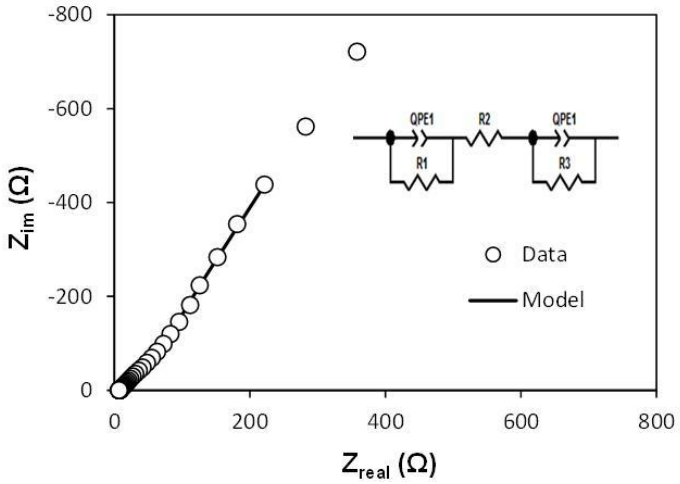

Figure 2. Nyquist plot and equivalent circuit in the Experiment 1

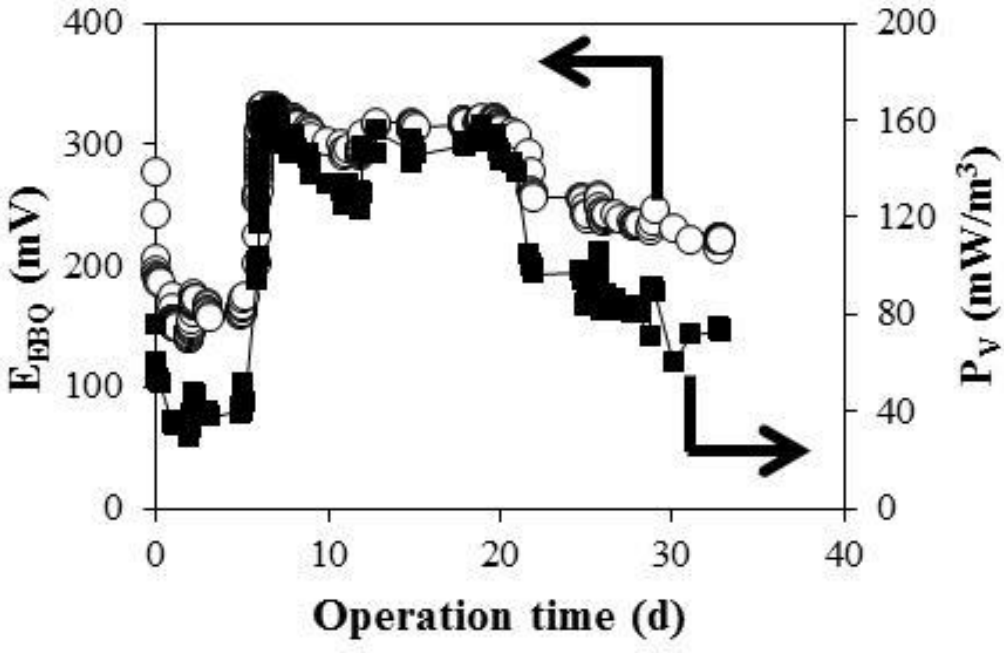

Figure 3. Electricity generation by an electrobiochemical slurry reactor during batch operation for 30 d in the Experiment 1.

Table 3. Average performance of the electrobiochemical slurry reactor in Experiment 1.

