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Review

Electrokinetic Remediation and Its Combined Technologies for Removal of Organic Pollutants from Contaminated Soils

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Electrokinetic (EK) remediation and its combined methods are emerging technologies to remove organic pollutants (OPs) from contaminated soils *in situ* in last decade. This paper reviews six main types of EK and combined remediation technologies for the removal of OPs from contaminated soils: direct EK technique, EK combined with Fenton technique, EK combined with surfactants / co-solvents technique, EK combined with bioremediation method, the method of Lasagna, and EK combined with ultrasonic remediation method. The basic principles, characteristics, application areas and research developments of these six methods are discussed, respectively. The prospects for the future development trends of EK and its combined remediation techniques for the removal of OPs from contaminated soils are also anticipated.

Keywords: Electrokinetic remediation, combined methods, organic pollutants, soil

1. INTRODUCTION

Nowadays, due to increased industrialisation and manufacturing processes, elevated amounts of organic pollutants (OPs) are released into the environment and result in soil contamination [1–8]. Soil contamination is a critical issue as a threat to public health, food system and groundwater [9–12]. OPs, especially hydrophobic organic compounds (HOC) have longer retention time and can penetrate the interface in different environmental media due to their low solubility, high lipophilicity, semi-volatility and low degradability, thus they can cover a large area and remain for quite a long time in the environmental media. These lead to the pesticide residue amounts exceed up to 16%–20% over the quality index for the major agricultural products, making agricultural products lack of security guarantee. Thus, the remediation of contaminated soils has currently become a research hotspot in environmental science as well as one of the most challenging research fields.

Electrokinetic (EK) remediation [13-17] is a green remediation technology developed in recent ten years, and has already been used for treatment of soils contaminated by heavy metals and OPs. It has become an important development direction in soil remediation and has showed promising application prospects [18]. The main advantages of EK remediation are as follows: (1) capable of used for remediation of soils with low permeability (the application of traditional technologies is restricted due to the hydraulic conductivity); (2) *in situ* remediation and decreasing on-spot pollution to the least; (3) shorting remediation time (no more than one month in the laboratory experiment); (4) lowering the cost (the cost is much lower compared with using other traditional remediation technologies for treatment of per ton or cubic meter soil). However, there are still some disadvantages for the technologies limiting their practical applications, such as poor solubility, weak desorption capacity, as well as low removal efficiency for non-polar OPs. However, the disadvantages by single EK technique, such as lower removal efficiency of pollutants and longer remediation time, could be improved by combined EK technologies.

Hence, the development of EK and its combined soil remediation technologies have become a research focus. Since the introducing EK technology by Acar and Alshawabkeh [13,17] in 1993, there have been much progresses achieved on its basic principles and EK processes for the degradation of contaminants.

Saichek and Reddy [14] summarized the applications of electrokinetically enhanced remediation of soils contaminated by hydrophobic organic compounds before 2005. Yap et al [19] reviewed Fenton based treatments specifically for polycyclic aromatic hydrocarbons-contaminated soils in 2011. We have summarized the enhanced EK remediation methods for contaminated soils [20] and the efficiency of two energy-supplying methods including potential controlling and current controlling [21], and the electrode materials used for the remediation were also discussed.

In this paper, six EK remediation and their combined technologies (direct EK technique [22], EK combined with Fenton technique [23–25], EK combined with surfactants / co-solvents technique, EK combined with biological techniques [26–29], the method of Lasagna, and EK combined with ultrasonic techniques [30]) for the treatment of OPs contaminated soils are summarized. The principles, features, applications and current researches of each technology are introduced and the development direction of this topic is also anticipated.

2. EK AND ITS COMBINED REMEDIATION TECHNIQUE FOR THE REMOVAL OF OPS FROM SOILS

2.1. Removing OPs from soils by direct EK technique

Now, direct EK technology has been used for treatment of various OPs contaminated soils, which are mainly including phenols [31–35], nitrobenzenes [17] and pesticides [36], etc. General and non-uniform EK methods are the two main aspects of this technique.

