Removal of 2,4-D herbicide in soils using a combined process based on washing and adsorption electrochemically assisted

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Abstract

In this work, it is presented an innovative soil remediation technology consisting of the combination of soil washing, GAC adsorption and electrolysis. This technology is applied for the remediation of soil polluted with herbicide 2,4-dichlorophenoxyacetic acid (2,4-D). The new combined process involves three steps into a single chamber: first step is related to the washing of soils using groundwater as soil washing fluid, the second step is related to the herbicide removal from the produced soil washing effluent by adsorption onto granulated active carbon and the third step is the use of electrolysis to oxidize the 2,4-D and provide bubbles that enhance the mixing and separation by

dissolved gas flotation. All processes are studied alone and in combination. The obtained results pointed out the possibility for total removing of the herbicide content in the contaminated soil, simultaneously to the herbicide removal contained in soil washing effluent, which become ready to be recycled as a fresh soil washing fluid. The proposed combined treatment for complete decontamination of soils polluted with 2,4-D herbicide was successfully tested for 0.1 kg soil, contained 20 mg herbicide per kg of soil, using 1 dm³ of synthetic groundwater as washing effluent and 10 g GAC, and passing through this mixture an electrical current of 0.5 A, during 2 h.

Keywords: soil washing, GAC adsorption, electrochemical process, 2,4-D, herbicide, remediation

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Highlights

- Soil washing can be efficiently used to remove 2,4-D herbicide from soils.
- Total extraction of 2,4-D herbicide is not attained using single soil washing.
- Combination with GAC adsorption allows to remove the 2,4-D herbicide from the SWE.
- Addition of electrolytic processes attain a more efficient removal of 2,4-D herbicide allowing its total depletion.

1. Introduction.

In the recent years, the population growth has led to the intensive using of herbicides in the agricultural sectors in order to prevent the growth of weed in crops. After the herbicide distribution on the soil surface, their accumulation is increasing in each year. Therefore, their concentrations would increase and overcoming the allowed limits. In the same time, the water from the precipitation leads to the soil washing and finally, the herbicides could contaminate the ground waters. Nonetheless, their presence in soils and groundwater should be avoided due to the harmful effects toward the human health. Taking into consideration all the above-mentioned aspects, the development of efficient treatments for removal of these compounds from the environmental components, becomes one of primordial priority. The most common technology applied for the pollutant removal from soils is the washing [1, 2], which consists of digging up of the polluted soil and treating it in a disposal facility. Therefore, it is possible to prevent the expansion of pollution in soil [3, 4].

Soil washing is a mechanical treatment in which the pollutant is transferred to a liquid stream, which is in contact with the polluted soil. In this process, it is necessary to assure an efficient mass transfer of the pollutant from soil to the soil washing fluid (SWF). Likewise, depending on the nature of the pollutant, the addition of surfactants during the washing process could be necessary [5]. After the soil washing, the resulted liquid stream (soil washing effluent, SWE) containing the herbicide, should be treated in order to remove this pollutant. Several authors have described the application of different treatments for the removal of a wide variety of pollutants in soil washing effluents [6-10]. In this context, Davezza et al. [11] described the use of three different surfactants for the removal of the pesticide bentazone in soil by washing. Then, they proposed a photocatalytic treatment using TiO_2 for the removal of the pesticide in soil

washing effluents. With this process, it is possible to achieve a complete removal of bentazone using 1500 mg dm^{-3} of TiO_2 and Brij 35 as surfactant. The required operation time was less than 1 h. However, the complete mineralization of the organic matter was slower. A similar heterogeneous and homogeneous photocatalytic treatment of pesticides was investigated by the group coordinated by I. Poulious [12].