Parameter	Value
$\eta_{Lindane}$ (%)	27.60 ± 6.33
$P_{An\text{-}max}$ (mWm^{-2})	6.62
$P_{V\text{-}max}$ (mWm^{-3})	165.31
$E_{EBCR\text{-}max}$ (V)	0.33
$I_{EBCR\text{-}max}$ (mA)	0.15
$P_{EBCR\text{-}max}$ (mW)	0.05
$P_{An\text{-}ave}$ (mWm^{-2})	4.12 ± 1.35
$P_{V\text{-}ave}$ (mWm^{-3})	103± 34
$E_{EBCR\text{-}ave}$ (V)	0.26± 0.07
$I_{EBCR\text{-}ave}$ (mA)	0.12 ± 0.03
$P_{EBCR\text{-}ave}$ (mW)	0.03 ± 0.01
η_{COD} (%)	72.36± 15
η_{SO4} (%)	22.07± 0.01

Notes: $\eta_{Lindane}$, lindane removal efficiency; P_{An}, surface area power density; P_V, volumetric power; E_{EBCR}, voltage; I_{EBQR}, current intensity; P_{EBCR}, power delivered; η_{COD}, organic matter removal efficiency as COD; η_{SO4}, sulphate removal efficiency. Subindices: max, maximum; ave, average.

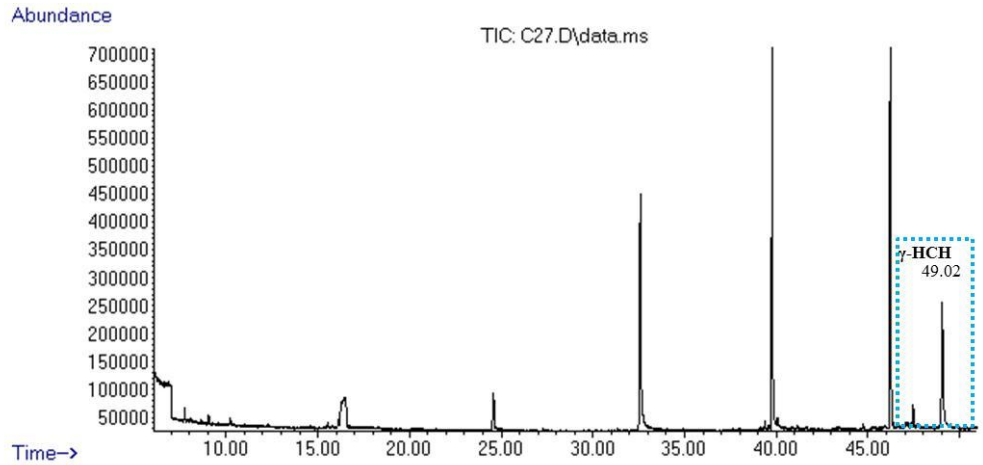

Figure 4. GC-MS detection of intermediate metabolites in electrobiochemical slurry reactor at time 30 days in the Experiment 2.

3.2 Experiment 2

3.2.1 Characterization of the electrobiochemical slurry reactor

The polarization curves and the power variation with current intensity of the EBCR at time 0 days are shown in Figure 5a and 5b respectively. The values obtained from the polarization curves method were 2046, 1288, 897 y 255Ω for face A, face B, connection in series and parallel, respectively (Table 4). The maximum volumetric power was obtained when the connections were in parallel (739 mW/m^3) followed for the face B, connection in series and face A with 421, 340 and 86 mW/m^3 respectively.

After 7 days of operation another reactor characterization was carried out. The internal resistances decreased very much compared to those of the first characterization. Their values were approximately o 140, 339, 442, 102 Ω for face A, face B, connection in series and connection in parallel, respectively. The maximum volumetric power was obtained for parallel connection (1531 mW/m^3, Table 4, Fig. 6); it was twice the volumetric power obtained with characterization at 0 days. The improved characteristics might be a consequence of the increased microbial activity resulting from enrichment of the biofilm on the anode [33]. The internal resistance was smaller than that obtained by Ringelberg *et al*. [32] and Wang *et al*. [18] who reported values of 10kΩ and 1kΩ, respectively. On the other hand the internal resistance obtained when the connection were in parallel was similar to low internal resistances of 100 Ω reported by Huang *et al*. [17] and Yan *et al.* [34].

