Thermal based remediation technologies for soil and groundwater: a review

Motasem Y.D. Alazaiza[a,*], Ahmed Albahnasawi[b], Nadim K. Copty[c],
Gomaa A.M. Ali[d], Mohammed J.K. Bashir[e], Tahra Al Maskari[a], Salem S. Abu Amr[f],
Mohammed Shadi S. Abujazar[g,h], Dia Eddin Nassani[i]

[a]Department of Civil and Environmental Engineering, College of Engineering, A'Sharqiyah University, 400 Ibra, Oman,
emails: my.azaiza@gmail.com (M.Y.D. Alazaiza), tahra.almaskari@asu.edu.om (T. Al Maskari)
[b]Gebze Technical University, Department of Environmental Engineering-Water Center (SUMER), 41400 Kocaeli, Turkey,
email: ahmedalbahnasawi@gmail.com
[c]Institute of Environmental Sciences, Bogazici University, Bebek, Istanbul, Turkey, email: ncopty@boun.edu.tr
[d]Chemistry Department, Faculty of Science, Al-Azhar University, 71524 Assiut, Egypt, email: gomaasanad@gmail.com
[e]Department of Environmental Engineering, Faculty of Engineering and Green Technology (FEGT),
Universiti Tunku Abdul Rahman, 31900 Kampar, Perak, Malaysia, email: jkbashir@utar.edu.my
[f]International College of Engineering and Management, P.O. Box: 2511, C.P.O Seeb, P.C. 111, Sultanate of Oman,
email: sabuamr@hotmail.com
[g]Faculty of Engineering, Karabuk University, Demir Campus, 78050 Karabuk, Turkey, email: mohammedshadi@hotmail.com
[h]Al-Aqsa Community Intermediate college, Al-Aqsa University, Gaza - P.B.4051 Palestinian Authority,
email: mohammedshadi@hotmail.com
[i]Department of Civil Engineering, Hasan Kalyoncu University, 27500 Gaziantep, Turkey, email: diaeddin.nassani@hku.edu.tr

ABSTRACT

Thermal remediation technologies are fast and effective tools for the remediation of contaminated soils and sediments. Nevertheless, the high energy consumption and the effect of high temperature on the soil properties may hinder the wide applications of thermal remediation methods. This review highlights the recent studies focused on thermal remediation. Eight types of thermal remediation processes are discussed, including incineration, thermal desorption, stream enhanced extraction, electrical resistance heating, microwave heating, smoldering, vitrification, and pyrolysis. In addition, the combination of thermal remediation with other remediation technologies is presented. Finally, thermal remediation sustainability is evaluated in terms of energy efficiency and their impact on soil properties. The developments of the past decade show that thermal-based technologies are quite effective in terms of contaminant removal but that these technologies are associated with high energy use and costs and can has an adverse impact on soil properties. Nonetheless, it is anticipated that continued research on thermally based technologies can increase their sustainability and expand their applications. Low temperature thermal desorption is a promising remediation technology in terms of land use and energy cost as it has no adverse effect on soil function after treatment and low temperature is required. Overall, selecting the sustainable remediation technology depends on the contaminant properties, soil properties and predicted risk level.

Keywords: Thermal remediation; Contaminated soil; Stream enhanced extraction; Microwave heating; Pyrolysis

* Corresponding author.

1. Introduction

Water and soil play crucial roles in the function of ecosystems. Nevertheless, human activities, especially industrial emissions contaminate both soil and water. Resulting in widespread pollution [1]. For example, industrial emissions has led to more than 130,000 and 100,000 contaminated sites are confirmed in the United States alone and in China, respectively [2]. Furthermore, in China the soil remediation market was around 0.4 billion USD in 2015. Thus, the Chinese central government proposed 0.9 billion USD for soil remediation in 2017 [3].

Although many remediation technologies have been developed over the last few decades, technologies that can quickly treat the contaminated soil with a wide range of pollutants are especially preferable. For instant, pump and treat are estimated to take decades to completely recover pollutants with low solubility and high sorption potential. Bioremediation of petroleum contaminated soil may take years, especially when non-biodegradable contaminants such as high molecular organic pollutants are present [4–6]. In contrast, as will be discussed in this review, thermal remediation technologies have the advantages of efficient and quick remediation (few hours to months), with removal efficiency reaching as high as 99% for a wide range pollutants, especially petroleum contaminants [7,8]. Thermal remediation processes which involve the use of heat to volatilize and/or mobilize contaminants are particularly effective for the removal of total petroleum hydrocarbon (TPH), and total hydrocarbon mass as high removal efficiency could be achieved in a short time [9–13].

The selection of appropriate remediation method is controlled by many considerations such as soil properties, the type of contaminants and the nature of selected and designed remediation technology [14]. However, in recent years, the concept of sustainable remediation has highlighted the need for consideration of a more integrated view of the remediation and decision making process instead of just focusing on technical issues [15]. Sustainability principles such as social, environmental, and economic should be integrated into remediation activities [16]. While thermal remediation technologies are considered reliable and quick in terms of soil and groundwater remediation, energy use during thermal remediation is high [15]. In addition, high-temperature treatment may disrupt land use as well as lead to the damaging of soil properties [17,18]. Thus, the sustainability of thermal remediation is a controversial issue as many researchers argue that high energy consumption and harming soil properties run opposite to the sustainable remediation concept [19]. Others argue that low temperature thermal remediation technologies still have the opportunities to become a sustainable remediation technology [2].

Recent life cycle assessment-based studies revealed that thermal remediation technologies compete with other remediation techniques such as off-site treatment and soil excavation [20], Solidification/soil stabilization [21], or electro-kinetic remediation [22].

This review summarizes the basics, advantages, and limitations of thermal remediation technologies. Moreover, this work, highlights the results from the recent laboratory and field studies of the past decade which focus on using thermal remediation technologies alone and/or in combination with other remediation technologies for more effective remediation practice. Finally, this review assesses the sustainability of thermal remediation technology especially land reuse and energy efficiency. The large number of recent studies cited in this review attests to the significant and rapid development thermally based technologies is experiencing.

2. Soil and groundwater remediation

Contamination of soil and groundwater resources by such as petroleum hydrocarbon and heavy metals, industrial emissions is a widespread problem. These contaminants pollute the environment and pose a risk for both human and ecosystems. Many remediation technologies have been developed to recover these pollutants. The mechanism of these technologies can be broadly classified as physical, chemical, and biological. According to the site of treatment, there can also be divided to in-situ and ex-situ remediation [23]. Nevertheless, the low removal efficiency and the required time and efforts hindered the application of many conventional remediation technologies such as pump and treat system [24]. Selecting a feasible remediation method for soil and groundwater remediation depend on many factors such as the contaminated site chemical, physical and biological characteristics, as well as contaminant properties [25–28]. Furthermore, the time/cost constrain, the mechanisms, and the regulatory requirements should be considered during the design and the application of remediation technology [29].

The most commonly encountered contaminants in soil, sediments, surface water and groundwater, include polycyclic aromatic hydrocarbons (PAHs), high and low molecular weight petroleum hydrocarbon compounds, polychlorinated biphenyls, organochlorinated pesticides, and heavy metals and xenobiotics. Many of the organic contaminants can be present in the form of non-aqueous phase liquids (NAPLs) because of their low solubility. Depending on their sorption properties, these contaminants can migrate long distances from the polluted source and affect ecosystems, flora and fauna [30]. The main mechanisms employed to remediate soil and groundwater are sequester, separate, extract, remove, destroy moralization and transform pollutants into unharmful, non-hazardous, less reactive forms [31].

Soil and groundwater remediation process could be implemented together or separately depending on the extent of pollution and the contaminate concentration. A combination of remediation technologies simultaneously or sequentially could enhance the overall remediation process [4].

The focus of this review is on thermal treatment technologies which are considered an effective remediation method for soil remediation due to high removal efficiency and rapid remediation comparing to other remediation technology. Although thermal treatments have been less used in real applications due to their high energy demand and potential impacts of thermal technologies on soil properties and soil ecosystems, recent studies have

shown that certain thermal-based remediation technologies may be comparable in their costs and energy needs to other technologies, thus motivating this work. In this review, the commonly used thermal remediation technologies are presented and discussed in terms of efficiency and sustainability [2]. This review present and discuss the latest research in this domain.

3. Thermal remediation technologies

Thermal technologies involve the use of heat to remove pollutants from the subsurface. These technologies rely on the dependence of pollutant properties such as solubility, sorption, volatilization, and viscosity on temperature. Existing variations of thermal remediation technologies are described below.