2.1.1. General electrokinetic method

The principle of this method [13–17] is similar to that of an electrolytic cell. Generally, a low-voltage DC electric field (uniform electric field) is applied to the polluted soil after inserting two electrodes into both terminals. Under the condition of low current density, pollutants soluble in water or adsorbed in the surface layer of the soil will move towards different electrodes according to charges what they hold, and the bonds between pollutants and soils will be broken down with anodic acidification. Water will flow in soil in the form of electro-osmotic flow and the fluids in the micropores can be brought to the anode, so as to make the dissolved pollutants transfer to the surface layer, and thus are removed.

2.1.2. Non-uniform EK method

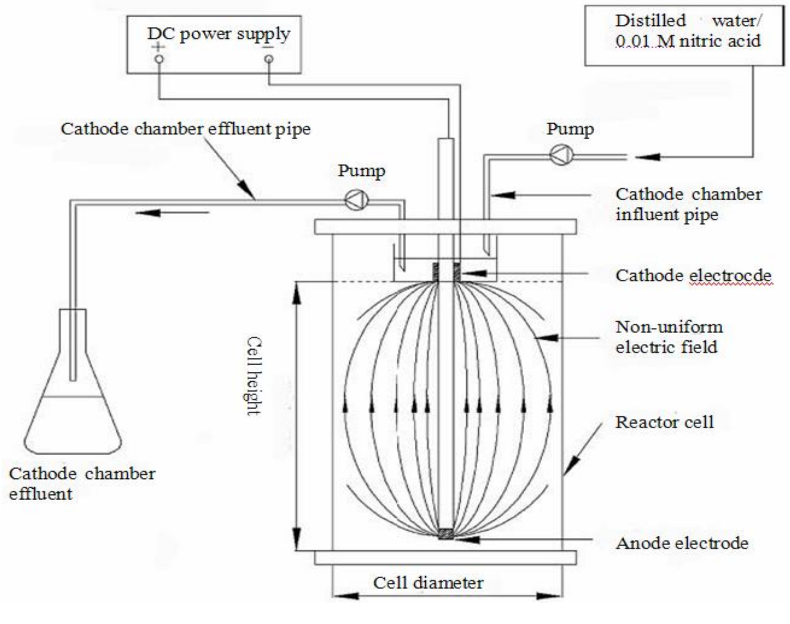

Figure 1. Schematic diagram of non-uniform electric field for removal of organic contaminants [22].

The characteristic of this technique is to exert a non-uniform electric field [22,27] (i.e. the strength and direction of the electric field are changing with the distances between two electrode-chambers) on the general EK equipment, so as to enhance the removal efficiency of pollutants or reduce remediation time [32,33]. During treatment process, the migrations of OPs [33] are simultaneously driven by electro-migration and electro-osmotic flow, and the main influencing factors on their migration velocity and direction are soil pH and electrode reactions. Under the condition of sub-acidity and neutrality, phenol and 2,4-dichlorophenol mainly migrate towards the cathode with electro-osmotic flows; however, when the pH is relatively high, the main migration mode is electro-migration and the pollutants will move towards the anode, in this way, the neutralizing of the soils can be easily realized. Fig. 1. shows a typical setup for removal of OPs by applied a non-uniform electric field.

2.2. Degradation of OPs in soils by EK combined with Fenton technique

EK combined with Fenton technique was firstly applied to the remediation of phenol polluted soils [23]. Nowadays, the OPs can be treated by this method including phenols [23], polycyclic aromatic hydrocarbons [24,37,38], halogenated hydrocarbons [25,39] and so on. Its basic principle is to create a condition of pH near 3 at the anode area. In the meanwhile, heavy metals and OPs in the soil solution are migrated with electro-osmotic flows and electro-migration, and degraded by hydroxyl free radicals produced at the anode in Fenton reactions [24].

