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A Review on Thermal Desorption Treatment for Soil Contamination

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ABSTRACT: Soil contamination is a major issue that must be prioritized, as food safety is mostly determined by soil quality. Soil quality has deteriorated significantly across the world with the continued expansion of industrial growth, urbanization, and agricultural activities. Soil contamination has become a growing issue and a barrier that must be addressed if we are concerned about re-establishing a healthy ecosystem. The activity is mostly driven by human activities, which include the use of pesticides, chlorinated organic pollutants, herbicides, inorganic fertilizers, industrial pollution, solid waste, and urban activities. While many methods have been developed to remediate significant pollutants generated by these activities, their degree of application may be constrained or inappropriate for a specific location. Parameters such as treatment duration, safety, and efficacy of soil/pollutant treatment all play a part in selecting the best appropriate technique. These technologies have been classified into three broad categories: physical, chemical, and bioremediation. This review shows and talks about thermal desorption (TD), which is a common way to clean up polluted soil.

KEYWORDS: Thermal desorption; soil contamination; combustion; thermodynamic

1. Introduction

Soil contamination is a major issue that must be prioritized, as food safety is mostly determined by soil quality. With the continued expansion of industrial growth, urbanization, and agricultural activities, soil quality has deteriorated significantly across the world [1-3]. Thermal desorption has produced excellent results in the treatment of semi-volatile and volatile pollutants in soils, such as helium, dichlorodiphenyltrichloroethane, polycyclic aromatic hydrocarbons, total petroleum hydrocarbons, and polychlorinated biphenyls [4,5]. Due to their widespread usage in industrial and commercial sectors, volatile organic compounds (VOCs) have been found in significant amounts across the world in both groundwater and soil media. These compounds are released gases from some liquids and solids and are composed of complex chemicals. They may be hazardous to human and animal health in both the long and short term. From home goods like wood preservatives, aerosol sprays, insecticides, and paints, to industrial products like furniture, office equipment, spills, and landfill leachates. Exposure to these chemicals has been proven to induce harm to the liver, kidneys, and central nervous system [4]. While soil media may naturally include volatile organic compounds (VOCs) produced by the indigenous microbial community, the introduction of foreign persistent man-made organic chemicals (SVOCs) such as PCBs and PAHs pose a significant health risk to both the human and animal population. Because of their ease of absorption into soil medium, these chemicals exhibit persistence and mobility [4,5]. A significant portion of petroleum oil is used as fuel on a global scale. Additionally, the breadth of their use and the associated situations in which they leak or are disposed of into the environment have become a growing source of worry for the environment. Their persistence and toxicity in the environment pose serious health risks to humans, plants, and animals [6]. Additionally, elevated levels of heavy metals are regarded as very harmful to creatures and vulnerable to plants. Heavy metal soil pollution is mostly caused by anthropogenic sources such as mining, smelting, and related activities [8,9]. With rising industrial and population expansion, demand for and use of heavy metals is likely to rise as well. This raises serious concerns for the environment and human health as a result of the by-products generated by such operations. Thermal desorption has shown many benefits so far, including high efficiency, treatment of a broad variety of different pollutants, high safety, low treatment times, recycling of both soil and contaminants, and the absence of secondary contamination [10,11]. Taking these factors into consideration, the system has been effectively deployed in areas with low volume, high pollutant concentrations, and a high demand for comprehensive treatment. Several previous studies and evaluations have been performed to determine the most practical techniques and their efficacy for both petroleum and pesticides [11].