On the other hand, the application of Fenton and photo-Fenton processes (advanced oxidation processes, AOPs) were developed by Bandala et al. [13] for the treatment of soil washing effluents polluted with the 2,4-D herbicide. They studied the influence of the ratio $\text{Fe}^{2+}/\text{H}_2\text{O}_2$ with and without UV light irradiation, finding that the optimum conditions for the removal of the 2,4-D herbicide and the surfactant (sodium dodecylsulfate, SDS) used were a concentration of Fe^{2+} of 0.3 mM and 4 mM of H_2O_2 with the irradiation of UV light. Under these conditions, an operation time less than 10 minutes was required for the removal of both pollutants (pesticide and surfactant). Nonetheless, authors do not describe a complete removal of the organic matter presented in the effluent and, therefore, it would be necessary a subsequent treatment that allow the total removal of the organic matter. Other AOP used for the treatment of soil washing effluents polluted with polycyclic aromatic hydrocarbons (PAHs) was ozonation [14]. Haapea and Tuhkanen carried out an integrated treatment based on ozonation and biological treatment after soil washing process. They described that high doses of ozone are required to decrease the concentration of PAH of about 45-65 %. However, small doses of ozone significantly improve the efficiency of the biological treatment, reaching a final removal of the pollutant of about 90 % with the combined system.

Rosas et al. [15] described the removal *p*-Cresol in SWEs using adsorption with different activated carbons. They studied the influence of the presence of surfactants

and its concentration, finding that the use of surfactant modifies the adsorption equilibrium. In this context, the adsorption capacity decreases when the concentration of surfactant increases. However, the kinetic constant is not influenced by the presence or absence of surfactants. It is important to remark that the adsorption processes allow removing the pollutants from soil washing effluents without modifying its structure. Therefore, an efficient adsorption of the pollutants could be achieved, which suggests that this method could be used for a complete removal of such pollutants.

More recently, our group have described the use of electrochemical techniques for the remediation of soil and water polluted with pesticides [16]. These technologies are very efficient for the removal of different kind of organic pollutants and, in particular, electrolysis with diamond anodes allows to attain a complete mineralization of the organic matter presented in soil washing effluents [17, 18]. During this process, high concentrations of oxidant species are generated by the electrooxidation of the ions contained in the effluents. These species attack the organic matter favoring its complete mineralization. Likewise, the generation of gas bubbles in the electrochemical cell by water electrolysis (Eqs. 1-2) improves the interactions between the oxidants electrogenerated and the organic matter.

Based on this background, the main aim of this work is to develop a novel treatment that allows the simultaneous removal of the 2,4-D herbicide in soil and soil washing effluents. In order to achieve these objectives, a combined process based on soil washing and adsorption onto granular activated carbon was studied using an electrochemical reactor. This device promotes the mixture of soil with the washing fluid and the adsorbent by gas bubbles generated from water electrolysis. Likewise, the

different densities of soil and granular activated carbon allow to the first one (soil) settles whereas the second (carbon) floats, make it possible an easily separation of the phases.

2. Material and methods.

2.1. Chemicals.

2,4-dichlorophenoxyacetic acid (2,4-D) was provided by Alfa Aesar (CymitQuímica, Spain) and used as received. $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, NaNO_3 , NaCl , KCl and CaCO_3 were purchased from Sigma Aldrich (Spain). Acetonitrile HPLC grade, 2,6-pyridinedicarboxylic acid and nitric acid (Sigma-Aldrich, Spain) were used for the mobile phase. All involved chemicals were of analytical degree. Using a Millipore Milli-Q system, the double deionized water with resistivity of $18.2 \text{ M}\Omega \cdot \text{cm}$ at 25°C was obtained, which was used for preparation of all necessary solutions.

2.2. Preparation of synthetic groundwater.

Synthetic groundwater was used as washing fluid during the process. It was prepared by dissolving the exact amounts of different salts in deionized water, following a typical composition of groundwater in Spain [19, 20]. Table 1 shows the composition of the groundwater used in this work.

Table 1. Composition of the used synthetic groundwater

Ion	Concentration (mg dm^{-3})
CO_3^{2-}	149.7
Cl^-	79.8
NO_3^-	95.0
SO_4^{2-}	253.3
Na^+	87.1
K^+	6.0
Ca^{2+}	100.0
Mg^{2+}	66.9

2.3. Preparation of spiked soil.

The preparation of soil was carried out by the procedure described in literature [21]. For the experiments, 0.25 kg of soil was contaminated with 0.05 dm³ of a solution of 2,4-D herbicide (100 mg dm⁻³). The soil was left one day at room temperature to evaporate the water and the final concentration of the herbicide in soil was about 20 mg kg⁻¹. Table 2 shows the mineralogical composition of the soil used in this work.