3.1. Incineration

Incineration is the simplest form of thermal remediation where the contaminated soil is heated up to 1,200°C. This high temperature destroys organic pollutants such as chlorinated hydrocarbons, petroleum hydrocarbons, dioxins and other organic compounds [4]. However, using incineration for soil remediation has many drawbacks. Moisture can hinder the incineration process and, therefore, must be removed before incineration application. Secondly, emissions from the incineration process such as sulfur oxides, hydrogen chloride, nitrogen oxides, metal emissions, and dioxins/furans should be controlled by air pollution control systems [32]. Many recent studies reported the performance of incineration for soil remediation and their impact on the environment. Samaksaman et al. [33] applied a two-stage fluidized bed incinerator for lube oil and heavy metals co-contaminated soil. The system was devised to control heavy metal emissions and gaseous pollutants. The temperature in the first stage was in the range of 500°C–700°C while the second stage was fixed at 800°C. A high removal efficiency was achieved with the investigated system ranging from 98.27% to 99.93%. In addition, it was reported that using a two-stage fluidized bed incineration system may decrease the emission of organic pollutants such as toluene, benzene, xylene, ethylbenzene and polycyclic aromatic hydrocarbons. In another study, Hu et al. [34] compared life cycle assessment (LCA) for two incineration technology: direct incineration (infrared high-temperature incineration (IHTI)) and indirect incineration (base catalyzed decomposition (BCD)) for the remediation of polychlorinated biphenyl (PCB) contaminated sites. The results indicated that energy consumption represents the major environmental impacts for both systems. Moreover, the global warming score for IHTI was 432.35 kg CO_2-eq whereas for BCD was 35.5 kg CO_2-eq, which indicates IHTI has higher environmental impact than BCD technology in the remediation of PCB contaminated soil.

3.2. Thermal desorption

Thermal desorption is a thermal remediation technology that uses the heat or steam (greater than 300°C) to enhance the volatilization of organic pollutants from soil and sediment. Secondary treatment system is required for produced gases desorption during the volatilization process [4,32,35]. Thermal desorption is considered a fast and reliable method for soil remediation. Nevertheless, the characteristic of soil such as density and compaction may be affected when high temperature is applied [1,36]. Thermal desorption is suited for semi-volatile and volatile contaminants such as TPH, PAHs, dichloro-diphenyl-trichloroethane, polychlorinated biphenyls (PCBs) and chlorophenol [36,37]. Many mechanisms occur during thermal desorption such as incineration, oxidation, and pyrolytic reactions. These mechanisms depend on the contaminant's oxygen distribution, temperature and the molecular wight [4,36]. Many recent studies have examined thermal desorption for soil remediation. Falciglia et al. [38] studied the performance of ex-situ thermal desorption (ESTD) at bench-scale for hydrocarbon-contaminated marine sediment remediation. The temperature and heat time was 280°C and 5–30 min, respectively. The result indicated that the maximum removal efficiency of 89% was achieved at 200°C for 30 min. The data demonstrate that compared to other remediation technology, ESTD is a suitable remediation method for marine sediment contaminated with TPH. Another study investigated the remediation of per- and polyfluoroalkyl substances (PFAS) contaminated soil by thermal desorption. The temperature ranged from 150°C to 550°C whereas the treatment time was 75 min. The results showed that a decrease of contaminant mass of 79% at 350°C temperature in the field test, whereas at temperature 550°C the removal efficiency increased to 99%, demonstrating the ability of thermal desorption to remove PFAS from contaminated soil. However, many further investigations are required to study the potential creation of transformation products, cost-effectiveness, and air-phase vacuum filtration techniques [39]. Zivdar et al. [40] used low thermal desorption technology (LTTD) for diesel remediation. They investigated the influence of temperature (180°C and 340°C), soil texture (sand, kaolinite, and bentonite clay) and treatment tome (5–20 min). The result indicated that the diesel removal rate was higher in soil containing a higher percentage of kaolinite than bentonite, with the maximum removal efficiency of 95.5% achieved at 340°C temperature, 20 min remediation time and soil mixture of (30% sand, 50% kaolinite, and 20% bentonite). The author suggested that reusing the waste heat from industries may reduce the cost of the thermal desorption method.

3.3. Stream enhanced extraction

Since the 1980s, steam enhanced extraction (SEE) has been used to enhanced oil recovery. In the last 30 y, extensive research, field studies, and simulations have been conducted to demonstrate the effectiveness of SEE technology for volatile contaminant removal from unsaturated subsurface. The SEE technology includes continuous injection of steam into subsurface using injection wells. The SEE process is strongly dependent on the heterogeneity of the subsurface [32,41] as the stream will generally follow the path of least resistance. During the application of SEE, three temperature zones are formed, named: ambient temperature, variable

temperature, and steam temperature. The contaminant viscosity and overall efficiency of the SEE process are influenced by those temperature zones. The main processes occurring during SEE are volatilization, evaporation, and condensation. The latter process occur while the collected steam it enters the extraction well [42]. Chen et al. [41] studied in the lab the performance of the superheated steam extraction process (SSEP) for oil-based drill cutting (OBDC) remediation. They used two types of OBDC: diesel from a vertical well and white oil from a horizontal well. In addition, the effect of water flow rates of 2–8 mL/min, temperature of 175°C–225°C, and pressure of 0.6–5.5 MPa on the performance of SSEP was also investigated. The results indicated that temperature had more effect than water and pressure on the process. Similarly, the OBDC characteristics had a significant effect on the removal efficiency. The optimal operation conditions were 225°C, 2.3 MPa and 6 mL/min, with removal efficiency of 83.09% for white oil type and 78.56% for diesel type. In another study, Hinchee et al. [43] conducted a field study to examine the removal of 1,4-dioxane from contaminated soil using enhanced soil vapor extraction. After 14 month of air injection with a total of 20,000 pore volumes, the temperature reached to 90°C close to the injection wells with 1,4-dioxane reduction of around 94%. In a subsequent study, Trine et al. [44] studied the formation of PAHs derivatives during and after SEE of creosote-contaminated soil. The results pointed out that after SEE, oxygenated PAH concentration increased while unsubstituted PAH concentration decreased. The results suggest that SEE efficient in reduces unsubstituted PAHs where the risk of more toxic PAH may occur.

3.4. Electrical resistance heating

In the last 20 y, electrical resistance heating (ERH) has been applied at many sites worldwide to remediate a range of volatile organic compounds (VOCs). ERH is considered a reliable technology to heat the subsurface for removal of volatile organic compounds [45]. Remarkably, researchers observed that many processes such as abiotic degradation, biodegradation, hydrolysis and other process might occur when the applying ERH to remove the contaminates. ERH is conducting by passing electrical current through ground and soil moisture. This slow heating evaporates VOCs in situ, followed by stream stripping [46]. Many recent studies investigated the performance of ERH for contaminated soil remediation, Munholland et al. [47] conducted a series of lab-scale experiments to study the gas production and transportation during the application of ERH for the remediation of dense non-aqueous phase liquids (DNAPLs). The results indicated that subsurface heating rates were affected by high groundwater velocities. Vertical migration of produced gas was observed. The produced gas entered a coarse sand lens, moved below an overlying capillary, and ultimately exited the heated zone. These findings indicate that, during ERH application, layered heterogeneity may facilitate the uncontrolled migration of contaminants outside the remediation zone through mobilization of the gas phase followed by condensation. This suggests that control mechanisms and vapor phase treatment unit is would be needed when ERH is applied heterogeneous soil remediation. In a subsequent study, Han et al. [48] conducted a lab scale to study the effect of ERH operation parameters, PAH removals and soil properties during the remediation process. The results demonstrated that electric conductivity was affected by salinity and moisture, where maximum temperature and heating efficiency were controlled by high electric strength. Regarding PAH removal efficiency, bond structure and benzene rings affected the boiling point which significantly affected the removal efficiency. The effect of ERH on soil characteristics such as particle size, organic matter, enzymatic activity, and fertility was limited; demonstrating that soil properties remain mostly intact when ERH is applied.

3.5. Microwave (radio frequency) heating

Microwave heating (MWH) is considered a promising thermal remediation technology for contaminated soil as it has many advantages, such as rapid selective and simultaneous heating [1]. The mechanism of heating by microwave involves the subsurface penetration and heating of a high dielectric substance. Thus, low temperature treatment is achievable. In addition, during the MWH treatment, less time and energy is required as mass and heat transfer limitation could be overcome by rapid and volumetric heating [49]. Mainly three different methods for MWH remediation have been developed: (1) contaminated surface heating, (2) contaminated material heating in a kiln, and (3) subsurface soil heating [9,49]. Recently, many studies intensively discussed the use of MWH for soil and groundwater remediation. Two studies by Falciglia et al [50,51] investigated the performance of bench-scale MWH treatment for PAH and nitro-polycyclic aromatic hydrocarbons (N-PAHs) contaminated soil. The results showed that pollutant properties such as polarity significantly affect the removal efficiency. The results demonstrated that many mechanisms such as thermal desorption, contaminant stripping, selective heating, and molecular bond breaking were involved in PAH/N-PAHs removal when MWH was used. In a subsequent study, Krouzek et al. [9] conducted a pilot-scale MWH remediation system for lipophilic organic contaminated remediation. The results from the pilot system confirmed the lab tests where high removal efficiencies for many contaminants were achieved at different temperatures and with less energy consumption. Recently, Luo et al. [49] applied low temperature MWH for petroleum contaminated soil remediation, revegetation, and soil rehabilitation. The results showed that a high percentage of oil was recovered (91.6%) and high removal efficiency was achieved at 250°C–300°C temperature and 20 min treatment time. In addition, it was reported that the fertility of the soil was not affected at 250°C treatment temperature. In another study, the TPH removal mechanism from contaminated soil was investigated using MWH. The results indicated that the low operating power density negatively affected the microwave effectiveness due to the soil's dielectric properties. Moreover, the result showed a relationship between the activation energy and particle size as the removal efficiency of fine soil was 71.2% after 30 min while its reached 91.1% in coarse soil after 15 min [52].