2. Mechanisms

Thermal desorption is defined as the process of heating specified semi-volatile and volatile soil contaminants to a desired temperature via indirect or direct heating under vacuum or carrier gas with the sole purpose of successfully separating the targeted contaminant from the soil medium of interest [12]. The process's off-gas is removed or recycled in the off-gas treatment system. If the system is constructed in such a manner that it vaporizes specific pollutants without oxidizing them, oxidation will happen; if oxidation happens, the process is classified as "incineration." Incineration is generally avoided since it may result in the production of chronically hazardous chemicals such as polychlorinated dibenzo-p-dioxins or dibenzofurans, benzene, and polycyclic aromatic hydrocarbons [13]. The two-step process shown in Figure 1 begins with the entry of contaminated material as the feed, which is heated directly or indirectly for media treatment. As a consequence, an off-gas is generated in the reaction chamber, and the gas is sent into another chamber for off-gas treatment. Essentially, the final products are treatment residues and simple compounds. The off gas is treated in three ways: burning, condensation, and collecting. While combustion occurs immediately after step 1, condensation and collecting occur ex-situ following step 1.

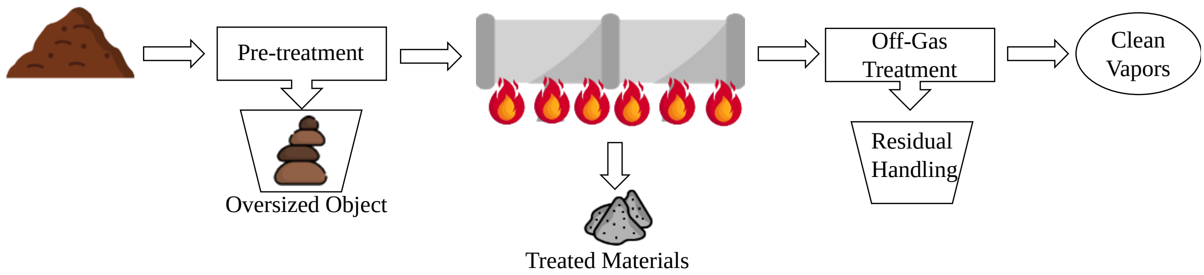

Figure 1. The general thermal desorption process [Icon from Flaticon Basic License CC3.0 (Creative Commons)].

3. Advantages and Disadvantages

The technique has been shown to be applicable to a wide variety of contaminants. Due to the system's low oxidation and degradation rates, the damage inflicted on the soil media by heating is limited, allowing for the prioritization of soil media recycling. Due to the process's relative stability across a variety of environmental conditions, it may be applied or transferred easily. Additionally, the technique has helped in the reduction of extremely hazardous secondary pollutants associated with contaminants like polychlorinated biphenyls (PCBs) [1,2]. If high temperatures are applied, treated soil may lose its ability to sustain microbiological activity that degrades pollutants. This may be a problem if the soil is restored to a previously polluted or partly contaminated location. With uneven heating profiles, temperature regulation may be problematic, resulting in the absence of oxygen level controls in the majority of thermal desorption operations. This may result in undesired over- or under-heating of contaminated soil media, resulting in soil degradation and increased energy consumption, which impacts the process's final outcome. Thus, it is important to keep the treatment temperature low throughout the process in order to save energy while still achieving adequate efficiency levels and increasing the potential use of the soil after treatment [12].

4. Classification

While different kinds of thermal desorption have been discussed in the current literature, there is little documentation of summary chart connection. Thermal desorption is classified as a technology in Figure 2. This helps in establishing a more distinct difference between theoretical temperature and technical implementations of the technology. Additionally, expanding on pertinent sub-category classifications such as the remediation site, the heating mode of the procedure, and the heating equipment utilized in the engineering application.

4.1. Temperature thermal desorption.

Thermal desorption is classified into two types based on the temperature at which pollutants are removed: low-temperature thermal desorption (LTTD) and high-temperature thermal desorption (HTTD). While the precise limit of a specific temperature is unknown, literature studies show that typical temperatures range between 300 °C and 350 °C [14]. When the process is carried out at temperatures lower than those specified above, it is classified as a low-temperature thermal desorption process (LTTD). These conditions are suitable for the treatment of volatile organic compounds (VOCs) with low boiling points (e.g. benzene). On the other hand, procedures with greater heating temperatures that exceed the specified temperature range are classified as high-temperature thermal desorption (HTTD). These high working temperatures are suitable for the treatment of semi-volatile organic chemicals (SVOCs) such as polychlorinated biphenyls (PCBs) and inorganic substances such as helium [2]. Due to the paucity of studies on the specificity of active pollutant removal within varied existing systems, temperatures for contaminants are few.