Table 2. Composition of the investigated clay soil

Mineral	Concentration (%)
Quartz	12
Feldspar	6
Calcite	1
Kaolinite	23
Glaucinite	24
Muscovite	8
Montmorillonite	20
Illite	6

2.4. Experimental procedures.

2.4.1. Soil washing.

Soil washing process was carried out using a Jar-Test system. Continuous agitation allows the formation of a homogeneous mixture between polluted soil and synthetic groundwater. During testing, room temperature was kept constant (20°C) and the evaporation of herbicide and water was controlled using paraffin to cover the 8 recipients with a capacity of 1.0 dm³. In these recipients, a constant volume of 0.4 dm³ of synthetic groundwater and different amounts of polluted soil were added (from 1 to 100 g). The system works at 150 rpm during 8 h.

2.4.2. Adsorption of 2,4-D herbicide onto granular activated carbon (GAC).

Equilibrium and kinetics adsorption of 2,4-D herbicide onto granular activated carbon were carried out in different vessels with agitation at 25 °C. Each vessel contained 0.1

dm³ of a solution of 100 mg dm⁻³ of 2,4-D herbicide and different amounts of granular activated carbon (from 0.01 to 1 g). The system was operated until the equilibrium was reached.

2.4.3. Combined soil washing and adsorption process.

The simultaneous removal of 2,4-D herbicide in soil and groundwater was carried out in a batch reactor equipped with an agitation system and an air pump to promote the mixture of different phases. Prior to study the process, the granular activated carbon (GAC) was selected based on its density. In this context, carbon with density lower than water was used in order to favor its separation from the soil and groundwater by gravity. During this process, 1.0 dm³ of synthetic groundwater was added to 0.1 kg of soil polluted with 20 mg kg⁻¹ of 2,4-D herbicide and 10 g of GAC.

2.4.4. Combined soil washing and adsorption process electrochemically assisted.

An electrochemical cell was used to attain a complete removal of the herbicide in soil and groundwater without an agitation system and an air pump. In this case, the gases generated during electrolysis (Eqs. 1-2) are enough to obtain the mixture of all phases. Platinized Mixed Metal Oxide (Pt-MMO) and titanium were used as anode and cathode, respectively. The anode area was 42.25 cm² and the cathode area was 84.50 cm². The cathode area was higher in order to increase the production of bubbles in the bottom of the reactor. The electric current was provided by a Delta Electronika ES030-10 power supply (0-30V, 0-10A). A current intensity of 0.5 A was applied in order to prevent the heating of system and therefore, the evaporation of the solution.

2.5. Analytical techniques.

Prior to each analysis, all samples were filtered with 0.22 µm nylon filters provided by Scharlab. The removal of 2,4-D herbicide was followed by reversed-phase

chromatography (Agilent 1100 series coupled to UV detector). A Phenomenex Gemini 5 μm C18 was used as analytical column. The mobile phase consisted of 60:40 v/v acetonitrile/2 % acetic acid (flow rate of $0.4\text{ cm}^3\text{ min}^{-1}$). The injection volume was 20 μL and the UV detection wavelength was 280 nm.

The concentration of different ions was measured by a Metrohm930 Compact IC Flex coupled to a conductivity detector. The column MetrosepA Supp 7 was used to analyze the anions and MetrosepA Supp 4 was used to determine the cations. The mobile phase consisted of a mixture 85:15 v/v 3.6 mM Na_2CO_3 /acetonitrile for the determination of anions with a flow rate of $0.8\text{ cm}^3\text{ min}^{-1}$. For the case of cations, 1.7 mM HNO_3 and 1.7 mM 2,6-pyridinedicarboxylic acid was used as mobile phase with a flow rate of $0.9\text{ cm}^3\text{ min}^{-1}$. The temperature of the oven was 45 and 30 $^\circ\text{C}$ for the determination of anions and cations, respectively. The injection volume was 20 μL .

The pH and conductivity were measured using a CRISON pH25+ and CRISON CM35+.

3. Results and discussion.

3.1 Soil washing

Figure 1 shows the variation of 2,4-D herbicide concentration (a) and the removal of herbicide released (b) in the liquid phase with the operation time during the soil washing process polluted with 20 mg kg^{-1} of 2,4-D herbicide. Synthetic groundwater was used as soil washing fluid (SWF).