3.6. Smoldering

The smoldering process is combustion without flame which initiates a wave of exothermic combustion. After starting the ignition process, the smoldering reaction continues in a self-sustaining way in the presence of oxygen and fuel. As a result, organic compounds may convert to energy, carbon dioxide (CO_2), and water. The produced high temperature triggers further combustion in the presence of contaminants and sufficient air supply [4,53]. Depending on contaminant availability and air supply, the generated temperature and heat vary temporally and spatially with temperature, ranging from 600°C to 1,100°C [54,55]. In addition, for an effective smoldering process, the permeability of impacted and contaminated soil must be enough to let adequate air flux to the remediation zone [6]. In a recent study, Solinger et al. [10] conducted a smoldering based technology self-sustaining treatment for active remediation applied ex-situ (STARx) for oil-contaminated soil. The results showed that the rate of oil destruction could be controlled by increasing the air flux. The results all suggest that full remediation is possible if the mixture is not homogeneous. In addition, the results predicted that the STARx technology is energy efficient and technically effective as it has a low carbon footprint. In another recent study, Duchesne et al. [56] investigated the remediation of PFAS from both; contaminated soil and impacted granular activated sludge (GAC) by smoldering combustion. The fate of fluorine and PFAS was assessed with emission and soil analysis. The results demonstrated that self-sustained smoldering could be achieved when the GAC/kg soil exceeded 35 g/kg where the produced temperature can be more than 900°C. Further, the concentration of PFAS in soil samples was below detection limits. The results showed that the remaining PFAS were emitted as volatile fluorinated and shorter-chain PFAS compounds.

3.7. Vitrification

Vitrification remediation technology is a thermal process in which contaminated soil is heated at a very high temperature in the range of 1,600°C–2,000°C which causes the soil and contaminant to melt, Subsequently, cooling is applied resulting in the chemically stable glass. During the vitrification process, the contaminant enters the glassy matrix and the leaching process of toxic materials is prevented [36,57]. This technology destroys most pollutants by pyrolysis with any remaining pollutants converted into glass [4]. Vitrification may be conduct in-situ by applying electrical current. In this process, the top layer of soil is melted and works as an electrical conductor. Thus, electricity and heat are transferred to the deeper layer of soil.

Many recent studies have investigated the performance of vitrification for soil and groundwater remediation. Chen et al. [58] investigated the vitrification by microwave sintering technology for radioactive nuclides remediation in soil. The results showed that the vitrification process, in 30 min at 1,400°C, could successfully vitrify the four tested kinds of strontium-contaminated soil without adding any additional components. The preliminary results from this research suggest the applicability of using microwave sintering vitrification for beta-radioactive contaminated soil remediation. In

another study, Shu et al. [59] investigated the immobilization of uranium-contaminated soil at concentration range of 0–50 mg/g by the vitrification process. The results indicated that, in 30 min, the vitrified form of uranium-contaminated soil was enveloped by a network that contained silicon and aluminum oxide polyhedral. When the uranium concentration is increases above 50 mg/g, the network is amended, and the local structure precipitated as mottle-shaped quarts. In addition, the uranium leaching rate was ($\sim 1 \times 10^{-6}$ g/(m^2 d)) in water after 42 d at 90°C, revealing the feasibility of using vitrification for uranium-contaminated soil. In another study Ballesteros et al. [60] investigated the leaching of highly toxic industrial waste Cr^{6+} after vitrification remediation. The results indicated that the final vitrified product was glass-ceramic materials that is highly stable in terms of chemical and mechanical behaviour with all Cr^{6+} reduced to Cr^{3+}. Leaching test results pointed that the ions relased from the new ceramic materials were negligible. Moreover, the final products showed a high mechanical resistance. Similary, Yan et al. [61] tested the irradiation behavior of Nd_2O_3 and CeO_2 vitrified glass samples under high fluences. The results showed that high chemical durability of vitrified glass samples. Thus, vitrification remediation may offer radiation stability for the radioactively contaminated soil.

Vitrification technology however require significant energy and are very expensive. To deal with this shortcomings, in-situ plasma vitrification has been proposed as a feasible alternative which uses a plasma torch to heat a soil up to 7,000°C in short time [62,63].

3.8. Pyrolysis

Pyrolysis thermal remediation includes heating contaminated soil in anoxic condition up to 1,200°C under pressure [64]. Pyrolysis involves an endothermic reaction that converts pollutants into by-products such as non-condensable gas, bio-oil, and chars [65,66]. When a soil contaminated with petroleum hydrocarbon remediated with thermal pyrolysis process, thermal desorption is responsible for removing the hydrocarbon at boiling temperature. However, when temperature increase up to 500°C, highly reactive free radicals are released as chemical bonds are broken. Those highly reactive radicals are involved in aromatic condensation reactions to produce char [4,67]. In the study of Özkan et al. [68] pyrolysis was used to remediate soil contaminated by metals (Pb, Cd and Zn). The authors, firstly applied phytoremediation remediation by different plants. Subsequently, the produced plants were subjected to thermal pyrolysis. The results showed that the metals in contaminated plants were stabilized in the char fraction. The solid product can then be sent to landfills as a waste. In another study, Li et al. [69] investigated a fast pyrolysis remediation method to remediate petroleum-contaminated soil as well as oil recovery. The results showed that, within 30 min at 500°C, both water-soluble organic matter and TPH were completely removed. In addition, the recovered carbon from oil was 50.9%, whereas the remaining carbon was stabilized without adverse effect on wheat growth. Song et al. [70] conducted the first pilot-scale pyrolytic remediation system for crude oil-contaminated soil. They used continuously fed rotary kiln rector at 420°C and for 15 min residence time. The results showed that

99.9% of TPH and 94.5% were removed under the investigated conditions with the fertility of the pyrolyzed soil was restored after the remediation. The result indicated that with longer resonance time and higher temperature, the removal efficiency of PAH and TPH increased, whereas soil fertility decreased. Recently, Kim et al. [71] used carbon dioxide (CO_2) as a pyrolysis medium for remediation of petroleum-contaminated soil. The results indicated that, at a temperature higher than 620°C, carbon dioxide (CO) was formed suggesting that CO_2 play a role in the transformation of petroleum hydrocarbons accumulated in the soil to CO during the pyrolysis remediation.

Table 1 summarizes the recent studies that employed thermal remediation methods for soil and groundwater remediation.

4. Combination of thermal remediation and other remediation technology

Recently, a combination of thermal remediation technologies with other mitigation methods have been proposed in recent years. Synergetic studies can be characterized as combining thermal remediation technologies with physicochemical as well as for bioremediation methods. In this section, an overview of the recent works in this domain is presented.

Many researchers have reported the combination of MWH with another remediation technology for soil remediation. One recent study by Kan et al. [72] studied the remediation of PAHs contaminated soil by Mn_xO_y enhanced microwave activated persulfate (MW/PS) system. Pyrene was selected as the target contaminant. The results showed that the addition of Mn_xO_y boosts the degradation of pyrene with the enhancement directly related to dosage. For example, the pyrene removal efficiency significantly increased, in 15 min, from 65.7% to 85.6% when MnO_2 dosage increased from 0 to 0.1 g. In another study, Kan et al. [73] investigated the performance of the MW/PS remediation system for the removal organophosphorus pesticide from contaminated soil, they selected parathion as the representative pesticide. The results showed that more than 90% of parathion was removed by chemical degradation after 90 min, which was remarkably higher than a single MWH or PS. Moreover, the higher removal efficiency was obtained at a higher microwave temperature, lower organic matter content and larger PS. In another study, Falciglia et al. [74] examined the combination of MWH and several agents for Hg-contaminated marine sediments remediation. The results showed that the Hg removal efficiency by MWH alone was 72%, whereas the removal efficiencies of the combination of MWH and agents methylglycinediacetic acid (MGDA) and (chelating agent and surfactant) were 87% and 99%, respectively. The enhancement was due to MGDA chelating ability while synergetic action and stripping processes of chelating agent and surfactant led to high removal efficiency of Hg. The results also showed that the combination of MWH and citric acid resulted in remarkable enhancement in Hg removal kinetics. In a recent study, Sivagami et al. [75] tried to remediate diesel contaminated soil by using the combination of MWH and hydrogen peroxide (H_2O_2) chemical oxidation. The results indicated that under the optimized condition of 60 min, 450 W power and H_2O_2 dosage of 2.5 wt.% the removal efficiency enhancement was 17.36%, 20.89% and 23.82% for three different soils compared to MHW alone.

Han et al. [76] studied the performance of ERH combined with chemical oxidation by sodium persulfate ($Na_2S_2O_8$) for PAHs contaminated soil remediation. The results showed that the removal efficiency of PAH was increased from 35.9% to 52.9% and 79.42% when 0.05 or 2.5 mmol/g $Na_2S_2O_8$ was added to ERH, respectively. Similarly, Bap removal efficiency was enhanced by 65% when ERH was coupled with $Na_2S_2O_8$. The results demonstrate a novel combined remediation approach for organic pollutants removal from contaminated soil. Subsequently, Li et al. [77] developed a comb system of low temperature ERH and persulfate for organic contaminants remediation. The results showed that the addition of persulfate might significantly improve the volumetric degradation of phenanthrene in the sand tank. The results suggest that the investigated combo system is a promising technology for applying of heat-activated persulfate in situ chemical oxidation. A study by Moradi et al. [78] developed a conceptual model to predict the performance of in-situ thermally enhanced bioremediation with renewable energy system for petroleum contaminated sites (Fig. 1). The results indicated that combining thermally-enhanced bioremediation and energy storage offer sustainable and efficient way to enhance the microbial activity by affording wanted temperature-moisture in soil. Aydin et al. [79] examined the combination of heat (hot water) with co-solvent flushing for the enhanced recovery of NAPLs from porous media. The study showed that the even relatively small variations in the temperature of the system can lead to significant increase in contaminant recovery. Hot water injection can increase both the performance of the remediation system while decreasing the amounts of injected co-solvents.

