Chemistry Africa
https://doi.org/10.1007/s42250-025-01257-5

ORIGINAL ARTICLE

# Evaluating the Bioremediation Potential of *Jatropha curcas* and *Ficus exasperata* Vahl Composts in Removing Phthalate Esters from Dumpsite Soils: Implications for Human Health

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Received: 17 December 2024 / Accepted: 16 February 2025


**Abstract**
The present study evaluated the bioremediation potential of *Jatropha curcas* and *Ficus exasperata* composts in removing phthalate esters (PAEs) from dumpsite soils and its implication for human health. A total of 49 untreated and remediated soil samples were collected from three major dumpsites in Ogun State, Nigeria, and treated with *J. curcas* and *F. exasperata* composts for PAE removal, using gas chromatography-mass spectrometry. The data were analyzed using descriptive and inferential statistics with SPSS for Windows (version 23.0). Geospatial maps of PAEs in the dumpsites were generated using ArcGIS (Geographical Information System). The health risk assessment of PAEs was conducted for both carcinogenic and non-carcinogenic effects using the United States Environmental Protection Agency (EPA) model. The results showed that Dibutyl phthalate (DBP) ($1.391 \pm 0.741$ mg kg$^{-1}$) was the highest measured phthalate congener in the dumpsite soils, followed by Diethyl phthalate (DEP) ($0.173 \pm 0.051$ mg kg$^{-1}$). The distribution of phthalate congeners in the dumpsite soils followed this pattern: DBP > DEP > Di-(2-ethylhexyl) phthalate (DEHP) > Dimethyl phthalate (DMP) > Dioctyl phthalate (DOP) > Benzyl butyl phthalate (BBP). Jatropha and Ficus composts were able to remove 39–100% and 49–100% of phthalate congeners, respectively, from the contaminated dumpsite soils. Human health risk data on phthalate esters indicated no carcinogenic or non-carcinogenic adverse effects in both treated and untreated dumpsite soils.

**Keywords** Phthalate esters · Bioremediation · Removal efficiency · Jatropha curcas · Ficus exasperata

## 1 Introduction

Phthalate esters (PAEs) are widely used plasticizers added to plastics such as polyethylene terephthalate (PET), polyvinyl chloride (PVC), styrene, and rubber to enhance their transparency, flexibility, and durability [1, 4, 8]. PAEs are also found in various commercial and industrial products, including automobiles, detergents, electrical items, packaging, paints, pesticides, and pharmaceutical pills [7, 28]. Exposure to PAEs can occur through ingestion, inhalation, and dermal contact from sources such as soil, water, food, air, personal care products, nutritional supplements, home furnishings, pharmaceuticals, medical devices, and phthalate-laden clothing [4, 10]. The main health effects linked to PAEs include endocrine system disruption, cancer, diabetes, heart disease, gonadal toxicity, teratogenesis, mutagenesis, hormonal imbalance, obesity, kidney disease, and respiratory disorders [4, 11].

Improper disposal of plastic materials in dumpsites or landfills leads to the release of PAEs into the environment, contributing to soil pollution [3, 6, 24]. In dumpsites, plastic materials, including PAEs, degrade through various mechanisms, such as biodegradation by microorganisms, phytodegradation by sunlight, hydrolysis by water, and thermal degradation at high temperatures [2]. Upon degradation, PAEs may leach into groundwater, bioaccumulate in plants, and biomagnify in the food chain, resulting in adverse health

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Published online: 20 March 2025

effects on humans. Therefore, it is crucial to mitigate PAE-polluted soils to ensure the safe production of food, particularly through bioremediation, such as composting. Bioremediation utilizes living systems, such as microorganisms and/or plants, to remove pollutants from environmental media [15, 16]. The primary goal of bioremediation is to restore contaminated sites to their pre-contamination state, often involving revegetation to stabilize the treated soil. In addition to reducing contaminant levels, composting improves plant growth by conditioning the soil and providing nutrients for a wide range of vegetation.

Bioremediation has been shown to effectively clean up soils contaminated with PAEs [5, 27], Zhao et al. 2015; [20]. Bioremediation and composting technologies have been used to remediate polyvinyl chloride-contaminated soil in Italy, where diethylhexyl phthalate (DEHP) was present [5]. The results showed that 89% of DEHP was successfully removed after 76 days of remediation using slurry and solid-phase reactors. Yuan et al. [27] demonstrated the biodegradation of PAEs in sludge and sludge-amended soil. *Providencia sp.* 2D strain, isolated from compost, completely degraded di-n-butylphthalate (DBP) within three days under optimal conditions, supporting the feasibility of remediating DBP-contaminated soils inoculated with the strain (Zhao et al. 2015). A recent review by Tran et al. [20] found that the application of compost and phytoremediation technologies to PAE-contaminated soils removed 25–100% of PAEs.

Studies on pollution, health effects, and remediation of plastic contaminants in soils are limited in the literature [23],2024). The present study utilized two different composts, Jatropha (*Jatropha curcas*) and *Ficus exasperata* Vahl, to remediate PAE-contaminated dumpsite soils. The study also assessed the human health risk to determine safe levels of PAEs in polluted and remediated soils.

## 2 Materials and Methods

### 2.1 Composting Experiment

Composting was performed through the aerobic degradation of organic wastes, including 35 kg of poultry manure, 10 kg of *Jatropha curcas* and *Ficus exasperata* Vahl leaves, and 2 kg of sawdust, as described by Taiwo et al. [19]. The composting process involved regular watering and weekly mixing over a period of ten weeks. The resulting composts had a C/N ratio ranging from $12.15 \pm 0.89$ for *Jatropha curcas* to $16.13 \pm 0.37$ for *Ficus exasperata* Vahl.

### 2.2 Soil Sampling and Experimental Design

Polluted soils were collected from the three largest municipal dumpsites in Ogun State: Saje in Abeokuta, Ijagun in Ijebu-Ode, and Kurata in Ota (Fig. 1). Composite soil samples were taken from the four cardinal points at each sampling site. The dumpsite soils were air-dried and sifted through a 2 mm mesh.