Figure 1. Time dependence of herbicide removal during the washing treatment of soils polluted with 2,4-D herbicide. (a) [2,4-D]_{SWF}; (b) pesticide released; (■) 1 g soil; (□) 5 g soil; (▲) 10 g soil; (△) 20 g soil; (●) 30 g soil; (○) 50 g soil; (◇) 100 g soil; [2,4-D]_{soil}: 20 mg kg⁻¹; V_{synthetic groundwater}: 0.4 dm³.

the herbicide concentration until reaching a final value from which remains constant. This final value should be the maximum concentration that can be obtained taking into account the ratio water/soil used. The higher concentration of 2,4-D herbicide the lower water/soil ratio. However, the maximum concentration released is lower than the maximum theoretical (discontinuous line) that should be obtained. This fact can be related to an irreversible adsorption of the herbicide in soil [22].

In addition, the release of the herbicide to the synthetic groundwater is completed in less than 8 h, regardless the ratio SWF/soil used (Figure 1b). Likewise, it is not necessary the addition of surfactants to attain a total herbicide removal in soil due to the polar character of 2,4-D herbicide. Nonetheless, the removal rate is higher when SWF/soil ratio is lower. In this context, an operation time of 1 h is enough to attain a complete herbicide removal when the soil quantities are higher than 30 g. On the other hand, the use of soil quantities from 1 to 20 g requires longer operation times (of almost 8 h) to achieve a complete herbicide removal in soil. This fact maybe related to the multilayer adsorption of 2,4-D herbicide molecules in the soil structure and to the capillarity mechanism of water transportation in solid; therefore, for the smaller soil quantities the driving forces for water transportation are smaller, and the time for herbicide removal is higher.

The synthetic groundwater contains different ions (Table 1), and they can be partially retained in soil during the soil washing treatment by ion exchange processes. Likewise, soil presents ions that can be released to synthetic groundwater during these physical-chemical processes. This is important for the later electrochemical processes, because they can modify importantly the conductivity of the soil washing fluid to be treated and in addition the ions contained can influence on the results of electrolytic processes. For this reason, the evolution of these species was monitored. Figure 2 shows the increasing

of the ionic concentration as a function of the soil quantities used during the washing treatment. A positive increasing indicates that ions have been released to synthetic groundwater whereas a negative increasing shows that ions are retained in soil.

Figure 2. Changing of ionic concentration due to the ion exchange process achieved during the soil washing process: (□) chloride; (▒) nitrate; (■) sulfate; (■) sodium; (■) potassium; (■) calcium; (■) magnesium; $[2,4-D]_{\text{soil}}$: 20 mg kg^{-1} ; $V_{\text{synthetic groundwater}}$: 0.4 dm^3 .

Chloride is the most released ion in the washing effluent (synthetic groundwater) while the sulphate is the most retained ion in soil. In addition, significant concentrations of nitrate and sodium are released to the liquid phase during the washing process. Finally, potassium and magnesium are retained in soil when the quantity of soil is higher than 50 g. These results suggest that the soil washing process not only achieved the herbicide transfer to the synthetic groundwater, but also involve the transfer of different ions. Likewise, the ions from the washing effluent (the synthetic groundwater) can be retained in soil and therefore, these results clearly reveal that an ion exchange process

takes place between the liquid and solid phases (synthetic groundwater and soil), during the soil washing treatment.

Figure 3 shows the changes in the pH of the SWE during the soil washing process in case of pollution with 20 mg of 2,4-D herbicide per kg of soil. As it can be observed, the pH values slightly increase during the operation time until reaching a final constant value of about 7.5. This behavior can be explained by the ion exchange that takes place during the soil washing process. In this context, the release or adsorption of different ions in soil can modify the physical-chemical properties of the synthetic groundwater and therefore, the pH values.

Figure 3. Evolution of pH with the operation time during washing treatment of soils polluted with 2,4-D. (■) 1 g soil; (□) 5 g soil; (▲) 10 g soil; (Δ) 20 g soil; (●) 30 g soil; (○) 50 g soil; (◇) 100 g soil; [2,4-D]_{soil}: 20 mg kg⁻¹; V_{synthetic groundwater}: 0.4 dm³.