Chowdhury et al. [80] proposed a novel concept of combining electro-kinetic (EK) oxidant delivery and low temperature electrical ERH to activate persulfate (PS) for contaminant remediation in low permeability soil. The benefits of the proposed system are the ability to deliver remediation agents in low permeable soil, with the same electrode is used for both EK and ERH phases. The results from laboratory-scale tests revealed that the tetrachloroethene concentration was reduced to lower than the detection limit. The results suggest that the investigated system is a viable strategy to remediate low permeability contaminated soil. In another study, Zhao et al. [81] studied the combination of thermal desorption and mechanochemical method for PCBs contaminated soil removal. The results demonstrated that after 30 min grinding, the removal efficiency was around 75.8%. Subsequently, after 60 min heating at 500°C, the PCB removal efficiency increased to 99.95% and the residual concentration was 247 ng/g. In another study, Liu et al. [82] studied the combination of thermal desorption and the addition of calcium hydroxide ($Ca(OH)_2$) for the remediation of PCB-contaminated soil. The results indicated that the removal efficiency was 94% in $Ca(OH)_2$, whereas 90% in blank soil. In addition, $Ca(OH)_2$ reduced the toxic equivalence quantity in soil and increased the ratio of lower chlorinated PCBs. Thus, the results from this study provide a remarkable enhancement on PCBs remediation.

Table 1
Recent studies that employed thermal remediation methods for soil and groundwater remediation

Technology	Contaminant	Experimental condition	Main findings	References
Low temperature two-stage fluidized bed incinerator	Lube oil (Yamaha SAE 85W-140 G-130); Heavy metals of Cd(II), Cr(III), Cu(II), Pb(II)	Temperature 500°C–700°C; Gas velocity 0.21–0.29 m/s; Soil particle sizes 53–300 μm; Initial concentration of Cd 1,435 mg/kg; Cr 1,326 mg/kg, Cu 1,212 mg/kg, Pb 1,256 mg/kg; Lube oil 50 g/kg	Removal efficiency of lube oil was around 99%; Concentrations of heavy metals in ashes were lower than regulated.	[33]
IHTI; BCD	Polychlorinated biphenyl (PCB)	Temperatures for IHTI 1,100°C–1,300°C; Temperatures for BCD 400°C	Energy consumption represents the major environmental impacts for both systems; Global warming score for IHTI was 432.35 kg CO_2-eq and for BCD was 35.5 kg CO_2-eq.	[34]
ESTD	TPH	Temperatures 280°C; Heating times 5–30 min; Initial concentration TPH 1,370 mg/kg	TPH removal efficiency was 75%–85% when the temperature was in the range of 200°C–280°C (for 10 min); At 200°C and for 30 min, the TPH removal efficiency was maximum at 89%; 5 min remediation time at 180°C was enough to reach the TPH standard limit 750 mg/kg.	[38]
Thermal desorption	PFAS	Remediation time 15–75 min; Temperatures 150°C–550°C; Initial concentration fortified soils ($\sum$9PFAS = 4 mg/kg), field-contaminated soil ($\sum$9PFAS = 0.025 mg/kg)	At 350°C, the concentration of $\sum$9PFAS decreased by 79% in field contaminated soil and 43% in fortified; At 450°C, the PFAS removal efficiency was above 99% for the fortified; At 550°C, the PFAS removal efficiency was between 71% and 99% for the field contaminated soil.	[39]
Low temperature thermal desorption (LTTD)	Diesel	Temperature 180°C and 340°C; Remediation time 5–20 min; Deferent soil texture (Bentonite clay and Kaolinite clay); Initial concentration 20,000 mg/kg	Removal efficiency of 95.6% at 340°C and 20 min residence time was achieved for diesel for the soil mixture (50% kaolinite, 30% sand, and 20% bentonite); Higher removal efficiency was observed in soil samples with high kaolinite than bentonite.	[40]
Superheated steam extraction process	OBDC	Pressures 0.6–5.5 MPa; Temperatures 175°C–225°C; Water flow rates 2–8 mL/min; Initial concentration 13.18% and 20.64%	Most important parameter was temperature, followed by pressure and water flow rate, and OBDC characteristics; Removal efficiency was 83.09% at the optimal conditions (temperature 225°C, pressure 2.3 MPa, and water flow 6 mL/min).	[41]
Enhanced soil vapor extraction	1,4-Dioxane	1,4-Dioxane initial concentration 10–30 mg/kg; Flow rates were generally in the 2.0–2.3 m³/min	Removal efficiency was 94% after 14 months of air injection, where the temperature and soil moisture reached 90°C and 45%, respectively.	[43]

(Continued)

Table 1 Continued

Technology	Contaminant	Experimental condition	Main findings	References
SEE	Creosote	Temperature 130°C	After SEE, oxygenated PAH concentration increased while unsubstituted PAH concentration decreased; SEE is efficient in reducing unsubstituted PAHs where the risk of formation of more toxic PAH may occur.	[44]
ERH	Trichloroethene (TCE); Chloroform (CF)	Power density (6–13) kW/m³	Heating rate was affected by high groundwater velocity; Contaminates transport was controlled by layered heterogeneity.	
ERH	PAHs	PAHs initial concentration 2 mg/kg; Initial moisture 12%; Electric strengths 4, 6, 8 V/cm; Salinity 0%, 0.1%, 0.5%, and 1%	Salinity and moisture were important factors affecting electric conductive capability; Maximum temperate can be achieved by high electric strength; Removal effacing was related to the molecular structure of PAHs (benzene rings and bond structure); Pollutants can be removed synchronously with evaporated water; ERH can limit the effect of soil properties.	[48]
MWH	PAHs, N-PAHs	Time period (5–60) min; Power 250–1,000 W; Initial concentration PAHs 226.9 mg/kg, N-PAHs 0.84 μg/kg	Contaminant polarity affects the reachable maximum temperature; Mechanisms such as contaminants stripping, selective heating, molecular bond breaking, and thermal desorption took place; Within 10 min, the PAH removal efficiency ranged between 70% and 100% at 1,000 W-MW, whereas N-PAH varied between 20% and 40% at 440 W and increased to around 90% after 60 min.	[50,51]
MWH	TPH	Microwave generator capacity 6 kW 2.45 GHz; Temperature up to 400°C in initial concentration of TPH 1,100–12,700 mg/kg	Output contaminant concentration TPH (100–300) mg/kg.	[9]
Low temperature microwave	TPH	Initial concentration of TPH (95,300) mg/kg; microwave power 1,400 W at the frequency of 2.45 GHz; Three linear heating rates such as 20, 30, and 40 K/min, from 25°C to 700°C, were chosen	High percentage of oil was recovered (91.6%); High removal efficiency was achieved at 250°C–300°C temperature and 20 min treatment time; Soil fertility was not affected at 250°C treatment temperature.	[49]
MWH	TPH	Soil structure 79.80%, silt 16.50%, clay 3.65%; TPH initial concentration 988.4 mg/kg; microwave power 800 W at the frequency of 2.45 GHz	Soil structures affect microwave effectiveness; The removal efficiency of the course soil was higher than fine soil; After 15 min treatment, the removal efficiency of the course soil was 91%, whereas after 30 min. It was 71.2% for the fine soil.	[52]