The experimental design followed a randomized complete block design with five treatments: 'soil only', 'soil + Ficus compost only', 'soil + Ficus compost + castor oil plant', 'soil + Jatropha compost only', and 'soil + Jatropha compost + castor oil plant'. The contaminated dumpsite soils were blended with the composts at a ratio of 1:4 (i.e., 150 g compost + 600 g soil). *Ricinus communis* (Castor oil plant) was introduced to enhance the bioremediation experiment.

### 2.3 Determination of Phthalate Esters in Compost and Soil

Approximately 15 g of soil samples were thoroughly ground with a Teflon pestle homogenizer, along with 10 g of anhydrous sodium sulphate. A 2 g portion of each sample was weighed, transferred to a cellulose extraction thimble, and placed into a Soxhlet apparatus. Each soil sample was then extracted with 100 mL of n-hexane. For sample cleanup, a glass column packed with 4 g of silica gel was used, which had been previously activated for 6 h at 130 °C in a petri dish and loosely covered with foil. Then, 2 g of anhydrous sodium sulphate was added to the column, followed by 10 mL of n-hexane.

The sample extract was transferred into the column and eluted with 20 mL of n-hexane. The extract was collected in a beaker and concentrated to 2 mL using a rotary evaporator.

The extract was analyzed for phthalate esters [Dibutyl phthalate (DBP), Diethyl phthalate [DEP], Di- (2-ethylhexyl) phthalate (DEHP), Dimethyl phthalate (DMP), Dioctyl phthalate (DOP) and Benzyl butyl phthalate (BBP)] using gas chromatography-mass spectrometry (GC–MS, Agilent 7820, CA, United States). Detailed operations of GC–MS are presented in Taiwo et al. [17].

Quantification of phthalate esters involved using external calibration curves prepared from standard solutions of each phthalate ester congener. The phthalate ester standard, with a concentration of 1000 mg $L^{-1}$ containing 6 congeners, was obtained from AccuStandard New Haven, CT, US).

### 2.4 Statistical Data Analysis

Data were evaluated using both descriptive statistics (mean, standard deviation, minimum, and maximum) and inferential statistics (Duncan Multiple Range Test) with the Statistical Package for the Social Sciences (SPSS) for Windows (version 23.0).

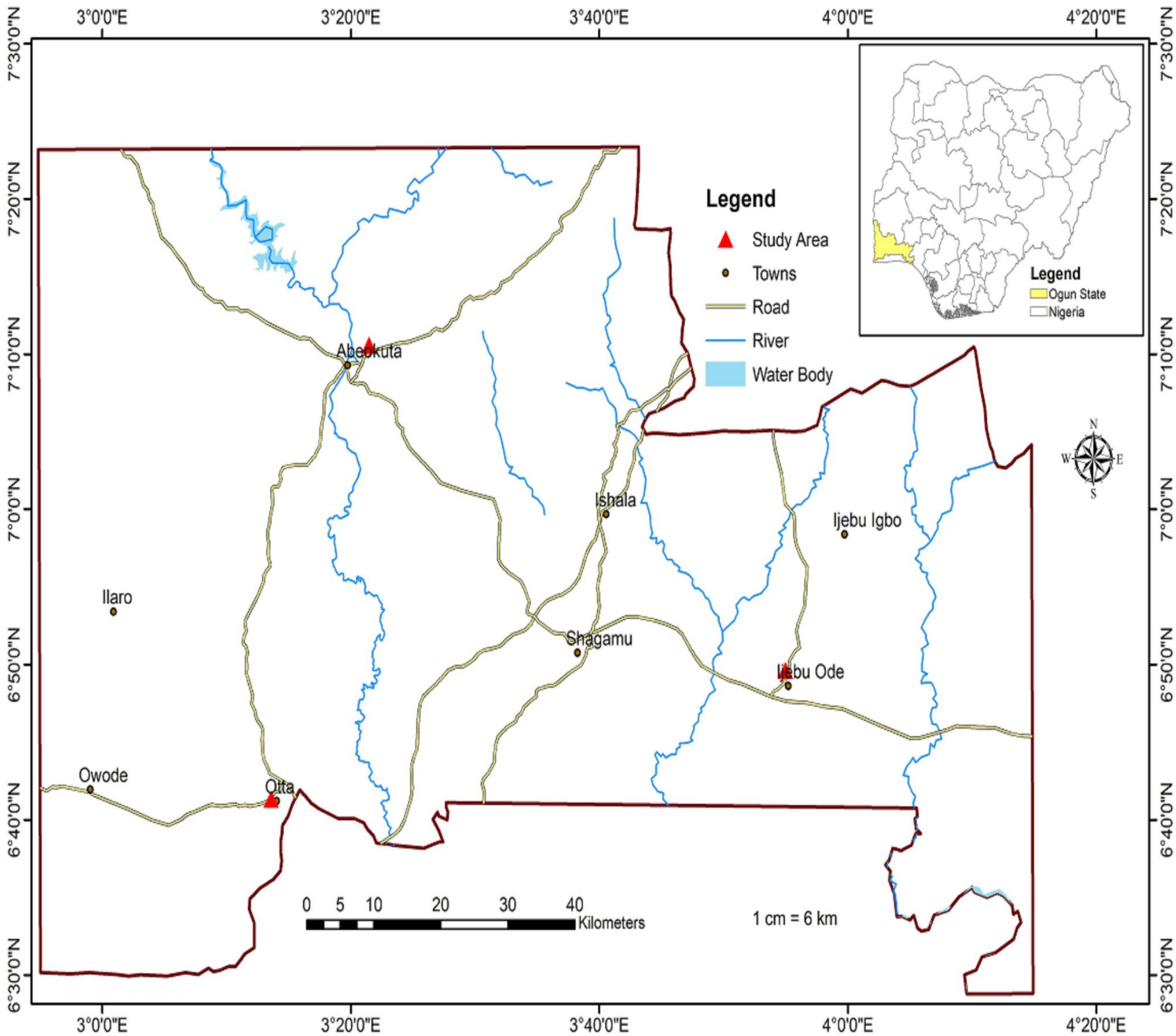


**Fig. 1** Map of the study area showing the dumpsites

### 2.5 Removal Efficiency

The portion of phthalate esters remediated by natural attenuation, "compost only," "plant only," and "compost + castor oil plant" in dumpsite-contaminated soils was calculated as shown in Eq. 1.

$$\% \text{ Removal efficiency } = \frac{\text{Cx} - \text{Cy}}{\text{Cx}} \times 100 \tag{1}$$

where $C_x$ is the concentrations of phthalate esters in contaminated soil before remediation; $C_y$ is the concentration of phthalate esters after remediation.