3.2 GAC adsorption of herbicide from soil washing effluents

Once the efficiency of soil washing was proven in the case of 2,4-D herbicide contaminated soils, the environmental pollution problem is relocated from the solid phase to the liquid phase. Therefore, the next stage of this research was focused on the recycling of the washing effluent, aiming to remove the 2,4-D herbicide using its adsorption onto the granular activated carbon. Figure 4 shows the adsorption isotherm and the adsorption kinetics of the 2,4-D herbicide contained in the soil washing fluid on GAC.

Figure 4. Adsorption equilibrium of 2,4-D herbicide onto the granular activated carbon. Onset: kinetics of 2,4-D removal. (■) 0.1 g; (□) 0.15 g; (●) 0.25 g; (○) 0.3 g; (▲) 0.4 g; (Δ) 0.5 g; (◆) 0.75 g; (◇) 1 g; (x) 5 g; (+) 10 g; $[2,4\text{-D}]_0$: 100 mg dm^{-3} ; $V_{\text{synthetic groundwater}}$: 0.1 dm^3 .

As it can be observed, the adsorption capacity linearly increases with the equilibrium concentration of herbicide until reaching a constant value after concentrations higher than 60 mg dm^{-3} . These results point out that the adsorption on the granular activated

carbon is an efficient technology for the removal of 2,4-D herbicide in wastewater polluted with up to 100 mg dm^{-3} herbicide. The maximum adsorption capacity of granular activated carbon for the removal of the herbicide is about 216 mg g^{-1} .

On the other hand, the adsorption kinetics shows that it is possible a complete removal of herbicide in wastewater when it is using carbon/wastewater ratios of 50 and respectively 100. Under these conditions, the concentration of 2,4-D herbicide decreases until reaching zero values in times lower than 180 minutes. The obtained data corresponding to the adsorption process were fitted using models characteristic to different isotherms (Freundlich, Langmuir, Temkin, Elovich, etc), but only the Freundlich model fitted well the experimental data ($K_F=9.0101$; $n=1.3577$; $r^2=0.954$).

3.3 Combined Soil washing-GAC adsorption process

Due to the promising results obtained during soil washing and adsorption on granular activated carbon of the 2,4-D herbicide, a combined process was developed based on both technologies. This new process consisted of a batch reactor with a volume of 1 dm^3 of synthetic groundwater, 10 g of granular activated carbon and 100 g of herbicide contaminated soil. The system was mechanically stirred, and an air diffusor was placed at the bottom of the reactor to provide aeration from a pump. Figure 5 shows a photo of the developed system in different steps of experimental progress.

Figure 5. Combined treatment of washing and adsorption for 2,4-D herbicide removal in soil. (a) Running system; (b) stopped system. $[2,4\text{-D}]_{\text{soil}}$: 20 mg kg^{-1} (100 g); GAC: 10 g; $V_{\text{synthetic groundwater}}$: 1 dm^{-3} .

As it can be observed, it is possible to blend different phases (soil, synthetic groundwater and granular activated carbon) with a stirrer and an air diffusion system (Figure 5a), ensuring the mass transfer of the herbicide from soil to other phases. Likewise, these phases are easily separated when the system stops (Figure 5b) because the soil settles to the bottom of the reactor, while the granular activated carbon floats. The process was operated during 120 minutes. Figure 6 shows the time dependence of 2,4-D herbicide released to the liquid phase during the combined process of washing and adsorption for the remediation of 100 g of soil polluted with 20 mg of 2,4-D herbicide per kg of soil.

Figure 6. Time dependence of herbicide removal in the liquid during the combined treatment of soil polluted with 2,4-D herbicide. $[2,4-D]_{\text{soil}}$: 20 mg kg⁻¹ (100 g soil); $V_{\text{synthetic groundwater}}$: 1 dm⁻³; CAG: 10 g.

The herbicide concentration increases in the synthetic groundwater during the operation time. However, different stages can be observed during the treatment. Initially, there is a rapid release of 2,4-D herbicide from soil to the synthetic groundwater due to the washing process, reaching the maximum value of the herbicide. This result indicates that the presence of GAC in the system does not influence the washing process and it is possible to attain a complete and rapid removal of the herbicide from soil. Then, the pollutant decreases with the operation time until reach a low constant value (but not zero) in the synthetic groundwater used as washing fluid.

The observed decreasing can be explained in terms of the adsorption of the herbicide onto the GAC and it is important to point out that despite it gets an efficient removal, this technology cannot obtain the total removal of the herbicide from the SWE because

of the dose of GAC used. In order to attain it, an increase in the dose of GAC should be required.