| Method	Contaminant	Operating conditions	Findings	Ref.
Smoldering	Growing stockpiles of waste oil sludge (WOS)	Treatment time 9 h; Flow rate 33 L/S; WOS initial concentration 40% by weight	Rate of oil destruction could be controlled by increasing the air flux; Full remediation is possible if the mixture is not homogeneous.	[10]
Smoldering	PFAS	PFAS-spiked, laboratory-constructed soil (≈4 mg PFAS/kg soil); PFAS-impacted field soil (≈0.2 mg PFAS/kg soil)	Self-sustained smoldering can be achieved when the GAC/kg soil exceeded 35 g where the produced temperature can be more than 900°C; Concentration of PFAS in soil samples were below detection limits.	[56]
Microwave sintering (Vitrification)	Strontium	Temperature 1,400°C; Remediation time 30 min; Strontium initial concentration (5–25) wt.%	Sr^{2+} was immobilized into glass structure; microwave sintering technology is a promising technology for vitrifying beta-radioactive contaminated soil.	[58]
Vitrification	Uranium	Uranium initial concentration 0–50 mg/g of uranium; Remediation time 30 min; Temperature 1,400°C	Vitrification successfully treated the uranium-contaminated soil at 1,400°C within 30 min, and uranium was immobilized into a glass structure; The leaching rate analysis demonstrated the feasibility of vitrification technology for contaminated nuclear soil.	[59]
Vitrification	Cr(VI)	Temperature 1,600°C; Cr initial concentration 0.33–4.58 wt.%	Cr^{6+} was reduced to Cr^{3+} and immobilized in glass-ceramic material that has high chemical and mechanical stability.	[60]
Vitrification	Nd_2O_3, CeO_2	Nd_2O_3, CeO_2 initial concentration 10, 20, 30 wt.%; Remediation time 30 min; Temperature 1,400°C	High chemical durability of vitrified glass samples. Thus, vitrification remediation may offer radiation stability for the radioactively contaminated soil.	[61]
Pyrolysis	Pb(II), Cd(II), Zn(II)	Initial concentrations Pb 900 mg/kg, Cd 12 mg/kg, Zn 900 mg/kg; Pyrolysis; Temperature 500°C; Heating rate 35°C/min	Metals in contaminated plants were stabilized in the char fraction. Thus, the solid product can be sent to landfills as its toxicity value is lower than the limit in Turkish regulation.	[68]
Pyrolysis	TPH	Temperature 250°C–600°C; Remediation time 30 min; TPH initial concentration 49.5 mg/g	Carbon recovery was 50.9% TPH removal efficiency was above 99% at 500°C.	[69]
Pyrolysis	Crude oil	Oil concentrations 3, 5 wt.%; TPH initial concentration 14,000–18,000 mg/kg; Residence time 15, 30, 60; Temperature 370°C, 420°C, and 470°C	After 15 min at 420°C, TPH removal efficiency was 99.9%, and PAHs removal efficiency was 94.5% and restored treatment at 420°C with only 15 min.	[70]
Pyrolysis	Crude oil	Pyrolysis medium (N_2 and CO_2) at flow rate 70 mL/min; Temperatures 25°C–900°C at heating rate 10°C/min	At a temperature higher than 620°C, CO was formed, which is considered a clue about the CO_2 role in causing the transformation of petroleum hydrocarbons accumulated on the soil to CO during the pyrolysis remediation.	[71]
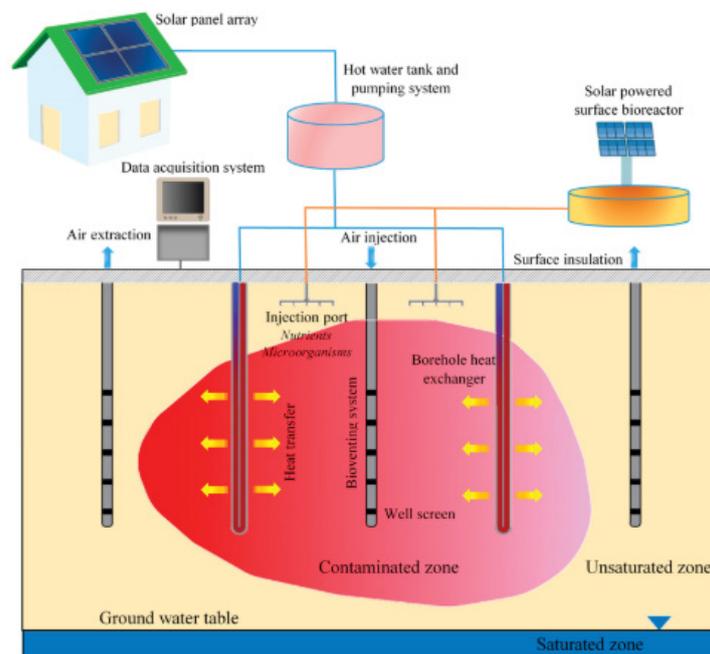
Fig. 1. In-situ thermally enhanced bioremediation coupled with renewable energy system [78].

5. Environmental sustainability consideration

Table 2 summarizes the recent studies that employed combination of thermal remediation technologies with other soil and groundwater remediation method.

Land use and energy efficiency are crucial indicators of sustainability. The potential of losing soil fertility and the energy intensiveness thermal process are two factors that have been can potentially diminish the attractiveness of such remediation alternatives [83]; however, thermal-based methodologies are constantly evolving; significant research is ongoing to render thermal remediation methods more competitive in terms of sustainability. This section discusses these opportunities.

A key parameter of the soil fertility is the organic matter (OM) content of the soil. OM can diminish significantly under high heat. For example, it was reported that heating soil to 955°C and 1,033°C could decrease the OM by 48% and 99%, respectively. [84]. Thus, high-temperature thermal remediation technologies such as vitrification, incineration and smoldering may change the soil properties in terms of OM. This suggests that, using thermal technologies may be more suited for sandy soils as OM is low and the stability of quartz is good under high temperatures. Recent studies demonstrate that thermal desorption technology does not significantly alter soil properties. Brien et al. [85] stated that thermal desorption treated soil properties are similar to native soil (before contamination) and even mixing treated soil with native soil enhances the properties of soil. In addition, in terms of safety, Brien et al. [86] found no uptake of polycyclic aromatic hydrocarbon by crops after remediation of petroleum contaminated soil by thermal desorption remediation. Han et al. [48] stated that using ERH for PAHs remediation did not effect on soil; particle size, OM, enzymatic activity and fertility. Lassalle et al. [87] investigated the recovery of soil function after smoldering remediation by N-P-K fertilization and organic amendment. The results showed that soil function was fully retrieved by the proposed strategies. Song et al. [88] developed as sustainable remediation assessment indicator set for China. The results showed a high score of thermal desorption in terms of work safety, waste generation, and local impacts.

Although thermal remediation is considered fast and effective than other remediation technologies, its cost may hinder the wide use of thermal-based remediation technology [89]. However, recent works point to the feasibility of thermal remediation technology in terms of cost. Hou et al. [90] found that LTTD could decrease the cost of conventional thermal desorption by 30% resulting in lower CO_2 emissions. For sandy soil, Falciglia et al. [91,92] found that MWH remediation could be the best method for hydrocarbon contaminated soil as the cost was between 18–27€/ton. Another line if research that shows that the furthermore, combination thermal remediation with other remediation could decrease the cost of alone thermal remediation. Hu et al. [93] stated that LTTD combined with stabilization/solidification be more cost-effective than secure landfill for remediation of OBDC. Chen et al. [94] found that the combination of in situ encapsulation and ESTD could be lower investment cost, environmental impact, and a high socio-economic effect remediation method.

6. Recommendations and future prospects

This review provides readers with a general overview of thermal remediation for environmental clean-ups, such

Table 2
Recent studies that employed combination of thermal remediation technologies with other remediation

Technology	Contaminant	Experimental condition	Key findings	References
Mn_xO_y and microwave activated persulfate	PAHs (pyrene)	Pyrene initial concentration 50 mg/kg; PS dosage 1.5 mol/L; MW temperature 40°C, 60°C, 80°C, or 100°C	MW/PS was enhanced by adding Mn_xO_y, which improved the production of activated persulfate.	[72]
Microwave-activated persulfate	Pesticide (parathion)	Parathion initial concentration 50, 200, 500, and 1,000 mg/kg; MW temperature 40°C, 60°C, 80°C, 100°C; 0.5 mL PS solution 0.3–2.0 mol/L	After 90 min of treatment, removal efficiency is around 90%.	[73]
Enhancing agents and microwave heating	Hg(II)	Agents (methylglycinediacetic acid, MGDA), surfactant (TweenO 80), citric acid); MW power 1,000 W; Hg initial concentration 43.2 mg/kg	High removal efficiency (99%) was observed when MWH combine with chelating agent and surfactant; Combination of MWH and citric acid could significantly decrease the remediation time.	[74]
Combined chemical oxidation and MWH	TPH	TPH initial concentration 12,900–13,550 mg/kg; Reaction time 10, 60 min; Microwave power 300, 450, 600 W; H_2O_2 dosage 1%, 2.5%, and 5%	At optimum conditions of H_2O_2 2% concentration and 450 MWH power, the TPH removal efficiency improvement was around 20% for three soil samples compared to MWH alone.	[75]
ERH coupling with chemical oxidation	PAHs	PAH initial concentration 101.61 mg/kg; ERH conditions; Electrical strength 8 V/cm; NaCl electrolyte solution 6 g of 0.1%; Temperature 90°C; $Na_2S_2O_8$ concentration 0, 0.05, 0.1, 0.5, 1, 1.5, 2, and 2.5 mmol/g; Remediation time 120 min	Removal efficiency of PAH was increased from 35.9 to 52.9% and 79.42% when 0.05 or 2.5 mmol/g $Na_2S_2O_8$ was added to ERH, respectively; Bap removal efficiency was enhanced by 65% when ERH was coupled with $Na_2S_2O_8$	[76]
Persulfate recirculation and ERH	Phenanthrene	Heating voltage 15, 25, 35 V; Remediation time 2 h; Phenanthrene initial concentration 411 mg/kg; PS dosage 0, 2, 10, and 50 g/L	Addition of persulfate may significantly improve the volumetric degradation of phenanthrene in the sand tank; Combo system is a promising technology for the application of heat-activated persulfate in situ chemical oxidation.	[77]
Combining electro-kinetic (EK) and ERH	Tetrachloroethene	PS dosage 10 g/L; EK DC voltage 12–18 V; ERH voltage 110 V	Tetrachloroethene concentration was reduced to lower than the detection limit; EK combine ERH system is a viable strategy to remediate a low permeability contaminated soil remediation.	[80]
Mechanochemical method and thermal desorption	PCBs	Grinding time 4 h; Heating for 60 min at 500°C; Organic matter content 3.02%; PCBs concentration in raw soil 505.1 μg/g	Total removal efficiency of 99.95% was achieved.	[81]
Thermal desorption combines with $Ca(OH)_2$	PCBs	Thermal desorption 300°C–600°C; $Ca(OH)_2$ dosage 1%; PCBs initial concentration 500 mg/kg	Removal efficiency was 94% in the presence of $Ca(OH)_2$, $Ca(OH)_2$ reduced the toxic equivalence quantity in soil and increased the ratio of lower chlorinated PCBs.	[82]

as soil and groundwater remediation. Significant research has been done in the past few years to develop different variations of heat-based remediation technologies. The underlying premise of heat-based technologies is that contaminant properties-solubility sorption, interfacial tension, volatility- can be radically altered through heat application that can enhance their recovery. This review focused mostly on the reviewing the research published in the last decade. The large volume of research published in this period and mentioned in this review is evidence of the potential and role of heat-based technologies for soil and groundwater remediation. However, further research is needed to optimize these technologies and identify areas where further improvements can be achieved. For steam enhanced extraction for DNAPL remediation.