There are two main procedures during the Fenton reaction. In the first step, hydroxyl free radicals are produced with the decomposition of H_2O_2 by the catalysis of Fe(II) (or in other ways); the oxidizing degradation of OPs by hydroxyl free radicals are involved in the second step (as showed in equation (1)). Fig. 2. shows the reaction principles of this technique.

$$H_2O_2 + Fe^{2+} \longrightarrow OH\cdot + OH^- + Fe^{3+} \quad H_2O_2 + S \longrightarrow OH\cdot + OH^- + S^+ \qquad (1)$$

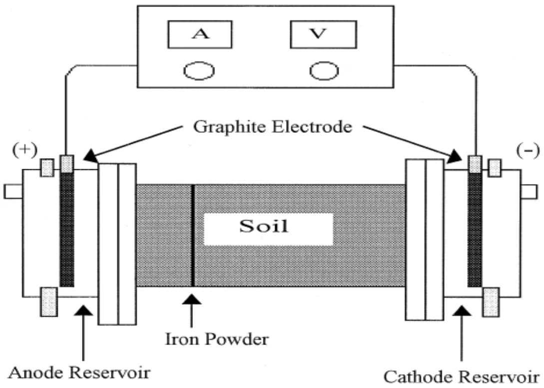

Figure 2. An experimental set-up for treating contaminated soils by the EK-Fenton process [23].

2.3. EK combined with surfactants / co-solvents technique

This combined technique [14] is to apply surfactants or co-solvents into the soils and make them permeate deep into the soil, interact and combine with OPs and ultimately form migratory compounds through its physicochemical actions of desorption, chelation, dissolution or complexation, etc. The solution containing OPs was migrated to collecting area by EK technique, and then for further treatment. The migration of OPs is mainly achieved by this combined technique through electro-osmotic flows and electrophoresis. The whole process involved in various knowledges, such as soil chemistry, colloid chemistry, environment chemistry, electro- chemistry, and surfactant chemistry, and all these factors should be taken into consideration as a whole. Fig. 3 is a schematic diagram of EK reactor enhanced by surfactants for the removal of OPs.

Surfactants used now are mainly classified into the following categories: ① cationic surfactants, such as CTAC [11]; ② anionic surfactants, such as sodium dodecyl sulfonate (SDS) [17,40,41], SDBS; 2,20-Azino-bis-(3-ethylbenzthiazoline sulfonate) (ABTS)[42] and Calfax 16L-35[43]; ③ nonionic surfactants, such as Tween 80 [44-47], Triton X-100 [14], Brij 35 [14,40], PANNOX 110 [41], Igepal CA-720 [14,46,48] and alkyl polyglucosides (APG)[37,40]; ④ biological surfactants, such as β-cyclodextrin [44], hydroxypmpyl-β-cyclodextrin (HPCD) [46,48-53], carboxymethyl-β-cyclodextrin (CMCD)[54] and rhamnolipid [14,55].

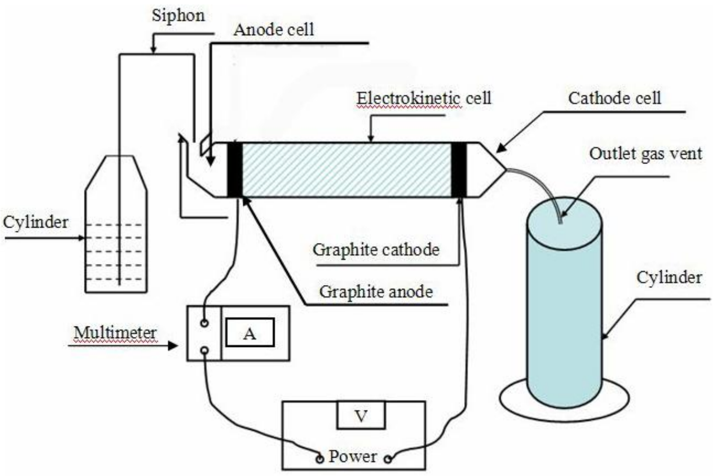

Figure 3. Schematic diagram of EK reactor enhanced by surfactants [47].

Among these surfactants, nonionic or biological surfactants are often selected because cationic surfactants have a high toxicity while anionic surfactants tend to migrate towards the anode, which is opposite to the direction of electro-osmotic flows.

At present, the co-solvents are used including methanol [14], ethanol [14,45], propanol [14], acetone [14,56], tetrahydrofuran [14], butylamine [14,46,57,58], chelates HEDPA [59] and so on. The most widely applied co-solvents are methanol [14], ethanol [14,45] and propanol [14], which are mutually soluble with water and can transport pollutants with electro-osmotic flows better.