3.4 Electrochemically-assisted soil washing-GAC adsorption process

Finally, the use of an electrochemical reactor was studied to carry out the simultaneous removal of the 2,4-D herbicide in soil and synthetic groundwater. The system is similar to the previous bath reactor used: 1 dm³ of synthetic groundwater and 10 g of granular activated carbon were added to 100 g of soil polluted with 20 mg of 2,4-D herbicide per kg of soil. However, the main difference between both devices is that the electrochemical reactor does not require an agitation and the air diffusion system to blend all phases. In this case, the production of bubbles from water electrolysis (Eqs. 1-2) allows to provide the required turbulence for blending the phases. This process is commonly known as electro-flotation. Figure 7 shows a scheme of the developed electrochemical reactor.

Figure 7. Combined treatment based on washing and adsorption, electrochemically assisted for the remediation of soil contaminated with 2,4-D herbicide. (a) Running system; (b) stopped system. I : 0.5 A; $[2,4\text{-D}]_{\text{soil}}$: 20 mg kg⁻¹ (100 g soil); $V_{\text{synthetic groundwater}}$: 1 dm³; GAC: 10 g.

As it can be observed, the production of oxygen and hydrogen bubbles over the electrodes is enough to ensure the blend of three phases (polluted soil, synthetic groundwater and granular activated carbon) using a current intensity of 0.5 A (Figure 7a). Similarly, it is possible to separate all phases when the current switches off (Figure 7b): soil settles whereas granular activated carbon floats. Figure 8 shows the results

obtained during the combined washing and adsorption process electrochemically assisted for the removal of the 2,4-D herbicide in soil.

Figure 8. Time dependence of herbicide removal in the liquid phase during the combined treatment of soil polluted with 2,4-D herbicide, electrochemically assisted: I: 0.5 A; [2,4-D]_{soil}: 20 mg kg⁻¹ (100 g soil); V_{synthetic groundwater}: 1 dm³; GAC: 10 g.

The concentration of 2,4-D herbicide follows a similar trend than that observed during the combined process in a batch reactor (Figure 6): there is a rapid increasing followed by a decreasing (not a stabilization like the one shown in the non-electrochemical process). However, the initial increasing is slower in the electrochemical device because the produced bubbles determine a smoother blend of the phases. In this context, it is necessary an operation time of 15 minutes to attain a complete herbicide removal in soil. In addition, the use of the electrochemical reactor allows to attain a complete removal of 2,4-D herbicide after 120 minutes because it does not only use adsorption for removing the pollutant but it also combines the destruction capability of the

electrochemical oxidation with Pt-MMO anodes, which allows to deplete the pollutant contained in the washing fluid in a single stage reactor and which it is clearly observed by comparing results of the last stage in figures 8 and 6.

As it was presented a high performance technology for pesticide removal from soil is available now, but the risk of contamination with pesticide from one site to other is permanent possible taking into consideration the transport of pesticides by precipitation water, surface water or ground water. For this reason, a continuous monitoring of pesticide concentration is recommended in each farm in order check if these concentrations are below the maximum limits allowed by EU legislation and national regulations (i.e. EC Regulation 396/2005) [23].

4. Conclusions.

The main conclusions obtained from this study are as follows:

- Soil washing can efficiently remove 2,4-D from soil producing an effluent with a good conductivity, enough for the application of anodic oxidation. There is a fraction of the herbicide that it is irreversible adsorbed onto the soil and cannot be extracted regardless of the ratio soil washing effluent/soil applied in the soil washing process.
- A high efficiency in the removal of 2,4-D from soil can be attained by combining two mass transfer controlled processes: soil washing (Solid –Liquid) and GAC adsorption (Liquid-Solid). The two processes can be performed simultaneously in a single using a stirrer and/or an air diffusion system.
- The combination of soil washing, GAC adsorption and electrolysis can be successfully applied for the remediation of soil polluted with herbicide 2,4-D.

This process allows to avoid mechanical stirring and it also helps to enhance the degradation of organic content in the soil washing effluent leading to the complete depletion of the herbicide. The application of current generates two processes: electro-oxidation of organic matter and the water electrolysis that generates bubbles of gases (oxygen and hydrogen) which provide the required turbulence for blending the different components.

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