OM plays an important role in soil fertility; more future research is required to understand the relation between soil properties, contaminates, and selected thermal remediation technology and mitigation strategies to recover the soil function after treatment. More works need to be done on using steam enhanced extraction for DNAPL remediation to identify the effectiveness of such a system.

Similarly, more field investigation on ERH should be done to evaluate the full-scale application as the lab tests have proved the ERH feasibility in terms of volatile and semi-volatile chlorinated and TPH from both saturated and vadose zone. Not only the combined remediation technology could increase the removal efficiency of pollutants, coupling thermal remediation with renewable energy systems could be performed to address the high energy demands for wide application of thermal remediation methods; thus, more studies need to be done in this domain to fully understand the suitability of such technologies.

7. Conclusion

This review focused on the developments thermal-based technologies have undergone in the past decade. The large number of papers reviewed attests to the rapid development the field has underwent. It is emphasized that thermal remediation technologies can achieve rapid and efficient treatment and will continue to occupy an important niche for the remediation of soils polluted by petroleum hydrocarbons. However, thermal technologies will not achieve the goal of restoring ecosystems without a holistic view of the effects on soils, plants, and ecosystems. Achieving this goal requires additional research beyond simply demonstrating high contaminants removal percentages. Incineration remediation approaches are suitable for sandy contaminated soil as lower OM contents and quartz nature resists changing soil properties due to high temperature. LTTD is a promising thermal remediation technology due to its low energy cost and not affecting soil function. Low power MWH is an effective tool for sandy soil remediation, especially when it used in conjunction with other technologies such as to activate persulfate chemical oxidation. Smoldering is cost-effective as it a self-sustaining method, but it does not work efficiently at sites with fine soils. Vitrification remediation has proven to be a feasible environmental mitigation method for radioactive and nuclear-contaminated soil but is very energy-intensive. Thermal remediation methods that apply heat below 250°C for a short time do not influence the soil properties, while applying renewable energy-based thermal remediation and coupled technology could improve the energy efficiency of all systems.

References

[1] H. Zhang, D. Ma, R. Qiu, Y. Tang, C. Du, Non-thermal plasma technology for organic contaminated soil remediation: a review, Chem. Eng. J., 313 (2017) 157–170.
[2] D. Ding, X. Song, C. Wei, J. LaChance, A review on the sustainability of thermal treatment for contaminated soils, Environ. Pollut., 253 (2019) 449–463.
[3] MEPC, China Earmarks 7.5 Billion Dollars for Environment Protection, 2017. Available at: http://en.people.cn/n3/2017/1124/c90000-9296386.html (accessed August 8, 2021).
[4] I.C. Ossai, A. Ahmed, A. Hassan, F.S. Hamid, Remediation of soil and water contaminated with petroleum hydrocarbon: a review, Environ. Technol. Innovation, 17 (2020) 100526, doi: 10.1016/j.eti.2019.100526.
[5] J.E. Vidonish, K. Zygourakis, C.A. Masiello, G. Sabadell, P.J.J. Alvarez, Thermal treatment of hydrocarbon-impacted soils: a review of technology innovation for sustainable remediation, Engineering, 2 (2016) 426–437.
[6] G.C. Scholes, J.I. Gerhard, G.P. Grant, D.W. Major, J.E. Vidumsky, C. Switzer, J.L. Torero, Smoldering remediation of coal-tar-contaminated soil: pilot field tests of STAR, Environ. Sci. Technol., 49 (2015) 14334–14342.
[7] G.L. Stegemeier, H.J. Vinegar, Chapter 4.6.1 – Thermal Conduction Heating for In-Situ Thermal Desorption of Soils, C.H. Oh, Ed., Hazardous and Radioactive Waste Treatment Technologies Handbook CRC Press, Boca Raton, 2001, pp. 1–37. Available at: http://s1052297.instanturl.net/pdf/white papers/paper18-11-6-09.pdf (accessed August 8, 2021).
[8] J.E. Vidonish, K. Zygourakis, C.A. Masiello, X. Gao, J. Mathieu, P.J.J. Alvarez, Pyrolytic treatment and fertility enhancement of soils contaminated with heavy hydrocarbons, Environ. Sci. Technol., 50 (2016) 2498–2506.
[9] J. Krouzek, V. Durdak, J. Hendrych, P. Masin, J. Sobek, P. Spacek, Pilot scale applications of microwave heating for soil remediation, Chem. Eng. Process. Process Intensif., 130 (2018) 53–60.
[10] R. Solinger, G.P. Grant, G.C. Scholes, C. Murray, J.I. Gerhard, STARx hottpad for smoldering treatment of waste oil sludge: proof of concept and sensitivity to key design parameters, Waste Manage. Res., 38 (2020) 554–566.
[11] M.W. Lim, E. Von Lau, P.E. Poh, A comprehensive guide of remediation technologies for oil contaminated soil — present works and future directions, Mar. Pollut. Bull., 109 (2016) 14–45.
[12] C.U. Kang, D.H. Kim, M.A. Khan, R. Kumar, S.E. Ji, K.W. Choi, K.J. Paeng, S. Park, B.H. Jeon, Pyrolytic remediation of crude oil-contaminated soil, Sci. Total Environ., 713 (2020) 136498, doi: 10.1016/j.scitotenv.2020.136498.
[13] C. Zhao, Y. Li, Z. Gan, M. Nie, Method of smoldering combustion for refinery oil sludge treatment, J. Hazard. Mater., 409 (2021) 124995, doi: 10.1016/j.jhazmat.2020.124995.
[14] M.Y.D. Alazaiza, A. Albahnasawi, G.A.M. Ali, M.J.K. Bashir, N.K. Copty, S.S. Abu Amr, M.F.M. Abushammala, T. Al Maskari, Recent advances of nanoremediation technologies for soil and groundwater remediation: a review, 13 (2021) 2186, doi: 10.3390/w13162186.

[15] D. Hou, A. Al-Tabbaa, Sustainability: a new imperative in contaminated land remediation, Environ. Sci. Policy, 39 (2014) 25–34.

[16] K.S. Holland, A framework for sustainable remediation, Environ. Sci. Technol., 45 (2011) 7116–7117.

[17] G. Lemming, M.Z. Hauschild, J. Chambon, P.J. Binning, C. Bulle, M. Margni, P.L. Bjerg, Environmental impacts of remediation of a trichloroethene-contaminated site: life cycle assessment of remediation alternatives, Environ. Sci. Technol., 44 (2010) 9163–9169.

[18] M.W. Lim, E. Von Lau, P.E. Poh, A comprehensive guide of remediation technologies for oil contaminated soil — present works and future directions, Mar. Pollut. Bull., 109 (2016) 14–45.

[19] D.E. Ellis, P.W. Hadley, Sustainable remediation white paper—integrating sustainable principles, practices, and metrics into remediation projects, Remediation, 19 (2009) 5–114.

[20] V. Cappuyns, D. Bouckenooghe, L. van Breuseghem, S. van Herreweghe, Can thermal soil remediation be sustainable? A case study of the environmental merit of the remediation of a site contaminated by a light non-aqueous phase liquid (LNAPL), J. Integr. Environ. Sci., 8 (2011) 103–121.

[21] D. Hou, L. Lu, Z.J. Ren, Microbial fuel cells and osmotic membrane bioreactors have mutual benefits for wastewater treatment and energy production, 98 (2016). https://doi.org/10.1016/j.watres.2016.04.017.

[22] P.P. Falciglia, C. Ingrao, G. De Guidi, A. Catalfo, G. Finocchiaro, M. Farina, M. Liali, G. Lorenzano, G. Valastro, F.G.A. Vagliasindi, Environmental life cycle assessment of marine sediment decontamination by citric acid enhanced-microwave heating, Sci. Total Environ., 619–620 (2018) 72–82.

[23] J.-W. Liu, K.-H. Wei, S.-W. Xu, J. Cui, J. Ma, X.-L. Xiao, B.-D. Xi, X.-S. He, Surfactant-enhanced remediation of oil-contaminated soil and groundwater: a review, Sci. Total Environ., 756 (2020) 144142, doi: 10.1016/j.scitotenv.2020.144142.

[24] C.K.J. Yeh, H.M. Wu, T.C. Chen, Chemical oxidation of chlorinated non-aqueous phase liquid by hydrogen peroxide in natural sand systems, J. Hazard. Mater., 96 (2003) 29–51.