This combined method has already been used to remediate soils polluted by alkanes [28], halogenated hydrocarbons [17,56], benzenes [14,41], phenols [52,59-63], polychlorinated biphenyl [47,51,56], polycyclic aromatic hydrocarbons [14,24,42-44,46,49,50,52,54,58,64], nitrobenzenes [14,17,53,54], etc.

2.4. Degradation of OPs in soils by EK combined with biological techniques

Microorganisms can use organic compounds for their growth and reproduction, organic compounds provide microorganisms with carbon sources, which are the basic component units for the new-born cells, as well as provide the electrons and the energy essential for their growth [28,29]. The biological techniques can not only degrade contaminants into less toxic products and oxidize them into carbon dioxide and water ultimately, but also change the mobility of the pollutants and make them settled in a certain place. Compared with traditional treatment techniques, it is a new environmental-friendly alternative technique with advantages of rapidness, safety and cheapness. However, the microorganisms degradation might be significantly influenced by environmental factors, such as soil temperature, pH, water content, concentration of pollutants, other OPs and metal ions [62,65–70]. Moreover, the microorganisms must have sufficient metabolism ability and the pollutants must be degradable by microorganisms. In the practical applications, the biological degradation efficiency may be decreased due to the difference of pollutants nature and soil components, as well as the existence of some inhibitory substances to microorganisms, which will limit its application. The combination of EK and biological techniques can make up for each other's deficiency [71,72], and thus achieve the aim of increasing remediation efficiency and lowering the energy costs. The bioavailability of OPs in the underground circumstance can be enhanced by this combined technology through using various EK effects produced by direct electric field applied. Another way is to transport various additives efficiently to underground polluted area, or to degrade OPs using biological techniques by using the electric thermal effects and electrode reactions to provide suitable temperature, pH and oxidation-reduction conditions for underground bio-transfer processes, and finally the OPs are degraded by biological techniques. Xu et al. [73] gave a review on the progress of EK combined with bioremediation for the treatment of contaminated soils and indicated that their synergistic effects make the EK combined bioremediation become a very promising technique in the future. EK combined with biological techniques was first used to the treatment of heavy metals-contaminated soils. At present, it is also used to remove OPs from soils, which including polycyclic aromatic hydrocarbons [74], alkanes [28], halogenated hydrocarbons [75-79], phenols [79-81] and so on. The most commonly used microorganisms include *Sphingomonas* sp. L138 [74], *Mycobacterium frederiksbergense* LB501TG

[74], *Burkholderia* spp. RASC c2 [77], *Burkholderia cepacia* G4 [78], *Pseudomonas mendocina* KR1 [79], *Pseudomonas* sp. strain PNP1 [80], *Thiobacillus ferrooxidans* [82,83] and so on. Fig. 4. shows a schematic diagram of EK reactor enhanced by bacteria for the removal of PAH. The applications of EK combined with biological techniques are mainly as follows:

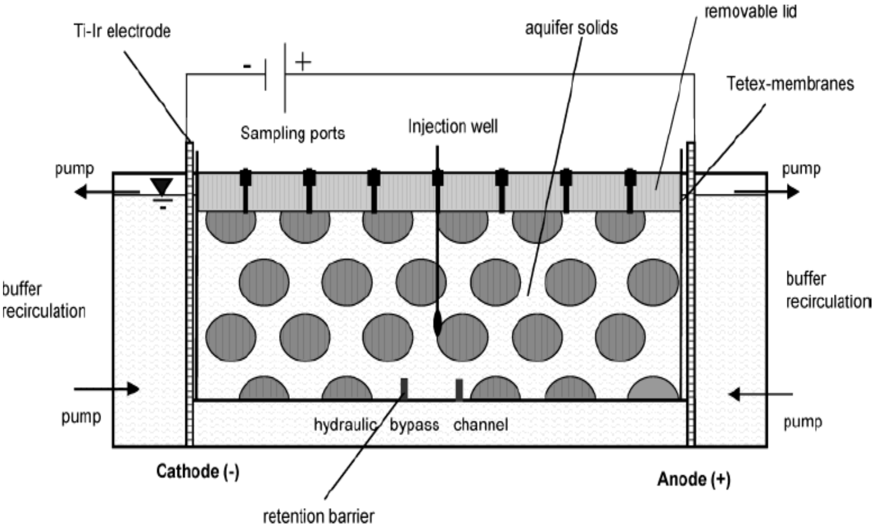

Figure 4. Schematic diagram of EK reactor enhanced by bacteria [74].