### 2.6 Health Risk Assessment

The health risk assessment of phthalate esters in soils was estimated for carcinogenic and non-carcinogenic adverse effects by adopting the models of the United States Environmental Protection Agency, presented in Eqs. 2–7 (USEPA, 2007).

$$\text{Estimated Daily Intake for ingestion (EDIing)} = \frac{C \times IR_{ing} \times F \times EF \times ED \times CF}{BW \times AT} \tag{2}$$

Estimated Daily Intake for inhalation (EDIinh)

$$= \frac{C \times IR_{inh} \times F \times EF \times ED}{PEF \times BW \times AT} \quad (3)$$

Estimated Daily Intake for dermal (EDIder)

$$= \frac{C \times CF \times SA \times AF \times ABS \times F \times EF \times ED}{BW \times AT} \quad (4)$$

where $EDI_{ing}$, $EDI_{inh}$, and $EDI_{der}$ (mg $kg^{-1}$ $day^{-1}$) = Estimated daily intake of phthalate esters in dumpsite soils through ingestion, inhalation and dermal contact, respectively; C = Concentrations of phthalate esters in soil (mg $kg^{-1}$); CF = Conversion factor = $10^{-6}$ kg $mg^{-1}$; EF = Exposure frequency = 250 days $year^{-1}$; ED = 30 years for carcinogenic effects (USEPA 2007); AT = Averaging time/life expectancy; for non-carcinogenic effects, AT = ED, while for carcinogenic effects, AT = 2190 days for children and 22,385.45 days for adults [14],$IR_{ing}$ = Ingestion rate of soil = 200 and 100 mg $day^{-1}$ for children and adults, respectively; $IR_{inh}$ = Inhalation rate of soil = 5 and 20 mg $kg^{-1}$ $day^{-1}$ for children and adults, respectively; ABS = Absorption factor = 0.001 [18],AF = Adherence factor = 0.07 mg $cm^2$; BW = Body weight = 15 and 60 kg for children and adults, respectively; F = Fraction of time spent outside per day = 6.94 ‰; PEF = Particle emission factor = $1.36 \times 10^9$ $m^3$ $kg^{-1}$; SA = Exposed skin surface area = 5,000 $cm^2$ $day^{-1}$.

$$\text{Hazard quotient}(HQ) = \frac{EDI}{RfD} \quad (5)$$

$$\text{Nol} - \text{cancer hazard index}(HI) = \sum_{i=1}^{n} HQi = 1 \ldots n \quad (6)$$

where EDI = Estimated daily intake of phthalate esters in dumpsite soils (mg $kg^{-1}$ $day^{-1}$); RfD = Reference dose of PAEs (mg $kg^{-1}$ $day^{-1}$) obtained from Integrated Risk Information System (USEPA 2007); n = numbers of analyzed phthalate esters; HQ > 1 indicates deleterious health effect; HQ < 1 illustrates no ill health effect.

$$\text{Cancer risk}(CR) = EDI \times CSF \quad (7)$$

where EDI = Estimated daily intake of PAEs in soil (mg $kg^{-1}$ $day^{-1}$); CSF = Cancer slope factor of PAEs ($mg^{-1}$ kg day) (USEPA 2007).

### 2.7 Spatial Distribution Map of Phthalate Esters

The Geographical Information System (GIS) technique was employed to produce spatial maps for the mean concentrations of phthalate esters in dumpsite soils in the study area. Mapping and spatial analysis were carried out using ArcGIS 10.3 and Quantum GIS 1.7.0 [18]. The chemical contents in soil samples were interpolated with the ordinary Kriging method (grid of $25 \times 25$ $m^2$).

## 3 Results and Discussion

### 3.1 Phthalate Ester Concentrations in Untreated and Treated Dumpsite Soils

The concentrations of phthalate ester (PAE) congeners in untreated and treated soil samples are presented in Table 1. Dibutyl phthalate (DBP) was the highest measured PAE in both the untreated ($1.3914 \pm 0.7413$ mg $kg^{-1}$) and treated (< 0.0001 – $0.7220 \pm 0.7661$ mg $kg^{-1}$) soil samples. A study by Wang et al. (2024) reported the concentrations of various PAE congeners, including DBP ($0.19 \pm 0.27$ mg $kg^{-1}$), DEHP ($1.72 \pm 1.79$ mg $kg^{-1}$), and DOP ($0.22 \pm 0.33$ mg $kg^{-1}$), in agricultural soils where different types of plastic films were used for vegetable production.

A recent study by Fagbemi et al. [6] documented very high concentrations of DEHP ($49.83 \pm 0.49$ mg $kg^{-1}$) in dumpsite soil samples collected from Obafemi Awolowo University Campus, Ile-Ife, Osun, Nigeria. The research showed that the combined concentrations of butylbenzyl phthalate (BBP) and DEHP accounted for more than 90% of the total PAEs measured in the soil samples.

According to Sokolowski et al. (2024), PAEs constitute up to 60% of the weight of agricultural films currently used on a large scale in the agricultural sector. Additionally, high levels of DBP (15.5 mg $kg^{-1}$) and DEHP (4.61 mg $kg^{-1}$) were detected in greenhouse soils from Handan, Hebei Province, as reported by Xu et al. [26].

DBP is classified as an endocrine-disrupting chemical (EDC), posing potential risks to both human health and ecosystems [13]. Its presence in untreated soil at dumpsites, especially at high concentrations, highlights the urgent need for remediation to reduce exposure risks. The successful reduction of contamination in treated soils demonstrates the effectiveness of soil remediation strategies in mitigating environmental hazards.