[25] C. Cameselle, R.A. Chirakkara, K.R. Reddy, Electrokinetic-enhanced phytoremediation of soils: status and opportunities, Chemosphere, 93 (2013) 626–636.

[26] M.A. Rodrigo, M.A. Oturan, N. Oturan, Electrochemically assisted remediation of pesticides in soils and water: a review, Chem. Rev., 114 (2014) 8720–8745.

[27] K. Sen Chang, W.H. Lo, W.M. Lin, J.X. Wen, S.C. Yang, C.J. Huang, H.Y. Hsieh, Microwave-assisted thermal remediation of diesel contaminated soil, Eng. J., 20 (2016) 93–100.

[28] J.L. Heiderscheidt, R.L. Siegrist, T.H. Illangasekare, Inter-mediate-scale 2D experimental investigation of in situ chemical oxidation using potassium permanganate for remediation of complex DNAPL source zones, J. Contam. Hydrol., 102 (2008) 3–16.

[29] H.W. Meinardus, V. Dwarakanath, J. Ewing, G.J. Hirasaki, R.E. Jackson, M. Jin, J.S. Ginn, J.T. Londergan, C.A. Miller, G.A. Pope, Performance assessment of NAPL remediation in heterogeneous alluvium, J. Contam. Hydrol., 54 (2002) 173–193.

[30] P. Thavamani, E. Smith, R. Kavitha, G. Mathieson, M. Megharaj, P. Srivastava, R. Naidu, Risk based land management requires focus beyond the target contaminants-a case study involving weathered hydrocarbon contaminated soils, Environ. Technol. Innovation, 4 (2015) 98–109.

[31] D. Camenzuli, B.L. Freidman, T.M. Statham, K.A. Mumford, D.B. Gore, On-site and in situ remediation technologies applicable to metal-contaminated sites in Antarctica and the Arctic: a review, Polar Res., 32 (2013) 1–20.

[32] S. Gan, E.V. Lau, H.K. Ng, Remediation of soils contaminated with polycyclic aromatic hydrocarbons (PAHs), J. Hazard. Mater., 172 (2009) 532–549.

[33] U. Samaksaman, T.H. Peng, J.H. Kuo, C.H. Lu, M.Y. Wey, Thermal treatment of soil co-contaminated with lube oil and heavy metals in a low temperature two-stage fluidized bed incinerator, Appl. Therm. Eng., 93 (2016) 131–138.

[34] X. Hu, J. Zhu, Q. Ding, Environmental life-cycle comparisons of two polychlorinated biphenyl remediation technologies: incineration and base catalyzed decomposition, J. Hazard. Mater., 191 (2011) 258–268.

[35] S. Koskei, Y. Cheng, W. Shi, Feasibility Studies of soil remediation for Kenya, Am. J. Life Sci., 5 (2017) 36–42.

[36] R. Rathna, S. Varjani, E. Nakkeeran, Recent developments and prospects of dioxins and furans remediation, J. Environ. Manage., 223 (2018) 797–806.

[37] R. Mahinroosta, L. Senevirathna, A review of the emerging treatment technologies for PFAS contaminated soils, J. Environ. Manage., 255 (2020) 109896, doi: 10.1016/j.jenvman.2019.109896.

[38] P.P. Falciglia, L. Lumia, M.G. Giustra, E. Gagliano, P. Roccaro, F.G.A. Vagliasindi, G. Di Bella, Remediation of petrol hydrocarbon-contaminated marine sediments by thermal desorption, Chemosphere, 260 (2020) 127576, doi: 10.1016/j.chemosphere.2020.127576.

[39] M. Sörengård, A.S. Lindh, L. Ahrens, Thermal desorption as a high removal remediation technique for soils contaminated with per- and polyfluoroalkyl substances (PFASs), PLoS One, 15 (2020) 1–10.

[40] Z. Zivdar, N. Heidarzadeh, G. Asadollahfardi, Remediation of diesel-contaminated soil by low temperature thermal desorption, Int. J. Environ. Sci. Technol., 16 (2019) 6113–6124.

[41] Z. Chen, J. Zhou, Z. Chen, H. Chen, G. He, X. Liu, X. Yuanjian, A laboratory evaluation of superheated steam extraction process for decontamination of oil-based drill cuttings, J. Environ. Chem. Eng., 6 (2018) 6691–6699.

[42] N.A. Azizan, S.A. Kamaruddin, S. Chelliapan, Steam-enhanced extraction experiments, simulations and field studies for dense non-aqueous phase liquid removal: a review, MATEC Web Conf., 47 (2016), doi: 10.1051/matecconf/20164705012.

[43] R.E. Hinchee, P.R. Dahlen, P.C. Johnson, D.R. Burris, 1,4-Dioxane soil remediation using enhanced soil vapor extraction: i. field demonstration, Groundwater Monit. Rem., 38 (2018) 40–48.

[44] L.S.D. Trine, E.L. Davis, C. Roper, L. Truong, R.L. Tanguay, S.L.M. Simonich, Formation of PAH derivatives and increased developmental toxicity during steam enhanced extraction remediation of creosote contaminated superfund soil, Environ. Sci. Technol., 53 (2019) 4460–4469.

[45] E.J. Martin, K.G. Mumford, B.H. Kueper, Electrical resistance heating of clay layers in water-saturated sand, Groundwater Monit. Rem., 36 (2016) 54–61.

[46] T. Powell, G. Smith, J. Sturza, K. Lynch, M. Truex, New advancements for in situ treatment using electrical resistance heating, Remediation, 17 (2007) 51–70.

[47] J.L. Munholland, K.G. Mumford, B.H. Kueper, Factors affecting gas migration and contaminant redistribution in heterogeneous porous media subject to electrical resistance heating, J. Contam. Hydrol., 184 (2016) 14–24.

[48] Z. Han, W. Jiao, Y. Tian, J. Hu, D. Han, Lab-scale removal of PAHs in contaminated soil using electrical resistance heating: removal efficiency and alteration of soil properties, Chemosphere, 239 (2020) 124496, doi: 10.1016/j.chemosphere.2019.124496.

[49] H. Luo, H. Wang, L. Kong, S. Li, Y. Sun, Insights into oil recovery, soil rehabilitation and low temperature behaviors of microwave-assisted petroleum-contaminated soil remediation, J. Hazard. Mater., 377 (2019) 341–348.

[50] P.P. Falciglia, G. De Guidi, A. Catalfo, F.G.A. Vagliasindi, Remediation of soils contaminated with PAHs and nitro-PAHs using microwave irradiation, Chem. Eng. J., 296 (2016) 162–172.

[51] P.P. Falciglia, G. De Guidi, A. Catalfo, F.G.A. Vagliasindi, Contaminant removal mechanisms in microwave heating remediation of PAH-contaminated soils, Chem. Eng. Trans., 57 (2017) 361–366.

[52] K. Cho, E. Myung, H. Kim, O. Purev, C. Park, N. Choi, Removal of total petroleum hydrocarbons from contaminated soil through microwave irradiation, Int. J. Environ. Res. Public Health, 17 (2020) 1–13.

[53] G.P. Grant, D. Major, G.C. Scholes, J. Horst, S. Hill, M.R. Klemmer, J.N. Couch, Smoldering combustion (STAR) for the treatment of contaminated soils: examining limitations and defining success, Remediation, 26 (2016) 27–51.

[54] C. Switzer, P. Pironi, J.I. Gerhard, G. Rein, J.L. Torero, Volumetric scale-up of smouldering remediation of contaminated materials, J. Hazard. Mater., 268 (2014) 51–60.

[55] A. Pape, C. Switzer, N. McCosh, C.W. Knapp, Impacts of thermal and smouldering remediation on plant growth and soil ecology, Geoderma, 243–244 (2015) 1–9.

[56] A.L. Duchesne, J.K. Brown, D.J. Patch, D. Major, K.P. Weber, J.I. Gerhard, Remediation of PFAS-contaminated soil and granular activated carbon by smoldering combustion, Environ. Sci. Technol., 54 (2020) 12631–12640.

[57] J.E. Vidonish, K. Zygourakis, C.A. Masiello, X. Gao, J. Mathieu, P.J.J. Alvarez, Pyrolytic treatment and fertility enhancement of soils contaminated with heavy hydrocarbons, Environ. Sci. Technol., 50 (2016) 2498–2506.

[58] S. Chen, X. Shu, F. Luo, H. Dong, C. Xu, B. Li, D. Shao, X. Lu, Rapid vitrification of simulated Sr^{2+} radioactive contaminated soil for nuclear emergencies, J. Radioanal. Nucl. Chem., 319 (2019) 115–121.

[59] X. Shu, Y. Li, W. Huang, S. Chen, C. Xu, S. Zhang, B. Li, X. Wang, Q. Qing, X. Lu, Rapid vitrification of uranium-contaminated soil: effect and mechanism, Environ. Pollut., 263 (2020) 114539, doi: 10.1016/j.envpol.2020.114539.

[60] S. Ballesteros, J.M. Rincón, B. Rincón-Mora, M.M. Jordán, Vitrification of urban soil contamination by hexavalent chromium, J. Geochem. Explor., 174 (2017) 132–139.