2.4.1. Electrokinetic remediation technique combined with biological lixiviation.

This technique was first brought forward by Maini et al. [82]. At first, pollutants are transformed into soluble through biological lixiviation and then transferred by electro-migration by combined biological lixiviation of thiobacteria with EK technique. This combined method avoids the deficiency of using a single method and has synergistic action, which can increase the remediation efficiency, shorten the remediation time and cut down the energy costs. Its disadvantage is that it can produce an acidic circumstance, in which the pollutants do greater harm to the bacteria, and thus decrease the activity of the bacteria.

2.4.2. A microorganism degradation remediation technology by migrating bacteria with electro- kinetic technique

Allogenetic active microorganism can be added to the polluted region through electrophoresis by this technique in order to improve the degradation efficiency of pollutants when there is lacking of active microorganisms or have not enough microorganisms [78]. Wick and co-workers [74] studied the mobility, viability and activity of polycyclic aromatic hydrocarbons degradation bacteria under the effect of electric field using *Sphingomonas sp.* L138 and *Mycobacterium frederiksbergense* LB501TG with different physicochemical surface properties and corresponding absorptive properties as testing microorganisms, and the results showed that electro-osmotic flow is probably the main mechanism of the surface bacteria migration.

2.4.3. A remediation technology by stimulating the activity and growth of microorganisms with electrokinetic technique

Nutrition and electron receptors can be conveyed efficiently for biological remediation by EK technique [84], in the meanwhile, iron ions can be regenerated by electrochemical reaction [70], which not only can increase biomass of bacteria, but also can enhance their activity and growth. The results of Matsumoto et al. [85] showed that by supplying electron donors and receptors for the growth of microorganisms through oxidizing Fe(II) into Fe(III) by controlling electric potential and applying oxygen micro-bubble generator, the method can obviously lengthen the growth time of *T. ferrooxidans*. Compared with conventional methods, this method can lengthen the growth time of the microorganisms for three times, at the same time increase the amount of bacteria greatly and lower the energy costs. The above-mentioned research results indicate that it is an efficient technology to stimulate the growth of bacteria by EK technology and used to remove the pollutants.

2.4.4. A remediation technology by combining electric infusing technique with microorganism degradation

EK technique [86] can efficiently provide the most appropriate environment conditions for the growth of microorganisms. Furthermore, EK methods [87] have no serious negative effect on 'soil microbial health'. Kim et al. [28] designed a novel electrolyte cycling method for the remediation of pentadecane-polluted kaolin. By continuously infusing extrinsic bacteria and nutrition ions with EK technique, pollutants can be degraded by microorganisms. Compared with conventional bioremediation techniques, this method has the merits of easier to control electrolyte pH, maintain bacterial activity, increase remediation efficiency and reduce the remediation time.

2.4.5. A remediation technology by combining biological degradation with exerting heterogeneous electric field

The characteristics of the method is to accelerate the matter transportation and the interactions between OPs and the soils by applying an alternating electric field, or OPs are fixed and then removed by biological technique [79,81]. Yee et al. [79] created a method combined pulsed electric discharge (PED) with biological remediation. At first, the halogenated pollutants was transformed by pulsed electric current, and then the products containing less chlorine was degraded by aerobium pseudo single-cell bacteria *mendocina* KR1. The results show that it can accelerate the migration of OPs and the biological degradation rate of OPs in the soils, and the biological degradation efficiency can be enhanced effectively by periodically reversing the polarity of the electric field.