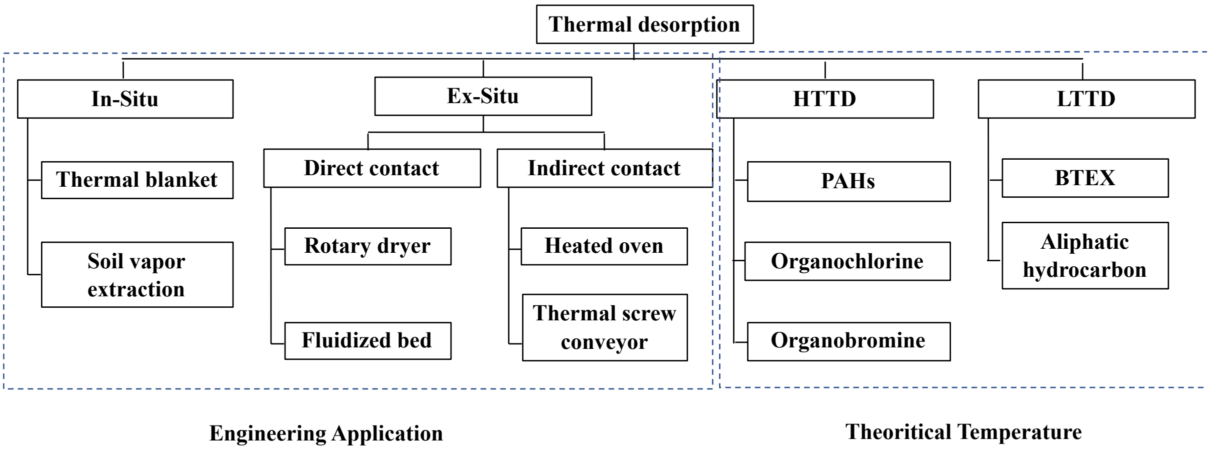

Figure 2. Thermal desorption classification.

4.2. Engineering application.

When it comes to engineering applications, the thermal desorption process may be further classified as ex-situ thermal desorption (ESTD) or in-situ thermal desorption (ISTD), depending on the location of the remedial process (Fig. 2). Ex-situ thermal desorption (ESTD) is usually used on sites with a high concentration of pollutants, a limited volume of contaminated soil, and a high risk. While the technique has been shown to be very effective in treating waste, it may also incur a significant cost of operation due to the possibility of external contamination during the excavation and transportation procedure. On the other hand, the in-situ thermal desorption (ISTD) technique eliminates the need for digging and transporting the contaminated soil of interest, further simplifies and lowers the cost of the entire soil treatment procedure, although at the expense of treatment time. The ISTD may be heated via improved soil vapor extraction or a thermal blanket/well [12]. The ESTD may be further classified into direct and indirect contact, depending on the kind of heating equipment available. The heat source for the direct contact technique is radiation generated by both the burning flame and the continuing convection of the combustible gas inside the chamber. By immediately exposing the contaminated soil of interest to the heat source, a high heat transfer capacity is apparent, resulting in an overall low cost of operation. Although this technique may result in high temperatures being produced throughout the process, it can also result in a significant level of complexity for subsequent off-gas treatment. The indirect contact technique provides heat indirectly through heat conduction. Due to the fact that the heat source is not in direct contact with the contaminated soil of interest, the availability of heat for application to the contaminated soil is very limited, resulting in a high total processing cost. In comparison to the direct contact technique, less off-gas is generated, necessitating minimal off-gas treatment.

Flammable gases generated during the first phase are immediately released into the environment. Figure 3 shows the types of contact rotary dryers: indirect and direct.