3.2.2 Performance of the electrobiochemical slurry reactor

Figure 7 shows voltage generation of the device when the anodes and cathodes of the EBCR were connected in parallel. The voltage with the EBCR in open circuit conditions (at the early 20 h) was approximately 530 mV (phase I). The voltage remained stable when the cell was operated with an external resistance of 120 Ω (first hours of phase II); however the voltage decreased to less than 200 mV afterwards. So, open circuit conditions were re-established in phase III) where an expected increase of voltage occurred. Subsequently, in phase IV, the cell was operated with an external resistance of 220 Ω and a drastic voltage decrease was observed. Again, open circuit conditions were re-established in phase V. Phase VI was run with an external resistance of 560 Ω. Approximately at day 8 the cell contents was mixed with nitrogen gas. It was found that cell voltage significantly increase after each mixing episode; however, after mixing the voltage decrease was very important (down to between 100 to 200 mV, Fig. 7, days 8 to 15). Due to pneumatic and hydraulic difficulties of mixing by bubbling N_2 gas, starting at day 15 the cell content was continuously mixed in a shaker at 100rpm. Voltage output recovered and was stabilized around 300 mV. This was accompanied by supplementation with 2g/L substrate (sucrose: sodium acetate: lactate) that was used as the fuel in the EBCR at 15d. Electricity generation began to increase and reached a voltage output of approximately 303 mV (Fig. 7). The power density normalized to anode area was 21.3 mW/m^2 and the average volumetric power was 531 mW/m^3. At approximately 20 days of operation, the cell reached a maximum voltage output of 329mV and volumetric power of 629 mW/m^3 (Table 5); the voltage remained constant until day 24. Afterwards, it decreased

again to a value of 260 mV. On day 25 the EBCR was fed with 2 gCOD/L of substrate and reached a voltage of 321mV, the EBCR voltages decreased below 280 mV at 28 day.

The maximum voltage output of the EBCR (330mV) and maximum power (25mW/m^2) were higher than those reported by Wang *et al.* [18] (155 mV and maximum power 0.85 mW/m^2) for a cell loaded with soil polluted with total petroleum hydrocarbon. Our results also compared very favorably to those observed by Yan *et al.* [34], a voltage as low as 17 mV in the treatment of sediment contaminated with phenanthrene and pyrene.

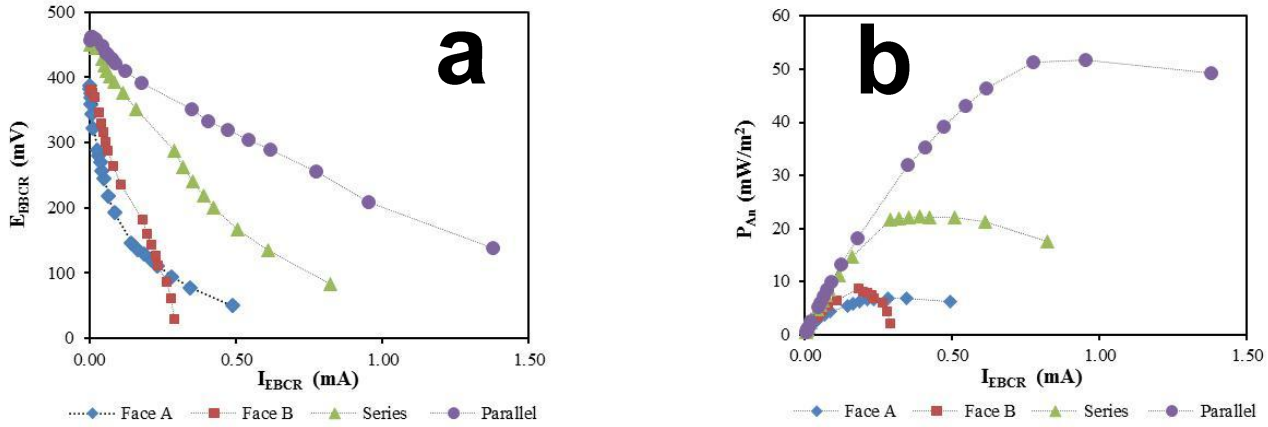

Figure 5. Characterization of the electrobiochemical slurry reactor at t0d (a) Polarization curves, (b) power densities in the Experiment 2