2.5. The method of Lasagna

This method [39,75,76,80] is an integrative method of many techniques and performs well on-the-spot treatment. Its main characteristic is by loading the polluted soils to the area with the function of adsorption / degradation between the two electrodes, and the OPs are migrated to the treatment area in soils mainly by electro-osmotic flows, and then removed by adsorption, solidification or biological degradation in the treatment area. It is widely used for the treatment of inorganic pollutants, OPs, as well as pollutants of mixed-type. The water flow direction and soil solution pH can be easily controlled in this method, with the merit of high efficiency and low cost.

2.6. EK combined with ultrasonic technique

Presently, many laboratory and on the spot researches show that ultrasonic may reinforce the migration and removal of the pollutants [30,88]. The possible reaction mechanisms by accelerating transportation rate and the processes of unit operation can be categorized into two types: 1. influencing on flowing granules, including processes of migration and accumulation; 2. some special phenomena, including radiant pressure, cavitation, acoustics flow, and instability on the interface (as show in Fig. 5.). Now, some OPs, such as alkanes [87] and polycyclic aromatic hydrocarbons [30] can be degraded by this technique.

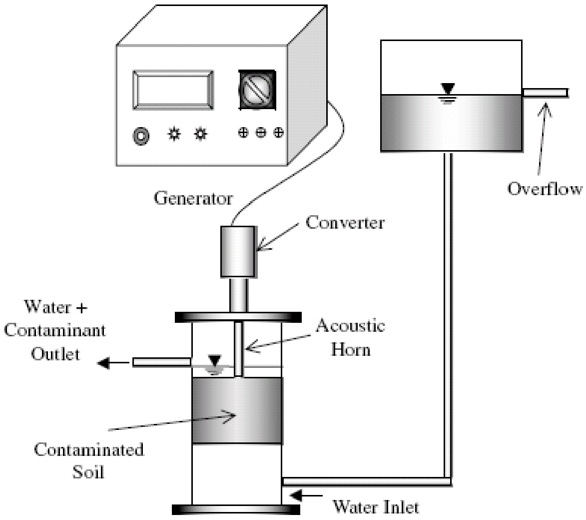

Figure 5. Test setup for EK and ultrasonic experiment [89].

3. CONCLUSIONS

EK remediation is a green remediation technology developed in recent ten years, and has already been used for treatment of soils contaminated by heavy metals and OPs either in lab experiment or practical applications. Table 1 summarized the practical applications of six combined EK methods. There are some distinct advantages or disadvantages for these six remediation technologies as followings:

1. For the removing OPs from soils by direct EK technique, its advantages are the neutralizing of the soils can be easily realized. Immobilization and acidification near the electrodes can be prevented;
2. For EK-Fenton method, the merits of both EK processes and Fenton technique are combined, which can degrade different kinds of OPs with a high efficiency and a low cost. One of the outstanding merits for surfactants / co-solvents enhanced EK technique are that it has a wide suitable object, and can be used to remove many kinds of OPs; meanwhile, it is easy to operate, highly permeable, and reasonable in its cost. However, at present, studies on how to lower the toxicity of surfactants / co-solvents and its interaction with soil grains are still need to improve their extracting efficiency and so on.
3. The combined EK with biological techniques can overcome some intrinsic disadvantages of conventional biological remediation methods, and avoid the shortcomings of a single method. The synergetic effect of combined EK with biological techniques is a green remediation technology; it is potentially capable of treating multiple contaminants in low permeability soils, enhancing the remediation efficiency, shortening remediation time and lowering the energy cost. The disadvantages are the concentration of OPs may exceed the toxic limit for the microbial population and lead to microorganisms die. Simultaneous bioremediation of various OPs may produce by-products, which may be high toxic to microorganisms and inhibit the bioremediation rates [90]. The Lasagna^{TM} process has several advantages in comparison to other techniques. It is possible to recycle the cathode effluent back to the anode compartment, which would favor neutralizing the pH and simplify water cycle process. In addition, the fluid flow may be reversed by simply switching the polarity [75]. But the major drawback is the gases produced by electrolysis may affect the electrical contact of the electrodes.
4. For ultrasonic combined with EK technique, it is particularly suitable for the degradation of both ionic and nonionic of pollutants, and has promising research and application prospects.