### 3.2 Removal Efficiency of Phthalate Esters in Treated Dumpsite Soils

The removal efficiency (RE) of the treatments and natural attenuation (represented by soil only) is shown in Fig. 2. Jatropha compost exhibited the highest removal efficiency for DOP, DEHP, DMP, and BBP, while the combined mixture of Ficus compost and the plant showed the highest

**Table 1** Levels of phthalate esters (mg $kg^{-1}$) in treated and untreated dumpsite soils

| Phthalate esters | Compositon | N | Mean | Std. Deviation | Minimum | Maximum |
|---|---|---|---|---|---|---|
| Dimethyl phthalate (DMP) | Untreated dumpsite soil | 10 | $0.0190^{b}$ | 0.0161 | < 0.0001 | 0.0567 |
| | Soil only | 9 | $0.0012^{a}$ | 0.0034 | < 0.0001 | 0.0103 |
| | Soil + Jatropha compost | 6 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| | Soil + Ficus compost | 9 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| | Soil + Plant + Jatropha compost | 9 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| | Soil + Plant + Ficus Compost | 6 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| Diethyl Phthalate (DEP) | Untreated dumpsite soil | 10 | $0.1729^{b}$ | 0.0508 | 0.0642 | 0.2322 |
| | Soil only | 9 | $0.1063^{b}$ | 0.1010 | < 0.0001 | 0.2072 |
| | Soil + Jatropha compost | 6 | $0.0822^{ab}$ | 0.1125 | < 0.0001 | 0.2113 |
| | Soil + Ficus compost | 9 | $0.1315^{b}$ | 0.0990 | < 0.0001 | 0.2126 |
| | Soil + Plant + Jatropha compost | 9 | $0.1319^{b}$ | 0.1023 | < 0.0001 | 0.2103 |
| | Soil + Plant + Ficus Compost | 6 | $< 0.0001^{b}$ | 0.0000 | < 0.0001 | 0.0001 |
| Dibutyl phthalate (DBP) | Untreated dumpsite soil | 10 | $1.3914^{b}$ | 0.7413 | 0.3420 | 2.9483 |
| | Soil only | 9 | $0.4884^{a}$ | 0.8965 | 0.0001 | 2.5426 |
| | Soil + Jatropha compost | 6 | $0.2279^{a}$ | 0.3122 | < 0.0001 | 0.5898 |
| | Soil + Ficus compost | 9 | $0.7220^{ab}$ | 0.7661 | < 0.0001 | 2.0642 |
| | Soil + Plant + Jatropha compost | 9 | $0.5937^{a}$ | 0.6377 | < 0.0001 | 1.4572 |
| | Soil + Plant + Ficus Compost | 6 | $0.0001^{a}$ | 0.0000 | < 0.0001 | 0.0001 |
| Benzyl butyl phthalate (BBP) | Untreated dumpsite soil | 10 | $0.0048^{a}$ | 0.0125 | < 0.0001 | 0.0403 |
| | Soil only | 9 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| | Soil + Jatropha compost | 6 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| | Soil + Ficus compost | 9 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| | Soil + Plant + Jatropha compost | 9 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| | Soil + Plant + Ficus Compost | 6 | $< 0.0001^{a}$ | 0.0000 | < 0.0001 | < 0.0001 |
| Di-(2-ethylhexyl) phthalate (DEHP) | Untreated dumpsite soil | 10 | $0.1376^{b}$ | 0.1341 | 0.0106 | 0.4537 |
| | Soil only | 9 | $0.0119^{a}$ | 0.0319 | < 0.0001 | 0.0964 |
| | Soil + Jatropha compost | 6 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| | Soil + Ficus compost | 9 | $0.0389^{a}$ | 0.1144 | < 0.0001 | 0.3439 |
| | Soil + Plant + Jatropha compost | 9 | $0.0369^{a}$ | 0.0689 | < 0.0001 | 0.2066 |
| | Soil + Plant + Ficus Compost | 6 | $0.0054^{a}$ | 0.0058 | < 0.0001 | 0.0106 |
| Dioctyl phthalate (DOP) | Untreated dumpsite soil | 10 | $0.0254^{a}$ | 0.0329 | < 0.0001 | 0.0850 |
| | Soil only | 9 | $0.0165^{b}$ | 0.0263 | < 0.0001 | 0.0710 |
| | Soil + Jatropha compost | 6 | $< 0.0001^{ab}$ | | < 0.0001 | < 0.0001 |
| | Soil + Ficus compost | 9 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| | Soil + Plant + Jatropha compost | 9 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |
| | Soil + Plant + Ficus Compost | 6 | $< 0.0001^{a}$ | | < 0.0001 | < 0.0001 |

Similar superscripts along the column are not significantly different ($p < 0.05$) according to Duncan Multiple Range Test

removal efficiency for DEP and DBP. The removal efficiency of the two composts and the plant ranged from 35 to 100% (Fig. 3), similar to a previous review by Tran et al. [20], which reported a 25% to 100% cleanup of PAEs from polluted soils.

Both Ficus and Jatropha composts achieved maximum removal efficiencies of 100% for DMP, BBP, and DOP. Additionally, both composts had an equal removal efficiency of 68% for DEP. However, Jatropha compost showed slightly better removal efficiency for the degradation of DEHP compared to Ficus compost, which removed 82%. Diethyl phthalate had the lowest removal efficiency for both composts, with Ficus compost showing a slightly higher level (49%) than Jatropha compost (39%).

Using alfalfa (*Medicago sativa* L.), Ma et al. [9] successfully phytoremediated PAEs in contaminated agricultural soils near electrical waste dismantling sites in eastern China. The study achieved a removal of 6 to 87% of the total PAEs in the polluted soils.