Table 4. Average values of several variables in electrobiochemical slurry reactor characterization after at 0days in the Experiment 2

Parameter	Face A	Face B	Series	Parallel
$R_{int}(\Omega)$	2046	1288	897	255
$P_{An\text{-}max}$ (mWm^{-2})	6.88	33.72	13.60	29.57
$P_{V\text{-}max}$ (mWm^{-3})	86	421	340	739
$I_{EBCR\text{-}max}$ (mA)	0.49	1.14	1.02	1.50
$E_{EBCR\text{-}max}$ (V)	0.39	0.38	0.45	0.46
$P_{EBCR\text{-}max}$ (mW)	0.03	0.13	0.10	0.23
$P_{An\text{-}ave}$ (mWm^{-2})	2.72	6.13	5.08	0.87
$P_{V\text{-}ave}$ (mWm^{-3})	34	76	127	22
$I_{EBCR\text{-}ave}$ (mA)	0.09	0.15	0.20	0.02
$E_{EBCR\text{-}ave}$ (V)	0.22	0.26	0.33	0.37
$P_{EBCR\text{-}ave}$ (mW)	0.01	0.02	0.04	0.07

Notes: P_{An}, surface area power density; P_V, volumetric power; E_{EBCR}, voltage; I_{EBQR}, current intensity; P_{EBCR}, power delivered. Subindices: max, maximum; ave, average.

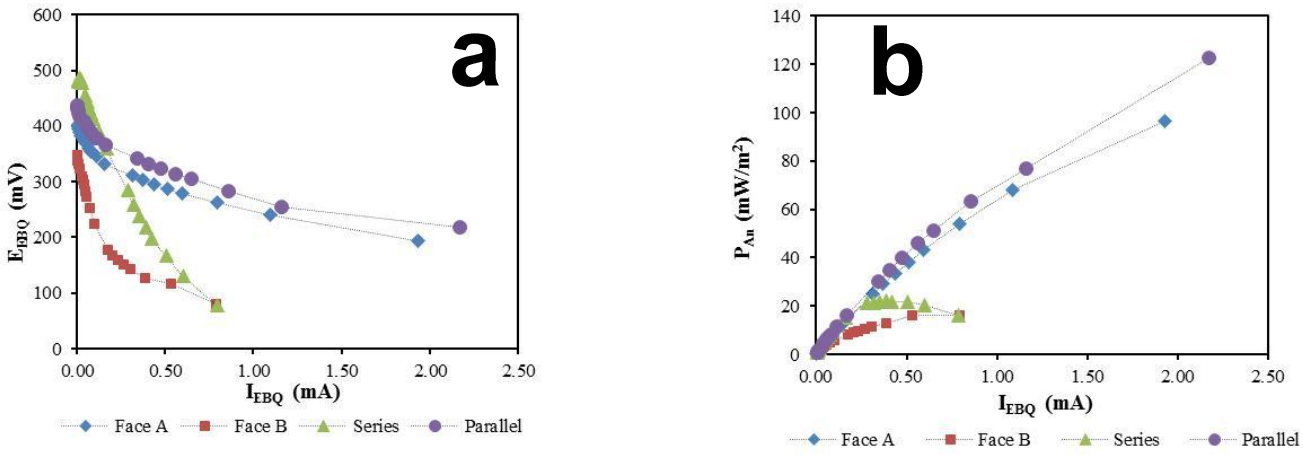

Figure 6. Characterization of the Electrobiochemical slurry reactor at t7d (a) Polarization curves, (b) power densities in the Experiment 2

Table 5. Average values of several variables in electrobiochemical slurry reactor characterization after at 7days in the Experiment 2