In conclusion, as a new *in situ* remediation technology, EK remediation techniques can be used to treat soils contaminated by OPs. The method is easy to operate, whereas its reaction mechanisms are very complex, involving knowledge of pollutant migration dynamics, physics, soil chemistry, aquatic chemistry, colloid chemistry, surface chemistry, environment chemistry, electrochemistry, and so on. The research direction will mainly concentrate on the following aspects: 1. strengthening researches on the remediation of complicated polluted soils; 2. exploring new remediation methods after optimizing parameters and combination of current contaminated soil remediation techniques; 3. studying the absorption / desorption processes and molecular transfer mechanisms of OPs in soil; 4. developing new types of pollution-free surfactants and cultivating new types of bacteria with high degradation efficiency; 5. investigating the impact of geochemistry reaction, such as absorption, dissolving and sedimentation on the remediation process. With the combinations of multidiscipline and the development of cross-discipline, EK remediation techniques will continuously be developed and improved, and make important contributions to the remediation of contaminated soils.

Table 1. The applications of combined technologies for removal of OPs

Enhanced methods	Contamination	Soil type	Removal effiiency	Ref.
2.1. Removing OPs from soils by direct EK technique				
Non-uniform EK	PAH, p-xylene	Kaolin	67%, 93%	[22]
2D non-uniform EK	2,4-dichlorophenol	Sandy loam	73.4%	[27]
Non-uniform EK	Phenol, DCP	Kaolin, sandy loam soil	83%, 89%, 94%	[33]
Non-uniform EK	Atrazine	Sandy soil	≥89%	[36]
Non-uniform EK	Phenol	Natural sandy loam	58%	[63]
Non-uniform EK	Molinate Bentazone	Sandy		[91]
Non-uniform EK	PCP DNT Lindane	Clay soil	40%-95% 28%-80% 26%-60%	[92]
Non-uniform EK	pentachlorophenol	Kaolin	52%-78%	[93]
Non-uniform EK	TCE	Clay soil	97%	[94]
Uniform EK	TPHs	Sandy soil	90%	[95]
Uniform EK	PAHs	Soil	94%	[96]
Uniform EK	Acid Blue 25	Kaolin soil	89%	[97]
2.2. Degradation of OPs in soils by EK combined with Fenton technique				
EK-Fenton process	Phenol	Sandy loam	99.7%	[23]
EK-Fenton process	PAH	Kaolinite	80%	[24]
EK-Fenton process	TCE	Loamy sand, sandy loam	75%	[25]
EK-Fenton process	PAH	EPK Kaolin, Hadong clay	75–80%	[37]
EK-Fenton process	Petroleum hydrocarbon-diesel	Kaolin	97%	[98]
EK-Fenton process	PAH	Sandy soil	81.6%	[99]
EK-Fenton process	PAH	Clayey soil		[100]
2.3. EK combined with surfactants / co-solvents technique				
SDS	PAH	Hadong clay	75–80%	[38]
SDS	Diesel	Sandy soil		[101]
APG, Brij30,SDS	PAH	Kaolinite	65%, 26%, 0	[40]
SDS and PANNOX 110	Ethylbenzene	Clayed soil	63–98%	[41]
APG, Calfax 16L-35	PAH	Kaolinite	93-98%,17-23%	[43]
Tween 80, Igepal CA-720 n-Butylamine, HPCD	PAHs	Aged MGP field soil		[46]
Tween 80 and β-CD	HCB	Clayed soil	>80%	[47]
Tween80, Igepal CA-720	PAH	Kaolin		[48]
Tween 80, SDBS	DDT	Spiked soil	13%	[102]
HPCD	PAH	Kaolinite	75%	[49]
HPCD	PAH	Kaolin	50%	[50]
β-CD	TeCB, i-TeCB, TCB	Clayed soil	>80%	[51]
HPCD	2,4-DNT	Kaolin, silty soil		[53]
CMCD	Naphthalene, 2,4-DNT		83%	[54]