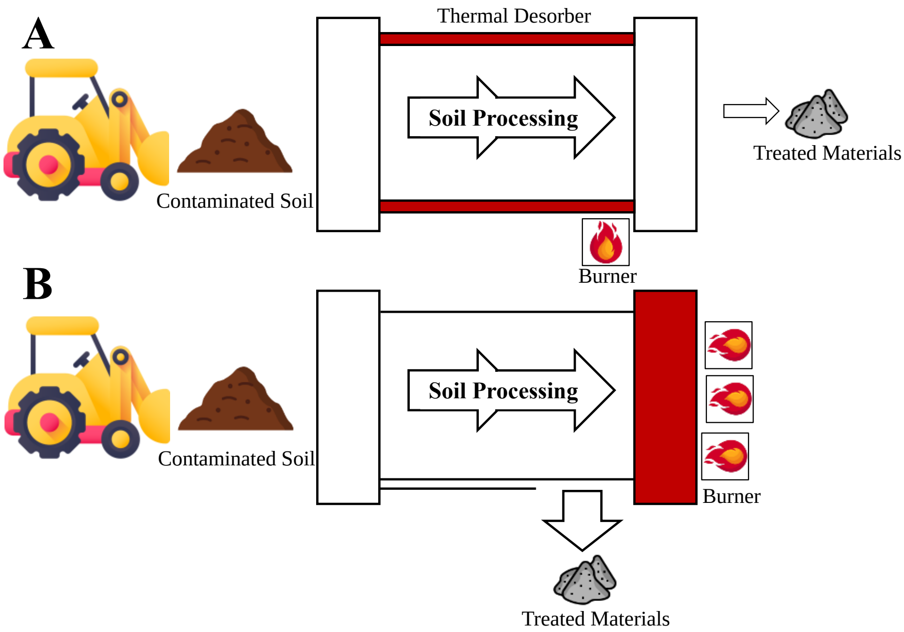

Figure 3. Type of contact rotary dryer: Indirect (A) and Direct (B). [Icon from Flaticon Basic License CC3.0 (Creative Commons)].

5. Influential factors of Thermal Desorption

The capacity of thermal desorption technology to efficiently and quickly remove pollutants while allowing for the re-use of contaminated materials has enabled it to be used in a wide variety of technical applications worldwide. Numerous benefits have been seen as a result of the technique, including an increase in site usage and a reduction in treatment time. Numerous studies in the existing literature suggest that temperature adjustment is the most direct approach for improving thermal desorption while also strengthening heat and mass transfer through equipment modification (vacuum enhanced, far-infrared, fluidized-bed, and microwave enhanced). Several previous studies have shown that altering the heat duration, heating rate, carrier gas, soil particle size, moisture content, contaminant input concentration, and finally the kind of pollutants may have a substantial impact on the process's efficacy [15-18].

5.1. Heating temperature.

Thermal desorption, as a thermal remediation method, is based on the concept of using a heat source at an appropriate temperature to successfully remove pollutants from a polluted medium. Thus, the heating temperature is critical to the overall efficiency of the system. According to some research, low temperatures do not promote pollutant removal [19]. While current literature indicates that raising temperatures results in an increase in overall system efficiency, experimental investigations into thermal desorption suggest that once sufficiently high temperatures are reached, system efficiency does not improve. One study on the removal of PAH-contaminated soil showed a substantial increase in the efficiency of total PAH removal from 350 °C to 650 °C during a 30-minute treatment period [16]. Another study focused on hexadecane removal and discovered that increasing system temperatures from 150 °C to 300 °C removed 99.9% of the hexadecane [20]. Additional temperature increases throughout the experimental research revealed no difference in terms of attaining greater efficiency. Thermal desorption technology that requires an enormous amount of heat to achieve high efficiency for contaminant removal is not ideal for real-world engineering applications, as studies have shown that extremely high heating temperatures can pyrolyze and volatilize organic matter, destroying the soil media of interest [21-23]. These conditions are not conducive to soil re-use or reclamation after treatment. This is a research priority for the future, in order to reduce operating temperature while maintaining a high removal efficiency rate.