Parameter	Face A	Face B	Series	Parallel
$R_{int}(\Omega)$	140	339	442	102
$P_{An\text{-}max}$ (mWm^{-2})	96.60	16.32	13.93	61.27
$P_{V\text{-}max}$ (mWm^{-3})	1207	204	348	1531
$I_{EBCR\text{-}max}$ (mA)	1.93	0.79	1.03	2.17
$E_{EBCR\text{-}max}$ (V)	0.41	0.35	0.49	0.44
$P_{EBCR\text{-}max}$ (mW)	0.37	0.06	0.11	0.47
$P_{An\text{-}ave}$ (mWm^{-2})	19.91	5.88	4.95	12.12
$P_{V\text{-}ave}$(mWm^{-3})	249	73	124	303
$I_{EBQ\text{-}ave}$ (mA)	0.30	0.15	0.19	0.33
$E_{EBQ\text{-}ave}$ (V)	0.34	0.25	0.34	0.38
$P_{EBQ\text{-}ave}$ (mW)	0.08	0.02	0.03	0.09

Notes: P_{An}, surface area power density; P_V, volumetric power; E_{EBCR}, voltage; I_{EBQR}, current intensity; P_{EBCR}, power delivered. Subindices: max, maximum; ave, average.

Table 6. Average performance of electrobiochemical slurry reactor in the Experiment 2

Parameter	Value
□Lindane (%)	78
Rint (Ω)	560
Pan-max (mWm-2)	25
$P_{V\text{-}max}$ (mWm^{-3})	634
$E_{EBCR\text{-}max}$ (V)	0.33
$I_{EBCR\text{-}max}$ (mA)	0.59
$P_{EBCR\text{-}max}$ (mW)	0.20
□Coul (%)	15
□COD (%)	76

Notes: P_{An}, surface area power density; P_V, volumetric power; E_{EBCR}, voltage; I_{EBQR}, current intensity; P_{EBCR}, power delivered, $\square_{COD}$, organic matter removal efficiency as COD. Subindices: max, maximum.

On the other hand, Huang *et al.* [17] registered a power density slightly superior (ca. 30 mW/m^2) and a lower voltage (150 mV) in the treatment of a waterlogged soil polluted with phenol.

3.2.3 Lindane removal and intermediate metabolites

Lindane removal achieved in the EBCR was 78%, whereas the removals of the biotic (live) control and abiotic control slurry reactors were 80 and 3%, respectively. Main metabolites due to lindane degradation were detected by analysis by GC/MS in the EBCR: 1,2,3-trichlorobenzene (1,2,3 TCB), 1,3-dichlorobenzene (1,3-DCB), 1,2-dichlorobenzene (1,2-DCB), and chlorobenzene (CB) (Figure 8).

Lindane removals observed in our EBCR compared very favorable with lindane removals reported for standard slurry bioreactors in the literature. Okeke *et al.* [35] carried out experiments with SB inoculated with *Pandorea* sp., with a presumably anaerobic operation of 9 weeks duration. Initial lindane concentration was 100 mg/kg; they found removals of 59.6% γ-HCH, Quintero *et al.* [5] treated a sandy soil polluted with a mixture of isomers α, β, γ and δ-HCH (100 mg/kg each) in anaerobic SB. Starch was supplemented at 2 g/L every 3 days. High removals of nearly 100% for α and γ isomers of HCH and 65 to 70% for β and δ HCH were found.

On other hand, Robles-Gonzalez *et al.* [10] assessed the bioremediation of a heavy soil polluted with 100 mg lindane/kg in full sulfate reducing slurry bioreactors. Removal was 88% whereas the detected metabolites after 30 d operation were PCCH; 1,2,4-TCB; 1,2,3-TCB; CB, and benzene.