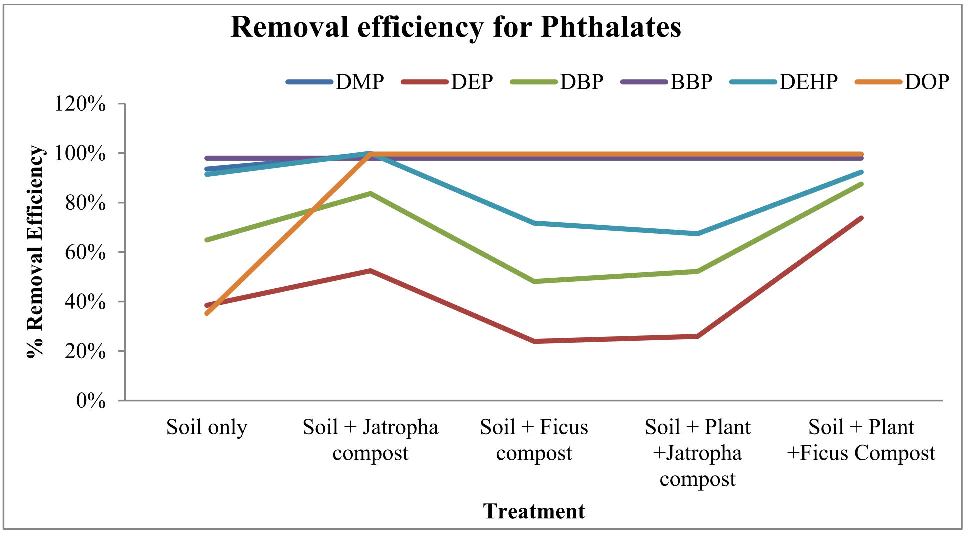


**Fig. 2** Percent removal efficiency by different treatments for phthalate esters. DBP—Dibutyl phthalate, DEP—Diethyl phthalate, DEHP—Di- (2-ethylhexyl) phthalate, DMP—Dimethyl phthalate, DOP—Dioctyl phthalate, BBP—Benzyl butyl phthalate. DMP,BBP and DEHP were mostly and efficiently removed by the two composts

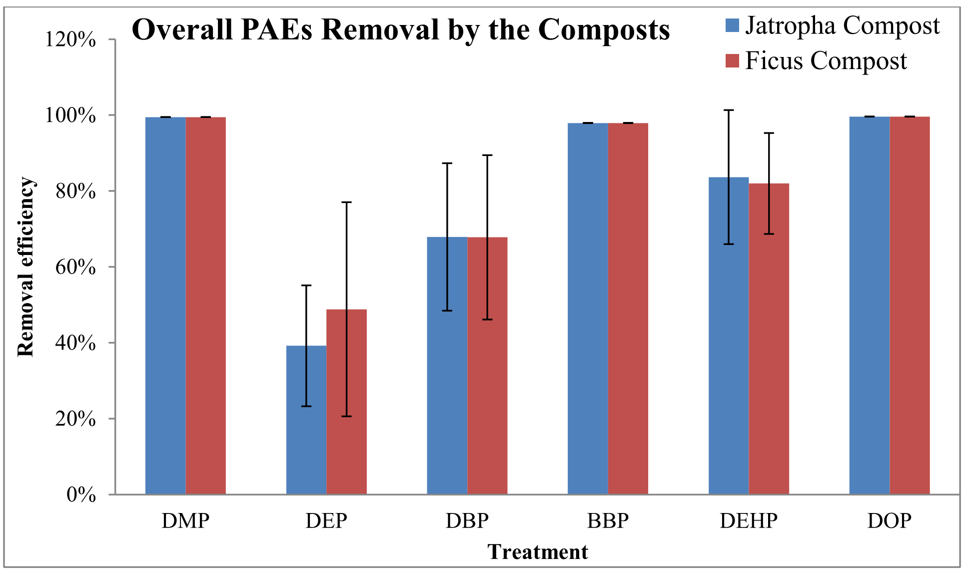


**Fig. 3** The comparison of Ficus and Jatropha composts in the removal of phthalate esters. DBP—Dibutyl phthalate, DEP—Diethyl phthalate, DEHP—Di- (2-ethylhexyl) phthalate, DMP—Dimethyl phthalate, DOP—Dioctyl phthalate, BBP—Benzyl butyl phthalate. DMP, BBP and DEHP were mostly and efficiently removed by the two composts

There was a general decrease in the PAE congeners across different treatments following the addition of Ficus and Jatropha composts. The composts completely removed Dimethyl phthalate (DMP), Benzyl butyl phthalate (BBP), and Dioctyl phthalate (DOP) from the various treatments applied to the dumpsite soils. Additionally, Di-(2-ethylhexyl) phthalate (DEHP) and DBP were completely degraded in the dumpsite soil treated with Jatropha and Plant + Ficus compost, respectively.

### 3.3 Health Risk Assessment of Phthalate Esters

Table 2 presents the combined Hazard Quotient (HQ) values for PAEs in untreated and treated dumpsite soils, to which both adults and children are exposed through ingestion, inhalation, and dermal contact. The individual HQs for each portal of entry in the treated and untreated dumpsite soils in the study area are provided in Tables S1-S3 (in the supplementary information). Notably, the distribution pattern of HQs by portal of entry followed the trend: ingestion > inhalation > dermal contact, which is consistent with previous studies [18],Taiwo et al. 2023). The HQ data suggest no adverse effects, as the values are generally below the permissible limit of 1.0. A related study on the non-carcinogenic risk assessment of PAE congeners in soils from suburban plastic film greenhouses in China indicated HQ values < 1.0 for DBP, DEHP, and DOP [23].

The cumulative effects of individual phthalate ester congeners, represented by the hazard index, are shown in Fig. 4. The mean Hazard Index (HI) for the PAE congeners was also below the threshold limit of 1.0, indicating no carcinogenic health effects, similar to the findings of Zhou et al. [30] on