[61] M. Yan, F. Luo, X. Shu, H. Tang, S. Chen, G. Wei, X. Yie, L. Wang, X. Lu, Response of simulated An^{3+}/An^{4+} radioactive soil vitrification under alpha-particle irradiation, Radiat. Phys. Chem., 187 (2021) 109567, doi: 10.1016/j.radphyschem.2021.109567.

[62] R.M. Abousnina, A. Manalo, J. Shiau, W. Lokuge, An overview on oil contaminated sand and its engineering applications, Int. J. Geomate, 10 (2016) 1615–1622.

[63] Z. Derakhshan Nejad, M.C. Jung, K.H. Kim, Remediation of soils contaminated with heavy metals with an emphasis on immobilization technology, Environ. Geochem. Health, 40 (2018) 927–953.

[64] S.C. Moldoveanu, Pyrolysis of Hydrocarbons, Pyrolysis Org. Mol., (2019) 35–161. Available at: https://doi.org/10.1016/B978-0-444-64000-0.00002-0.

[65] J.E. Vidonish, P.J.J. Alvarez, K. Zygourakis, Pyrolytic Remediation of oil-contaminated soils: reaction mechanisms, soil changes, and implications for treated soil fertility, Ind. Eng. Chem. Res., 57 (2018) 3489–3500.

[66] R.H. Venderbosch, A.R. Ardiyanti, J. Wildschut, A. Oasmaa, H.J. Heeres, Stabilization of biomass-derived pyrolysis oils, J. Chem. Technol. Biotechnol., 85 (2010) 674–686.

[67] J.E. Vidonish, K. Zygourakis, C.A. Masiello, G. Sabadell, P.J.J. Alvarez, Thermal treatment of hydrocarbon-impacted soils: a review of technology innovation for sustainable remediation, Engineering, 2 (2016) 426–437.

[68] A. Özkan, Z. Günkaya, M. Banar, Pyrolysis of plants after phytoremediation of contaminated soil with lead, cadmium and zinc, Bull. Environ. Contam. Toxicol., 96 (2016) 415–419.

[69] D.C. Li, W.F. Xu, Y. Mu, H.Q. Yu, H. Jiang, J.C. Crittenden, Remediation of petroleum-contaminated soil and simultaneous recovery of oil by fast pyrolysis, Environ. Sci. Technol., 52 (2018) 5330–5338.

[70] W. Song, J.E. Vidonish, R. Kamath, P. Yu, C. Chu, B. Moorthy, B. Gao, K. Zygourakis, P.J.J. Alvarez, Pilot-scale pyrolytic remediation of crude oil-contaminated soil in a continuously-fed reactor: treatment intensity trade-offs, Environ. Sci. Technol., 53 (2019) 2045–2053.

[71] Y. Kim, J.I. Oh, S.S. Lee, K.H. Lee, J. Lee, E.E. Kwon, Decontamination of petroleum-contaminated soil via pyrolysis under carbon dioxide atmosphere, J. Cleaner Prod., 236 (2019) 117724, doi: 10.1016/j.jclepro.2019.117724.

[72] H. Kan, D. Wu, T. Wang, G. Qu, P. Zhang, H. Jia, H. Sun, Crystallographic manganese oxides enhanced pyrene contaminated soil remediation in microwave activated persulfate system, Chem. Eng. J., 417 (2021) 127916, doi: 10.1016/j.cej.2020.127916.

[73] H. Kan, T. Wang, J. Yu, G. Qu, P. Zhang, H. Jia, H. Sun, Remediation of organophosphorus pesticide polluted soil

[74] P.P. Falciglia, D. Malarbì, R. Maddalena, V. Greco, F.G.A. Vagliasindi, Remediation of Hg-contaminated marine sediments by simultaneous application of enhancing agents and microwave heating (MWH), Chem. Eng. J., 321 (2017) 1–10.

[75] K. Sivagami, B. Rajasekhar, S. Mujahed, I.M. Nambi, A.K. Rajan, Application of combined chemical oxidation and microwave treatment for hydrocarbon-contaminated soil from an urban oil spill site, J. Hazard. Toxic Radioact. Waste, 25 (2021) 04020074, doi: 10.1061/(asce)hz.2153-5515.0000570.

[76] Z. Han, S. Li, Y. Yue, Y. Tian, S. Wang, Z. Qin, L. Ji, D. Han, W. Jiao, Enhancing remediation of PAH-contaminated soil through coupling electrical resistance heating using $Na_2S_2O_8$, Environ. Res., 198 (2021) 110457, doi: 10.1016/j.envres.2020.110457.

[77] J. Li, L. Wang, L. Peng, Y. Deng, D. Deng, A combo system consisting of simultaneous persulfate recirculation and alternating current electrical resistance heating for the implementation of heat activated persulfate ISCO, Chem. Eng. J., 385 (2020) 123803, doi: 10.1016/j.cej.2019.123803.

[78] A. Moradi, K.M. Smits, J.O. Sharp, Coupled thermally-enhanced bioremediation and renewable energy storage system: conceptual framework and modeling investigation, Water, 10 (2018) 1288, doi: 10.3390/W10101288.

[79] G.A. Aydin, B. Agaoglu, G. Kocasoy, N.K. Copty, Effect of temperature on cosolvent flooding for the enhanced solubilization and mobilization of NAPLs in porous media, J. Hazard. Mater., 186 (2011) 636–644.

[80] A.I.A. Chowdhury, J.I. Gerhard, D. Reynolds, D.M. O'Carroll, Low permeability zone remediation via oxidant delivered by electrokinetics and activated by electrical resistance heating: proof of concept, Environ. Sci. Technol., 51 (2017) 13295–13303.

[81] Z. Hua Zhao, X. Dong Li, M. Jiang Ni, T. Chen, J. Hua Yan, Remediation of PCB-contaminated soil using a combination of mechanochemical method and thermal desorption, Environ. Sci. Pollut. Res., 24 (2017) 11800–11806.

[82] J. Liu, H. Zhang, Z. Yao, X. Li, J. Tang, Thermal desorption of PCBs contaminated soil with calcium hydroxide in a rotary kiln, Chemosphere, 220 (2019) 1041–1046.

[83] P.L. O'Brien, T.M. DeSutter, F.X.M. Casey, E. Khan, A.F. Wick, Thermal remediation alters soil properties – a review, J. Environ. Manage., 206 (2018) 826–835.

[84] S.J. Croat, P.L. O'Brien, C.K. Gasch, F.X.M. Casey, T.M. DeSutter, Crop production on heavily disturbed soils following crude oil remediation, Agron. J., 112 (2020) 130–138.

[85] P.L. O'Brien, T.M. DeSutter, F.X.M. Casey, A.L.M. Daigh, J.L. Heitman, N.E. Derby, E. Khan, Daytime surface energy fluxes over soil material remediated using thermal desorption, agrosystems, Geosci. Environ., 1 (2018) 1–9.

[86] P.L. O'Brien, T.M. DeSutter, F.X.M. Casey, A.F. Wick, E. Khan, Wheat growth in soils treated by ex situ thermal desorption, J. Environ. Qual., 46 (2017) 897–905.

[87] G. Lassalle, V. Gassend, G. Michaudel, R. Hédacq, C. Weber, C. Jennet, P. Souquet, A. Credoz, A multicriteria approach for assessing the recovery of soil functions following high-temperature remediation of hydrocarbons, Sci. Total Environ., 775 (2021), doi: 10.1016/j.scitotenv.2021.145891.

[88] Y. Song, D. Hou, J. Zhang, D. O'Connor, G. Li, Q. Gu, S. Li, P. Liu, Environmental and socio-economic sustainability appraisal of contaminated land remediation strategies: a case study at a mega-site in China, Sci. Total Environ., 610–611 (2018) 391–401.

[89] J. Ren, X. Song, D. Ding, Sustainable remediation of diesel-contaminated soil by low temperature thermal treatment: improved energy efficiency and soil reusability, Chemosphere, 241 (2020) 124952, doi: 10.1016/j.chemosphere.2019.124952.

[90] D. Hou, Q. Gu, F. Ma, S. O'Connell, Life cycle assessment comparison of thermal desorption and stabilization/solidification of mercury contaminated soil on agricultural land, J. Cleaner Prod., 139 (2016) 949–956.

[91] P.P. Falciglia, F.G.A. Vagliasindi, Techno-economic analysis of hydrocarbon-polluted soil treatment by using ex situ

microwave heating: influence of soil texture and soil moisture on electric field penetration, operating conditions and energy costs, J. Soils Sediments, 16 (2016) 1330–1344.

[92] P.P. Falciglia, P. Scandura, F.G.A. Vagliasindi, Modelling and preliminary technical, energy and economic considerations for full-scale in situ remediation of low-dielectric hydrocarbon-polluted soils by microwave heating (MWH) technique, J. Soils Sediments, 18 (2018) 2350–2360.

[93] G. Hu, H. Liu, C. Chen, H. Hou, J. Li, K. Hewage, R. Sadiq, Low temperature thermal desorption and secure landfill for oil-based drill cuttings management: pollution control, human health risk, and probabilistic cost assessment, J. Hazard. Mater., 410 (2021) 124570, doi: 10.1016/j.jhazmat.2020.124570.

[94] C. Chen, X. Zhang, J. Chen, F. Chen, J. Li, Y. Chen, H. Hou, F. Shi, Assessment of site contaminated soil remediation based on an input output life cycle assessment, J. Cleaner Prod., 263 (2020) 121422, doi: 10.1016/j.jclepro.2020.121422.