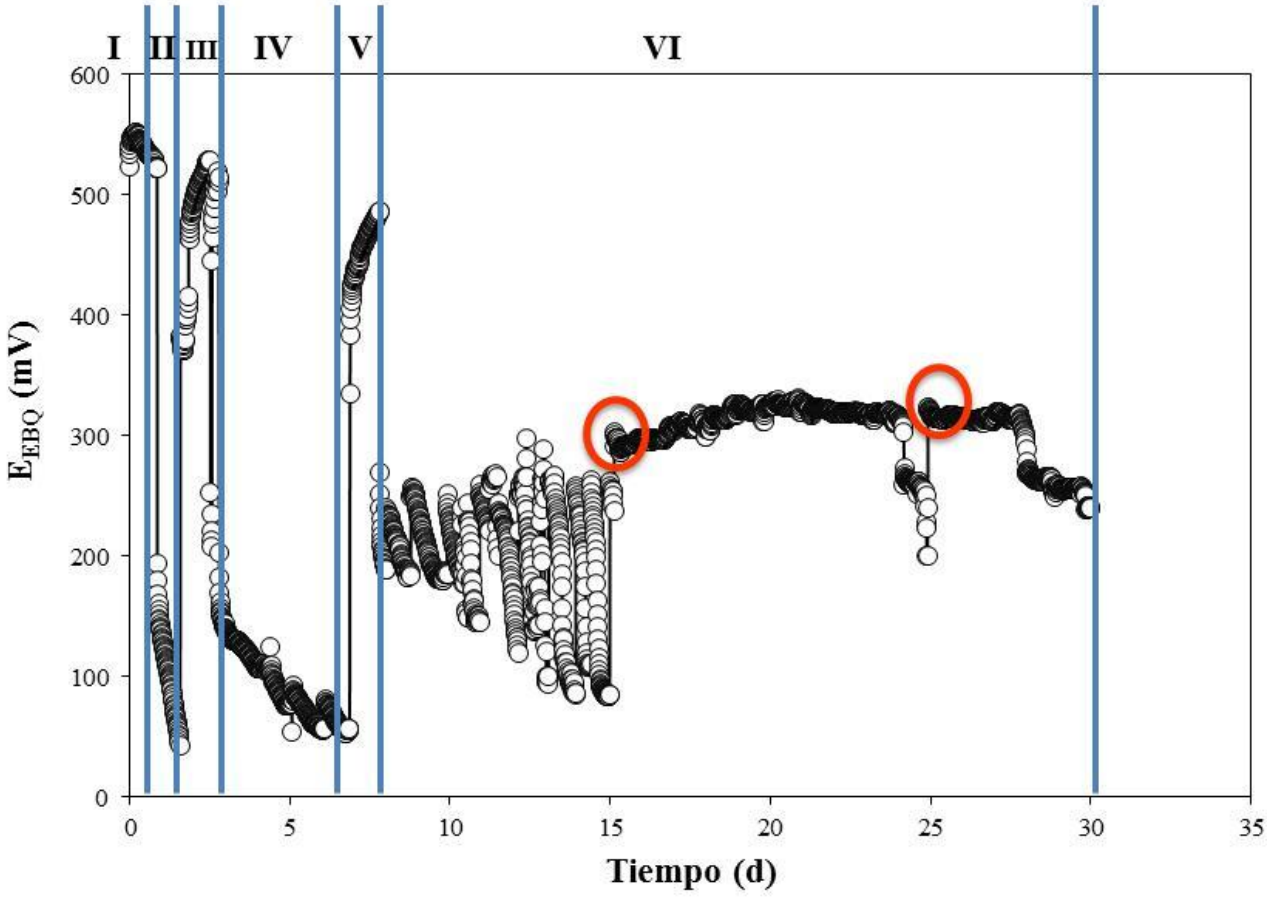

Figure 7. Electricity generation in electrobiochemical slurry reactor during batch operation for 30 d in the Experiment 2. The addition of substrate is indicated by the red circles. Phase I, open circuit; phase II, closed circuit with external resistance 120Ω; phase III, open circuit; phase IV, external resistance 220Ω; phase V, open circuit; phase VI, external resistance 560Ω.