**Table 2** Combined hazard quotient (HQ) values of phthalate esters in untreated and treated dumpsite soils

| | | Adults | | | | Children | | | |
|---|---|---|---|---|---|---|---|---|---|
| Phthalate ester | Experimental Design | Mean | Std. Deviation | Minimum | Maximum | Mean | Std. Deviation | Minimum | Maximum |
| Dimethyl phthalate (DMP) | Untreated dumpsite soil | 7.7E-09 | 6.5E-09 | 2.1E-11 | 2.3E-08 | 1.3E-07 | 1.1E-07 | 3.4E-10 | 3.8E-07 |
| | Soil only | 4.9E-10 | 1.4E-09 | 2.1E-11 | 4.2E-09 | 8.0E-09 | 2.3E-08 | 3.4E-10 | 6.9E-08 |
| | Soil + Jatropha compost | 2.1E-11 | 9.9E-28 | 2.1E-11 | 2.1E-11 | 3.4E-10 | 7.9E-27 | 3.4E-10 | 3.4E-10 |
| | Soil + Ficus compost | 2.1E-11 | 1.8E-27 | 2.1E-11 | 2.1E-11 | 3.4E-10 | 8.8E-27 | 3.4E-10 | 3.4E-10 |
| | Soil + Plant + Jatropha compost | 2.1E-11 | 1.8E-27 | 2.1E-11 | 2.1E-11 | 3.4E-10 | 8.8E-27 | 3.4E-10 | 3.4E-10 |
| | Soil + Plant + Ficus Compost | 2.1E-11 | 9.9E-28 | 2.1E-11 | 2.1E-11 | 3.4E-10 | 7.9E-27 | 3.4E-10 | 3.4E-10 |
| Diethyl Phthalate (DEP) | Untreated dumpsite soil | 8.4E-07 | 2.5E-07 | 3.1E-07 | 1.1E-06 | 1.4E-05 | 4.0E-06 | 5.1E-06 | 1.8E-05 |
| | Soil only | 5.1E-07 | 4.9E-07 | 0.0E+00 | 1.0E-06 | 8.4E-06 | 8.0E-06 | 0.0E+00 | 1.6E-05 |
| | Soil + Jatropha compost | 3.3E-07 | 5.1E-07 | 0.0E+00 | 1.0E-06 | 5.5E-06 | 8.5E-06 | 0.0E+00 | 1.7E-05 |
| | Soil + Ficus compost | 6.3E-07 | 4.8E-07 | 2.4E-10 | 1.0E-06 | 1.1E-05 | 8.0E-06 | 4.0E-09 | 1.7E-05 |
| | Soil + Plant + Jatropha compost | 4.2E-07 | 5.0E-07 | 0.0E+00 | 1.0E-06 | 7.0E-06 | 8.3E-06 | 0.0E+00 | 1.7E-05 |
| | Soil + Plant + Ficus Compost | 2.4E-10 | 0.0E+00 | 2.4E-10 | 2.4E-10 | 4.0E-09 | 1.3E-25 | 4.0E-09 | 4.0E-09 |
| Dibutyl phthalate (DBP) | Untreated dumpsite soil | 5.4E-05 | 2.8E-05 | 1.3E-05 | 1.1E-04 | 8.8E-04 | 4.7E-04 | 2.2E-04 | 1.9E-03 |
| | Soil only | 1.9E-05 | 3.5E-05 | 1.9E-09 | 9.9E-05 | 3.1E-04 | 5.7E-04 | 3.2E-08 | 1.6E-03 |
| | Soil + Jatropha compost | 7.3E-06 | 1.1E-05 | 0.0E+00 | 2.3E-05 | 1.2E-04 | 1.9E-04 | 0.0E+00 | 3.7E-04 |
| | Soil + Ficus compost | 2.5E-05 | 2.9E-05 | 0.0E+00 | 8.0E-05 | 4.1E-04 | 4.8E-04 | 0.0E+00 | 1.3E-03 |
| | Soil + Plant + Jatropha compost | 1.5E-05 | 2.3E-05 | 0.0E+00 | 5.7E-05 | 2.5E-04 | 3.7E-04 | 0.0E+00 | 9.2E-04 |
| | Soil + Plant + Ficus Compost | 1.9E-09 | 6.3E-26 | 1.9E-09 | 1.9E-09 | 3.2E-08 | 1.0E-24 | 3.2E-08 | 3.2E-08 |
| Benzyl butyl phthalate (BBP) | Untreated dumpsite soil | 3.7E-08 | 9.6E-08 | 3.9E-10 | 3.1E-07 | 6.1E-07 | 1.6E-06 | 6.3E-09 | 5.1E-06 |
| | Soil only | 3.9E-10 | 2.8E-26 | 3.9E-10 | 3.9E-10 | 6.3E-09 | 8.4E-25 | 6.3E-09 | 6.3E-09 |
| | Soil + Jatropha compost | 3.9E-10 | 1.6E-26 | 3.9E-10 | 3.9E-10 | 6.3E-09 | 2.7E-25 | 6.3E-09 | 6.3E-09 |
| | Soil + Ficus compost | 3.9E-10 | 2.8E-26 | 3.9E-10 | 3.9E-10 | 6.3E-09 | 8.4E-25 | 6.3E-09 | 6.3E-09 |
| | Soil + Plant + Jatropha compost | 3.5E-10 | 1.3E-10 | 0.0E+00 | 3.9E-10 | 5.6E-09 | 2.1E-09 | 0.0E+00 | 6.3E-09 |
| | Soil + Plant + Ficus Compost | 3.9E-10 | 1.6E-26 | 3.9E-10 | 3.9E-10 | 6.3E-09 | 2.7E-25 | 6.3E-09 | 6.3E-09 |
| Di-(2-ethylhexyl) phthalate (DEHP) | Untreated dumpsite soil | 2.7E-05 | 2.6E-05 | 2.0E-06 | 8.8E-05 | 4.3E-04 | 4.1E-04 | 3.3E-05 | 1.4E-03 |
| | Soil only | 2.3E-06 | 6.3E-06 | 9.7E-09 | 1.9E-05 | 3.8E-05 | 1.0E-04 | 1.6E-07 | 3.1E-04 |
| | Soil + Jatropha compost | 9.7E-09 | 2.5E-25 | 9.7E-09 | 9.7E-09 | 1.6E-07 | 8.1E-24 | 1.6E-07 | 1.6E-07 |
| | Soil + Ficus compost | 7.6E-06 | 2.2E-05 | 9.7E-09 | 6.7E-05 | 1.2E-04 | 3.7E-04 | 1.6E-07 | 1.1E-03 |
| | Soil + Plant + Jatropha compost | 7.2E-06 | 1.3E-05 | 9.7E-09 | 4.0E-05 | 1.2E-04 | 2.2E-04 | 1.6E-07 | 6.5E-04 |
| | Soil + Plant + Ficus Compost | 1.0E-06 | 1.1E-06 | 9.7E-09 | 2.0E-06 | 1.7E-05 | 1.8E-05 | 1.6E-07 | 3.3E-05 |

vegetable and crop soils from the Huang-Huai-Hai region of China. The HI for PAEs was higher in children than in adults. Furthermore, the HI values for DMP, DEP, DBP, and DOP in soils from tobacco-producing areas in Guizhou Province, southwest China, were all below the acceptable threshold of 1.0.