5.2. Heating time and rate.

According to a previous study, heating for a brief amount of time did not favor pollutant elimination. Heating time is mainly determined by the heating temperature; a lower heating temperature results in a longer heating time in order to achieve better contaminant removal efficiency. This has been shown in many experiments using both Pb and Rh catalysts to remove PCB from soils contaminated with PCB. With heating temperatures up to 573 K, removal efficiency reached 52%, increasing to 96% when a longer heating period of 60 min was used. Additional heating time has been found to have a negligible effect on removal efficiency [24]. Another study found that heating PCB-contaminated soil at 600 °C for 20 min, 40 min, and 60 min resulted in removal efficiencies of 20.86%, 64.47%, and 95.7%, respectively [2]. The removal rate was found to be greater over the 20 to 40-min time specified, owing to the presence of water, which also had a lower boiling point than the existing PCBs. Taking this into consideration, the main process is water volatilization. This is accomplished via a fast-heating procedure that removes semi-volatile chemicals until all of the water content is evaporated. One study did indicate that by increasing the heating duration, significant damage to soil structures might be avoided [25]. In one experimental investigation, there was a significant positive connection between the effectiveness of PCB removal and the heating duration in one experiment. The heat transfer rates between the soil and the carrier gas are mostly determined by the heating time factor, as well as degradation rates and desorption processes, which ultimately influence the system's total removal efficiency [22].

5.3. Carrier gas.

Following their separation from the soil through volatilization and pyrolysis, pollutants within the soil medium are transformed into gaseous phases and then transferred to step 2 of the thermal desorption process for off-gas treatment via carrier gas (Figure 2). Thus, the carrier gas's composition may have an effect on the degree to which the entire system's efficiency is determined. Because a contaminant's volatility dictates its partial pressure in relation to the surrounding gases, the volatilization of volatile compounds or contaminants present must occur constantly while the process is operating [26]. Another experiment using nitrogen as a carrier gas showed an improvement in the removal effectiveness of organic materials when the nitrogen concentration was raised through flowrate [27]. These findings were then compared to theoretical simulations, which likewise indicated a significant improvement in efficiency levels. Another element that affects the overall effectiveness of thermal desorption technology is the carrier gas type used. The impacts of oxygen as a gas carrier may act as precursors to PCDF, potentially increasing the degree of toxicity. Nitrogen is a popular carrier gas, but steam has been used in the past to remediate soil polluted with phenanthrene and *p*-xylene [28]. The steam performance as a carrier gas in place of nitrogen is comparable or better than with nitrogen. However, steam is particularly advantageous for semi-volatile substances with a high boiling point.

5.4. Initial contaminant concentrations.

Numerous studies have shown a connection between high pollutant concentrations within a soil medium and efficient contaminant removal efficiency. Taking these findings into account, it is possible to hypothesize that when a particular contaminant is present in low initial concentrations, high-energy adsorption sites within soil media adsorb the contaminant, resulting in low removal efficiencies as absorbed contaminants become difficult to desorb. When the initial concentration is high, these high-energy adsorption sites become saturated, allowing pollutants to be exposed to the soil surface for easy removal. The initial concentration inside the medium should not be too high, since this would require the system to be supplied with more energy and time. As a consequence of the high expense and damage to the soil medium caused by severe temperatures, the soil application for post-treatment re-use/recycling is eventually devalued [29]. One difficulty encountered by the researchers was the uneven distribution of contaminants throughout the contaminated soil medium. This complicates the task of determining the optimal operating conditions for the thermal desorption system. Without an equal dispersion of treatment agents across the soil medium, treatment effectiveness will be inconsistent. If operating parameters are established in line with high starting concentrations in the soil, maximum efficiency should be ensured. Due to the uneven distribution of pollutants, this would cause regions with low concentrations to overheat, potentially destroying or damaging the soil medium while using an unnecessary amount of energy. On the other hand, a low or insufficient amount of heat applied to the contaminated soil based on average initial concentration measurements may not be sufficient to offer adequate treatment with high efficiency removal. Numerous solutions and methods have been developed over the years to assist in the uniform distribution of pollutants within the soil medium. To date, methods such as stirring, screening, and crushing have been employed to ensure that the soil is well mixed while also regulating the particle size of the soil. Further research shows that soil media can be grouped into parcels based on their concentration levels.