			89%	
n-butylamine,THF, acetone	PAH	Glacial till clay	43%	[57]
n-butylamine	PAHs	Kaolin soil		[58]
HEDPA	Phenol	Natural, sod-podzolic soil	80-95%	[59]
Humic acid	DCP or diuron	Kaolinite	90%	[61]
CD	HCB	Kaolin	76%	[103]
SDS	PAH	Iron-rich clayey soil	70%	[104]
β-CD	TPH			[105]
HPCD	PAH	Mine soil	70%	[106]
CAS	PAH	Medric soil, Black soil, and CEMRS soil	44%–60%	[107]
Ethanol or Brij 35	Benzo[a]pyrene	Kaolin	73%	[108]
Tween 80 and Na2SO4	PAH	Kaolin	40%	[109]
HPCD	HCB	Aged sediment		[110]
HPCD	HCB	Aged sediment	40%	[111]
Triton X-114	Hydrocarbon	Gleysol soil	66%	[112]
Brij 35, Tergitol NP10, Tween 20, Tween 80, Tyloxapol	PAHs PAHs PAHs PAHs PAHs	Kaolin Kaolin Kaolin Kaolin Kaolin	 82% 88% 	[113]
Tween 80	PAH	Mine soil	96%	[114]
Tween 80	PAHs	Clayey soils	30%	[115]
Tween 80 and EDTA	PAH	Kaolin clay Sandy soil	90% 70%	[116]
Non-ionic surfactant	Waste-lubricant oils	Clayey soil	45.1–55.0%	[117]
Triton X-100	HCB	Clayey soil	60%	[118]
Igepal	PAH, pyrene benzo[a]pyrene	Silty sand	40%, 30% 20%	[119]
Cetyltrimethylammonium bromide (CTAB)	Benzene, toluene, ethylbenzene, xylenes [BTEX] and three selected PAHs	Clay soil	97%	[120]
Rhamnolipid	Gasoil	Sandy clay loam	86.7%	[121]
Triton X-100 and rhamnolipid	PAH	Unsaturated soils	30%	[122]
40% Ethanol and 20% Tween 20	PAH	Kaolinite	95%	[123]
2.4. Degradation of OPs in soils by EK combined with biological techniques				
Bioremediation	Pentadecane	Kaolinite	77.6%	[28]
Biodegradation	PAH	Clay, loamy sand	66%	[29]
Bacteria	Phenol	Natural sandy loam	58%	[63]
Bacteria	TCE	Sand, sediment	72-89%, 69%	[78]
Bioremediation	PCE, DCP		74%	[79]
Bacteria	Diesel	Soil		[124]
Bioremediation	PAH	Clayey soil	80%	[125]
Biostimulation	Diesel fuel	Loamy-sand soil	64 %	[126]
Biodegradation	PAH	Calcaric fluvisol		[127]
Bioremediation	Vinyl chloride	Low permeable soils	90%	[128]
Bioremediation	Petroleum	Soil	45.5%	[129]
Bioremediation	TEP	Kaolin soils	73%	[130]
Bioremediation	PCP	Silty clay soil		[131]
2.5. The Lasagna technology				
The Lasagna technology	TCE	Sandy clay loam	>99%	[75]
The Lasagna technology	TCE	Stiff clay soil	95%-99%	[76]
The Lasagna Process	p-Nitrophenol	Kaolinite	95%	[80]
LasagnaTM	TCE	Clay soils	93.2%	[132]
2.6. EK combined with ultrasonic technique				
Ultrasonic technologies	PAH	Natural clay	90%	[30]
Ultrasonic technologies	Chrysene	Kaolin	54 %	[133]

Ultrasonic technologies	HCB PAH Fluoranthene	Kaolin	70–83% 82–96% 82–97%	[134]
Ultrasonic technologies	Toluene, xylenes	Soil		[135]

PAH: Phenanthrene; HCB: Hexachlorobenzene; TCE: Trichloroethylene; DCP: 2,6-dichlorophenol; TPH; Total petroleum hydrocarbon; TCB: l,2,3-trichlorobenzen; *i*-TeCB: l,2,4,5-tetrachlorobenzene; TeCB: l,2,3,4-tetrachlorobenzen; 2,4-DNT: 2,4-dinitrotoluene; TEP: triethyl phosphate; PCP: pentachlorophenol.

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