The cancer risk (CR) values (through ingestion) of Di-(2-ethylhexyl) phthalate, a notable carcinogen in untreated and treated dumpsite soils, are presented in Table 3. The

**Table 2** (continued)

| Phthalate ester | Experimental Design | Adults | | | | Children | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Minimum | Maximum | Mean | Std. Deviation | Minimum | Maximum |
| Dioctyl phthalate (DOP) | Untreated dumpsite soil | 9.8E-06 | 1.3E-05 | 1.9E-08 | 3.3E-05 | 1.6E-04 | 2.1E-04 | 3.2E-07 | 5.4E-04 |
| | Soil only | 6.5E-06 | 1.0E-05 | 1.9E-08 | 2.8E-05 | 1.0E-04 | 1.7E-04 | 3.2E-07 | 4.5E-04 |
| | Soil + Jatropha compost | 1.9E-08 | 5.1E-25 | 1.9E-08 | 1.9E-08 | 3.2E-07 | 1.6E-23 | 3.2E-07 | 3.2E-07 |
| | Soil + Ficus compost | 1.9E-08 | 5.6E-25 | 1.9E-08 | 1.9E-08 | 3.2E-07 | 2.9E-23 | 3.2E-07 | 3.2E-07 |
| | Soil + Plant + Jatropha compost | 1.9E-08 | 5.6E-25 | 1.9E-08 | 1.9E-08 | 3.2E-07 | 2.9E-23 | 3.2E-07 | 3.2E-07 |
| | Soil + Plant + Ficus Compost | 1.9E-08 | 5.1E-25 | 1.9E-08 | 1.9E-08 | 3.2E-07 | 1.6E-23 | 3.2E-07 | 3.2E-07 |

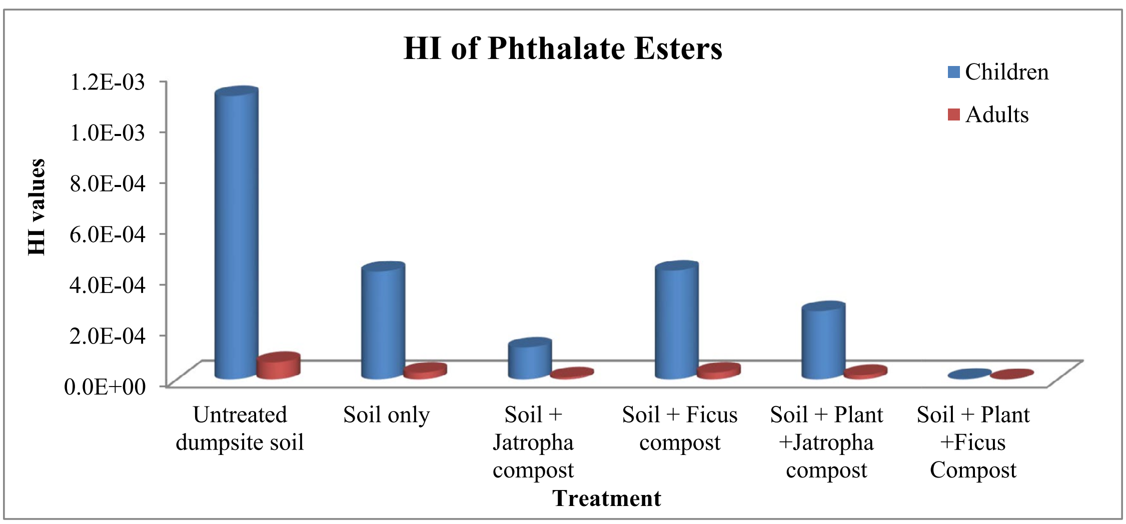


**Fig. 4** Hazard index values of phthalate ester congeners. The HI levels exhibited highest levels for untreated dumpsite soil and lowest for treated soil using combined composts and plants

**Table 3** Cancer risk values of Di-(2-ethylhexyl) phthalate ingested by adults and children in untreated and treated dumpsite soils

| Experimental design | Adults | | | | Children | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Std. Deviation | Minimum | Maximum | Mean | Std. Deviation | Minimum | Maximum |
| Untreated dumpsite soil | 7.5E-09 | 7.3E-09 | 5.7E-10 | 2.5E-08 | 1.2E-07 | 1.2E-07 | 9.4E-09 | 4.0E-07 |
| Soil only | 6.4E-10 | 1.7E-09 | 2.7E-12 | 5.2E-09 | 1.1E-08 | 2.8E-08 | 4.4E-11 | 8.6E-08 |
| Soil + Jatropha compost | 2.7E-12 | 6.2E-29 | 2.7E-12 | 2.7E-12 | 4.4E-11 | 0.0E+00 | 4.4E-11 | 4.4E-11 |
| Soil + Ficus compost | 2.1E-09 | 6.3E-09 | 2.7E-12 | 1.9E-08 | 3.5E-08 | 1.0E-07 | 4.4E-11 | 3.1E-07 |
| Soil + Plant + Jatropha compost | 2.0E-09 | 3.7E-09 | 2.7E-12 | 1.1E-08 | 3.2E-08 | 6.0E-08 | 4.4E-11 | 1.8E-07 |
| Soil + Plant + Ficus Compost | 2.9E-10 | 3.1E-10 | 2.7E-12 | 5.7E-10 | 4.7E-09 | 5.1E-09 | 4.4E-11 | 9.4E-09 |