5.5. Moisture content.

Thermal desorption has a high removal effectiveness for pollutants such as hexachlorocyclohexane (HCH) when the moisture content of the contaminated soil medium is low, but a poor removal efficiency when the moisture content is high. Other research on dichlorodiphenyltrichloroethane (DDT) and dichlorodiphenyldichloroethylene (DDE) demonstrated significant effects when the moisture content of the contaminant medium exceeded 16%. The authors concluded that the moisture content of the soil media being treated should be between 10% and 20% to achieve maximum efficiency [30]. On that point, it is essential that the moisture content inside the system be within the specified range for optimal and effective functioning. When soil media are very dry, they should be sprayed and humidified; this enables polar water molecules to occupy high-energy adsorption sites, thus increasing pollutant removal. While water readily evaporates into steam during the evaporation stage, studies indicate that the presence of steam accelerates the pace of vapor extraction and distillation, thus improving the operation's removal efficiency. Moisture content may decrease the presence of mobile dust particles at the feed stage, thus decreasing or preventing dust particles from being collected by the carrier gas. On the other hand, contaminated soil media with a very high moisture content should be dried before being added to feed. Increased moisture content leads to the development of an intracrystalline water layer inside the soil medium, affecting mass transfer between particles and the overall rate of process removal. Additionally, a higher moisture content needs more energy during the evaporation process, which results in higher operating expenses; and finally, a higher moisture content results in more steam produced during evaporation, which leads to increased off-gas treatment time and operation. Thus, prior to thermal treatment, it is critical that the soil moisture level be between 10% and 20%. While soil drying has remained a traditional technique for decreasing the high moisture content of contaminated soils, the process has been shown to be inefficient in terms of energy and resource use. One new alternative technique described included the use of a drying agent, quick lime, during dry treatment, demonstrating that soil density remained unaffected although soil moisture was decreased. Other impacts included a decrease in soil viscosity and the release of significant quantities of heat through the hydration process, which eventually improved the thermal desorption process's overall efficiency [31-32].

5.6. Soil particle size.

Coarse particles are difficult to aggregate in real-world engineering applications. To maintain sufficient thermal conductivity, it is critical that the bulk of the surface area remains exposed to the heat source during the operation. Previous research showed that the connection between particle size and thermal desorption efficiency is inversely proportional. Thermal desorption treatment of PCB showed that particle sizes smaller than 250 mm had a greater thermal removal effectiveness than coarse particles ranging in size from 420 to 841 μm [2]. Additionally, another research showed that diesel-contaminated soil medium had a substantially greater rate of removal than coarse particles [14]. Another research found that the removal effectiveness of HCHs and DDT reduced as particle size increased. Based on the examples provided, soil media composed of tiny particles provide a larger surface area for reaction to occur while also allowing for rapid heat transmission, allowing the material to heat up more quickly. Where the diffusion rate limits the effectiveness of removal, pollutants contained within the tiny particles readily desorb. Although if the particles are sufficiently tiny, the problem of being transported to the off-gas treatment step by the carrier may emerge, burdening the process and resulting in high costs [28]. The impact of several variables such as soil composition and particle size on the overall removal effectiveness of the system is being investigated. Thus, further research should be conducted on these variables in order to increase current information about the effects these elements may have on a particular thermal desorption system [31].