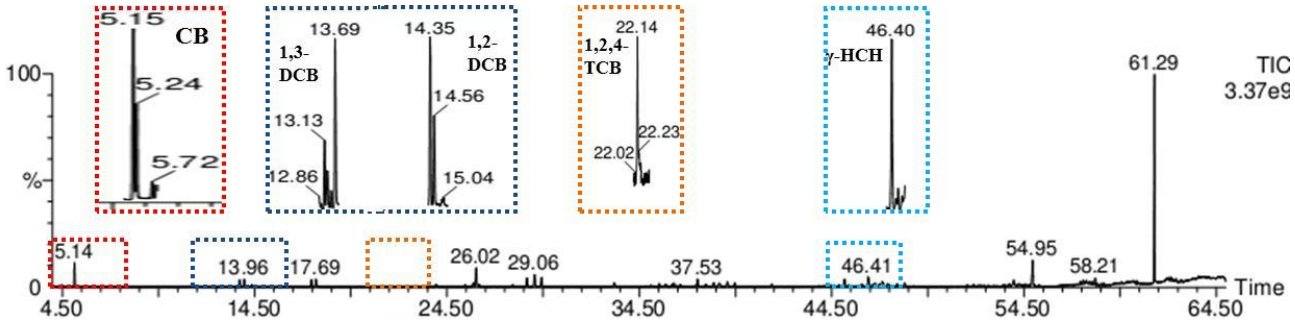

Figure 8. GC-MS detection of intermediate metabolites in electrobiochemical slurry reactor at time 30 days in the Experiment 2.

Quintero *et al.* [23] reported the degradation of HCH isomers in slurry reactors in anaerobic conditions. They found traces of diverse intermediate metabolite, such as pentachlorocyclohexane isomers, tetrachloro-cyclohexene, 1,2,3-trichlorobenzene, 1,3-dichlorobenzene and clorobenzene. The low concentrations of the metabolites indicated that intermediate compounds were not accumulated and they proceed to their further degradation to CB, the end product in the degradation mechanism. In a work by Boyle [36] it was found that lindane could be dechlorinated by anaerobic bacteria (sulfate-reducing bacteria among others) with generation of monochlorobenzene and benzene as main intermediates. Quintero *et al.* [23] observed total depletion of α and γ-HCH in a polluted soil after 3 days anaerobic incubation; they used an initial lindane concentration of 100 mg kg-1 soil, bioaugmentation with a high concentration of methanogenic anaerobic sludge (8 g VSS L^{-1} in the bioreactor), and starch (2 g COD/L) as electron donor. During the degradation, traces of diverse intermediate and end-products compounds were detected, such as pentachlorocyclohexane isomers (PCCH), tetrachlocyclohexane (TCCH), 1,2,3-trichlorobenzene (1,2, 3-TCB), 1,3-dichlorobenzene (1,3-DCB), chlorobenzene CB.

The relatively high lindane removals obtained in our work in only 30 d of EBCR operation are very promising: EBCR emerges as a fast and attractive technology for pesticide degradation and soil remediation. Indeed, it has been reported the recalcitrance (persistence) of organo-chlorinated pesticides in soils, with half lives of the order of 2 to 5 years. In particular, lindane has an average half-life of 2.6 years in soils, depending on the physico-chemical characteristics of soils (texture, organic matter, depth, etc.) as well as environmental conditions [37].

4. Conclusion

-The bioremediation of lindane in soil can be significantly enhanced generation in an ECBR, with the additional bonus of simultaneous electricity generation, compared to conventional slurry bioreactor and other bioremediation technologies.

-Mixing and the supplementation with organic substrate seemed to significantly improve the EBCR performance, both the efficiency of the removal of lindane and the production of electricity significantly increased.

-We detected intermediate metabolites typical of anaerobic degradation pathways of lindane that were similar to those reported in previous research in conventional anaerobic slurry bioreactors.

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Abbreviations and Acronyms

1,2, 3-TCB	1,2,3-trichlorobenzene
1,3-DCB	1,3-dichlorobenzene
1,4-DCB	1,4-dichlorobenzene
Ave	Average
BOD	Biochemical oxygen demand
CB	Chlorobenzene
COD	Chemical oxygen demand
EBCR	Electrobiochemical slurry reactor
E_{EBCR}	Voltage
EIS	Electrochemical impedance spectroscopy
GC-MS	Gas chromatography coupled to mass spectrometry
HCH	Hexachlorocyclohexane
I_{EBQR}	Current intensity
Max	Maximum
MFC	Microbial Fuel Cell
NOM	Native organic matter
P_{An}	Surface area power density
P_{EBCR}	Power delivered
P_V	Volumetric power
R_{int}	Internal resistance
SB	Slurry bioreactors
SMFC	Soil microbial fuel cell technology
SR	Sulphate reducing

Greek characters

□	Removal efficiency