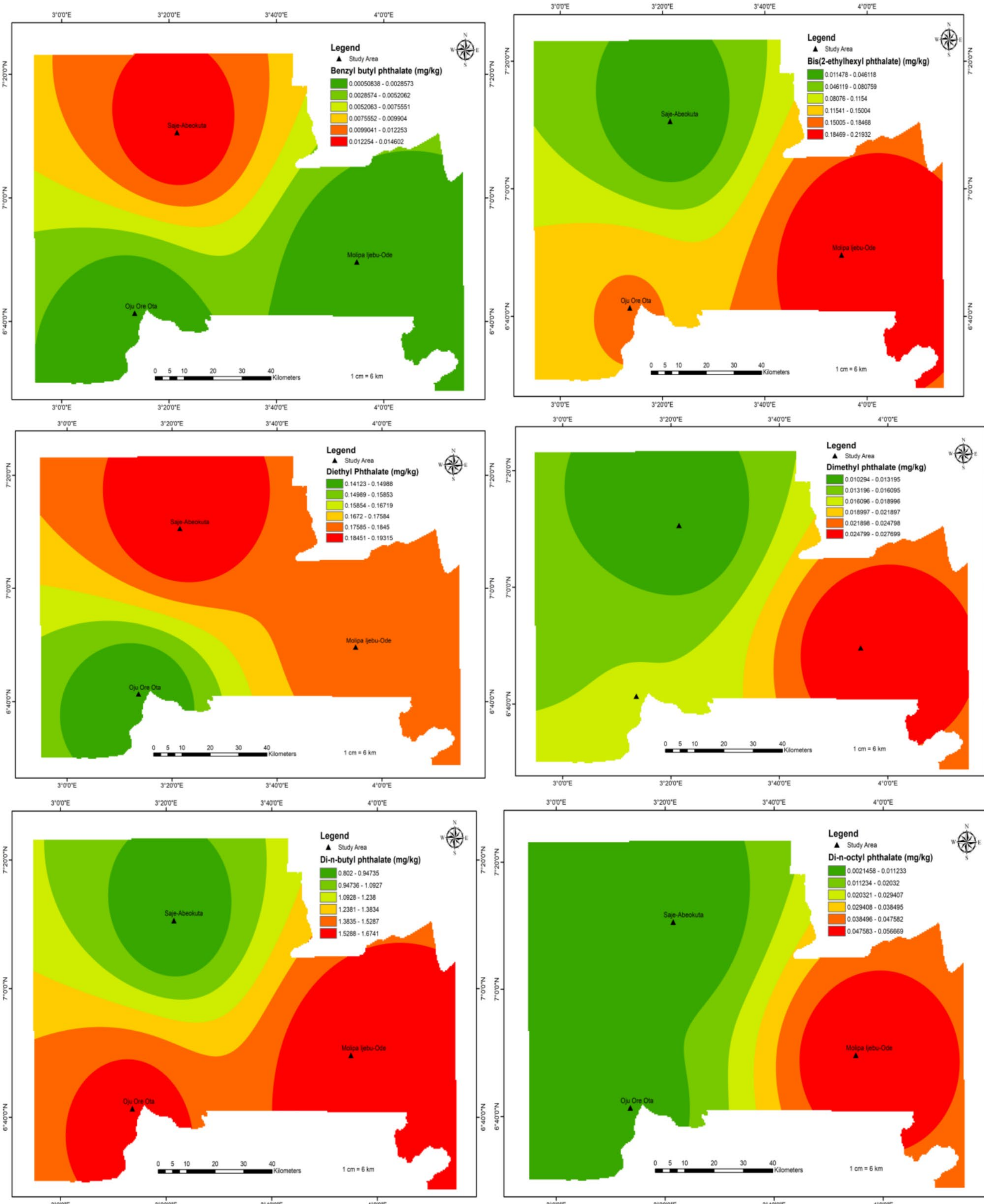


**Fig. 5** Spatial distribution of phthalate esters concentrations in dumpsite soils in the study area. The red colours indicate highest spatial concentrations, while the deep green colours show the lowest spatial levels of PAEs

CR values were generally below the permissible limit of $1.0 \times 10^{-4}$, suggesting no significant carcinogenic health risk. A higher carcinogenic risk value of *ca.* $3.94 \times 10^{-5}$ was observed for DEHP in adults exposed to plastic film greenhouses soils [23]. The study by Xia et al. [25] has reported CR values less than the acceptable limit of $1.0 \times 10^{-4}$ in urban soils of Beijing, China. The study by Ma et al. [10] also showed the no carcinogenic risk for PAEs measured in soil samples from tobacco-producing areas in Guizhou province, southwest China.

### 3.4 Geospatial analysis

The spatial concentrations of phthalate esters in the study area are presented in Fig. 5. Abeokuta indicated hotspots for phthalate esters such as Benzylbutyl phthalate and Diethyl phthalate. Ijebu-Ode showed hotspots for Benzyl butyl phthalate, Di-(2-ethylhexyl) phthalate, and Dioctyl phthalate. Both Ijebu-Ode and Ota dumpsite soils had the highest concentrations of Dibutyl phthalate.

## 4 Conclusion

This study demonstrates that the use of Jatropha and Ficus composts is highly effective in removing phthalate esters (PAEs) from dumpsite soils. Both composts, whether applied alone or in combination with castor oil plants as a complementary treatment, successfully eliminated between 35 and 100% of PAEs from the contaminated soils. Health risk assessment results revealed no significant risks associated with phthalate esters, indicating that they pose no substantial carcinogenic or non-carcinogenic threats. These findings underscore the promising potential of Jatropha and Ficus composts as sustainable solutions for remediating polluted soils. The ability to effectively reduce PAE contamination not only helps in restoring dumpsite soils but also opens up opportunities for their rehabilitation into safe, usable land for agricultural purposes. Thus, this approach offers a viable and eco-friendly method for environmental remediation and agricultural land restoration.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s42250-025-01257-5.

**Acknowledgements** The authors are grateful for the financial support provided by the Tertiary Education Trust Fund (IBR) through Grant Number FUNAAB/DRIP/40, administered by the Federal University of Agriculture, Abeokuta.

**Funding** No funds, grants or other support was received.

**Data availability** All data generated or analyzed during this study are included in this published article [and its supplementary information files].

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** Not applicable.

**Informed consent** Not applicable.

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