5.7. Additives.

The creation of additives has long been pursued with the sole objective of changing the physicochemical characteristics of contaminated soil media in order to increase the overall thermal desorption system's removal effectiveness. Mercury's current heating temperature range is between 600 and 800 °C, which is quite high and results in significant operating and capital expenses [33]. Another research developed Na_2S leaching to help in lowering the basal heating temperature and promoting a more cost-effective thermal desorption method to address this. Initially, direct heating at 550 °C for 60 min decreased the mercury content from 168 mg/kg to 32.4 mg/kg. However, when Na_2S heating was used, a minimum heating temperature of 350°C was obtained. Additionally, a 1.0 mg/Kg Hg concentration during a 60 min heating period [34]. This technique demonstrated the possibility for Na_2S leaching to be used as an additive for other contaminating volatile chemicals. A previous study demonstrated that granular activated carbon enhanced the removal of crude oil-contaminated soil via microwave thermal remediation, achieving removal efficiencies of only 12% at temperatures of 230 °C for a heating time of only 30 min without the addition of granular activated carbon. However, a second experiment using the same circumstances and 10% granular activated carbon resulted in a temperature of 670 °C with a 99% removal efficiency after 20 min of heating. The experiment demonstrated the possibility of the addition of activated granular carbon (GAC) to polluted soil to successfully raise the optimal temperature while attaining remarkable removal efficiencies [35]. A previous research demonstrated the effects of nano zerovalent iron (nZVI) on PCB-contaminated soil at a temperature of 600 °C, with one sample containing pure contaminated soil (blank) and the other containing 100 mg of nZVI. After one hour of heating, the findings revealed a removal efficiency of 97.40% for the blank sample and 98.35% for the sample containing 100 mg of nZVI. Thus, nZVI has the potential to be a useful addition to increase the efficiency of thermal desorption systems [15]. Another research demonstrated the efficacy of calcium hydroxide as an addition in the dichlorination, detoxification, and removal of PCBs using rotatory kiln equipment. At 600 °C, the PCB-contaminated soil sample without $Ca(OH)_2$ addition showed a removal efficiency of 90.0%, whereas the PCB-contaminated soil sample with 1% $Ca(OH)_2$ additive demonstrated a removal efficiency of 94.0%. Additionally, the two investigations concluded that high temperatures are suggested for engineering applications if high removal rates from contaminated soil media are desired [36].

6. Destructive Technique of Off-gas

Once pollutants have been volatilized from contaminated soil media, they are transferred through the carrier gas to the thermal desorption system's off-gas treatment (step 2). The thermal desorption system's gaseous pollutants include volatile inorganic compounds, SVOCs, and VOCs. Secondary treatment is necessary only if these pollutants can be successfully eliminated. As a result, primary research on off-gas treatment for thermal desorption is required. Various off-gas treatment methods for thermal desorption have been developed to date. Due to the direct exposure of the contaminated soil media and heat source to the direct contact thermal desorption system, a greater quantity of gas is produced, resulting in poor recovery rates. Thus, destructive off-gas treatment methods such as catalytic combustion, thermal combustion, low-temperature plasma technique, and photocatalytic oxidation are often recommended. In comparison, the off gas generated by the indirect contact thermal desorption method is negligible. This is caused by a high concentration of contaminated soil media with high recovery values as a consequence of the soil media's main indirect interaction with the heat source. Off-gas treatment methods such as soil adsorption, condensation, membrane separation, and liquid adsorption are suggested and used in this situation. Several damaging techniques are discussed here, along with their major benefits and disadvantages, which should be considered before adopting a thermal desorption system.

6.1. Combustion thermodynamic.

Off-gases generated in step 1 of the thermal desorption process are injected into a combustion chamber and combusted. Fine and light soil particles that were transported by the off-gas are also eliminated. The degree to which the off-gas is combustible is determined by the flammability of the pollutants existing in the off-gas when it enters the combustion chamber, where it is converted into carbon dioxide, water, and other molecules that were originally in the off-gas. Thermal combustion has a plethora of benefits and drawbacks, as previously stated. As a consequence, the off-gas is completely purified, resulting in a considerably higher removal efficiency. The technique requires the least amount of space due to the simplicity of the equipment set in comparison to other ways. With an integrated thermal desorption system, the high temperature generated by the vessel may readily be utilized for various purposes. However, lean combustion may result in a wide variety of combustion variations. Additionally, the high temperatures produced may result in decreased operational safety. When entering off-gas concentrations are low, a high temperature generated by combustion may not be sufficient to complete the operation. Finally, under such circumstances, off-gas including acidic components such as sulfur, nitrogen, and other halogens may develop [37].

6.2. Catalytic combustion.

This technique entails the addition of a catalyst to the combustion chamber in order to facilitate the oxidative breakdown of the gaseous pollutant into carbon dioxide, water, and other molecules that were present in the off-gas at low temperatures. The technique is based on the thermal combustion idea, which allows for more flexibility in the creation of novel catalysts, resulting in reduced operating costs while increasing system efficiency. Previously published research examined the catalytic combustion of non-noble metal catalysts, metal oxide catalysts, and catalysts incorporating Au [33]. Numerous benefits have been discovered since the method's creation and use. Due to the low temperature operation, safety is regarded as good, and the possibility of NOx generation is reduced, which ultimately helps with cost reduction. Reduced operating temperatures also lower fuel costs, making the approach more economical and extending the life of equipment. However, there are several disadvantages to this technique, including the need to pre-treat the off-gas, which may necessitate the construction of a more sophisticated system. Because the catalysts are composed of valuable metals, their replacement or regeneration may entail additional operating expenses. Given the possibility of producing acidic gases during operation, wet scrubbers and emergency cooling systems may be necessary, resulting in an increase in costs due to increased maintenance [38]. Therefore, it is suggested to apply catalytic combustion to treat off-gas at low concentrations and low or high flow rates.

6.3. Biodegradation.

This technique employs microorganisms to breakdown gaseous pollutants in off-gas as a source of nutrients and food, resulting in the production of carbon dioxide, water, and other innocuous inorganic salts [39]. The technique may be further classified into two sub-categories based on the kind of microorganism population present: biological washing and biofiltering. The biofilter is the most commonly used technique. It consists of pre-treated off-gas that is fed into a humidifier through a fan. Adjustments are made to the humidity of the off-gas entering the chamber in order to avoid excessive water loss in the filter material, which may result in cracking. The off-gas is then directed into the biofilter, where pollutants are absorbed by organisms that have adhered to the filter medium and are naturally oxidized and decomposed [39]. Because the employment of natural organisms substantially reduces operating expenses, it is worth additional investigation to determine how to optimize the method's use. The technology's advantages include increased safety, ease of implementation and maintenance, and reduced energy usage [40-43]. Complete oxidative breakdown occurs with very little to no secondary pollutants. However, the technique requires a vast growth space for the microorganism, which results in a lengthy processing time. Additionally, the technique has achieved low removal efficiency so far and needs considerable care for the environment, since microorganisms are very sensitive to changes in their habitat.

7. Conclusion and Future Perspectives

In summary, we have discussed the application of thermal desorption to treat polluted soils. Its ability to successfully remove contaminants, its enormous size, and its reusability have resulted in an increase in site usage and a decrease in treatment time. However, several factors must be modified to maximize the process's efficacy, such as the heat duration, heating rate, carrier gas, soil particle size, moisture content, contaminant input concentration, and kind of pollutants. Further, the obtained off gas generated from the thermal desorption process has been treated by any of the following methods, e.g., catalytic combustion, thermal combustion, low-temperature plasma technique, and photocatalytic oxidation, whose major benefits and disadvantages should be considered before their adoption in a thermal desorption system. Engineering applications of off-gas treatment methods should become the focus of future studies to assure high removal efficiency, minimize secondary pollution, and economic efficiency.

Credit Author Statement

Risky Ayu Kristanti: Conceptualization, Supervision, Data curation, Writing – original draft, Writing – review and editing. **Wilawan Khanitchaidecha and Gaurav Taludar**: Visualization, Writing –review and editing. **Peter Karácsony**: Data curation. **Linh Thi Thuy Cao:** Writing – review and editing. **Tse-Wei Chen**: Writing – review and editing. **Noura M. Darwish**: Methodology. **Bandar M. Al Munqedhi**: Writing - review and editing. **Murat Yilmaz**: Writing – review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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