



Assessment of Fate and Transport of Mixed Contaminants in Soil: An Incubation Experiment

J. Dharani ^a, E. Parameswari ^{a*}, K. Suganya ^a, P. Malathi ^b and R. Sunitha ^c

^a *Department of Environmental Sciences, Tamilnadu Agricultural University, Coimbatore -03, India.*

^b *Department of Soil Science & Agricultural Chemistry, Tamilnadu Agricultural University, Coimbatore- 03, India.*

^c *Department of Sustainable Organic Agriculture, Tamilnadu Agricultural University, Coimbatore-03, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2022/v12i1130974

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://www.sdiarticle5.com/review-history/89476>

Original Research Article

Received 04 May 2022
Accepted 09 July 2022
Published 12 July 2022

ABSTRACT

A study on fate and transport of mixed contaminants (Cr, Cd and PFOA- Perfluorooctanoic acid) in soil was studied through incubation experiment. The study was carried over in Department of Environmental Sciences, Tamilnadu Agricultural University, Coimbatore between February 2022 and April 2022. The experiment includes 10 treatments with 3 replications and studied for 60 days of incubation. The contaminants (Cr, Cd and PFOA) and amendments (Biochar and humic acid) were spiked in known concentration in the unpolluted soil and analytical methods (physical and chemical properties) carried over to know their degradability, mobility, availability in soil. After 60 days of incubation period, the concentration of chromium, cadmium and PFOA was reduced to 31.5 per cent, 27.5 per cent and 30 per cent respectively. This was due to the addition of organic amendments (Biochar and humic acid). These amendments act as a sorbent in accumulating the contaminants within their pore spaces. Hence the concentration of the contaminants reduced in the soil during the incubation period.

Keywords: Incubation; chromium; cadmium; perfluorooctanoic acid.

1. INTRODUCTION

Soil is considered as an unconsolidated material on the earth's surface that has been exposed to and impacted by the genetic and environmental elements of parent material, as well as climate, creatures and terrain mall of which have acted through time [1]. The major soil available in India is alluvial soil – 43 per cent of any other soil. The paramount soils of Tamilnadu are red loam, laterite, black, alluvial and saline soils. The red loam soil- 62 per cent occupies major part of Tamilnadu especially inner and coastal districts [2]. Environmental pollution is on-going topic of the day and so air, water and soil are being polluted. Soil can be considered as “universal sink” which hold up largest burden of environmental pollution [3]. In recent years, heavy metal contamination in soil is a major issue due to uncontrolled anthropogenic activities. Heavy metals are a class of metals and metalloids with a high density that are harmful even at low concentrations (ppb). Pb, As, Hg, Cd, Zn, Ag, Cu, Fe, Cr, Ni, Pd, and Pt are among examples [4]. Toxic metals (Ni, Cd, Hg, Zn, Pb, and Cr) & minerals (F and As) that cause pollution are currently a major national concern in India. Gujarat, Maharashtra, and Andhra Pradesh are responsible for 80 percent of India's heavy metal pollution [5]. Along with heavy metals, persistent organic pollutant also plays a major role in contaminating the soil. In 2006, India became a party to the Stockholm Convention, which added PFOS (Perfluorooctane sulfonic acid) to its global list of restrictions in 2009. However, India has refused to accept the modification identifying this compound, and it, like other PFAS (Per and polyfluoro Alkyl Substances), is unregulated. In women from Chidambaram, Kolkata, and Chennai, high PFAS levels for PFOS, PFOA (Perfluoro octanoic acid), PFHxS (Perfluoro hexane sulfonic acid), and PFBS (Perfluoro butane sulfonic acid) were discovered in 2008 research. Overall, PFOS levels in Indian breast milk averaged 46 ppt, more than double the health advice limit of 20 ppt for drinking water [6]. In this article, the fate and transport of mixed contaminants which includes Chromium, Cadmium and Perfluorooctanoic acid in unpolluted soil are discussed. The incubation experiment of soil along with above mentioned contaminants have been studied for 60 days.

2. MATERIALS AND METHODS

2.1 Collection of Soil

The unpolluted soil of 60 kg was collected from Eastern block of Tamil Nadu Agricultural University, Coimbatore – 641003. The soil was of clay loam soil. The soil was then sieved in 2mm sieve and dried at room temperature. The initial parameters of the soil including physical, chemical and biological properties were analyzed (Table 3).

2.2 Spiking Soil with Mixed Contaminants and Amendments

The experiment follows 10 treatments with 3 replications. Each pot was filled with 2 kg of soil. For incubation experiment optimum moisture was maintained through alternate wetting and drying method were followed to maintain the moisture of the soil. The water holding capacity of soil was found to be 54%. Accordingly, each pot of soil the moisture was maintained. Cr (III), Cd (II), PFOA, biochar and humic acid at fixed concentration were added according to the treatment details (Table 1). The soil was spread on a plastic sheet. The water with the chemicals and amendments were added little by little and mixed thoroughly by flipping the sheets from four corners. This ensures uniform mixing of all chemicals and amendments in the soil [7].

Table 1. Treatment details of incubation experiment

Treatment details	
T ₁	Absolute Control
T ₂	Heavy metals (Cr@200mg/kg, Cd@ 2mg/kg)
T ₃	PFOA @5 µg/kg
T ₄	Heavy metals + PFOA
T ₅	Heavy metals + Humic acid @ 20kg/ha
T ₆	PFOA + Humic acid @ 20kg/ha
T ₇	Heavy metals + PFOA + Humic acid @ 20kg/ha
T ₈	Heavy metals + Biochar @ 5t/ha
T ₉	PFOA + Biochar @ 5t/ha
T ₁₀	Heavy metals + PFOA + Biochar @ 5t/ha

2.3 Incubation Period

The first three days after spiking was considered to be stabilization stage where the spiked chemicals stabilize in the soil. The incubation period was counted after the stabilization stage completes. During the 30 days of incubation period, the soil was taken for analysis at 15th, 30th, 45th and 60th day for physico- chemical analysis.

2.4 Parameters to be Analyzed

The fate and transport of the mixed contaminants was studied by analyzing the physical, chemical and biological properties of experimental soil (Table 3). The results of the analysis taken at 15th, 30th, 45th and 60th day of analysis were compared with the initial parameters.

2.5 Characterization of Soil

2.5.1 Physical properties of soil

The bulk density and particle density were determined by following Cylinder method [8]. It was determined from the apparent and true volumes of the soil measured by adding a known quantity of water to a measuring cylinder containing a weighed quantity of soil.

2.5.2 Chemical properties of soil

The pH and EC of the soil samples were examined by using digital pH and EC meter respectively [9]. Organic carbon was estimated by following [10] method. Estimation of Calcium and Magnesium is done by following Versenate method.

Total Chromium and total Cadmium was estimated using Microwave Plasma Atomic Emission Spectroscopy (MP- AES). It is an atomic emission technique, once an atom of a specific element is excited, it emits light in a characteristic pattern of wavelengths, as it returns to the ground state. The samples were digested initially in Microwave digestion works by exciting water molecules to tear sample material apart. Adding Aquaregia (3:1 ratio of hydrochloric acid and nitric acid) of about 10 ml added to each sample speeds up the sample homogenization [11].

2.5.2.1 Speciation of heavy metals

Metals can form organic complexes with dissolved organic materials, inorganic complexes

with dissolved anions and free hydrated metal ions in soil solution. Speciation refers to the chemical form in which metals reside in the solid and solution phases of the soil [12].

Determination of chromium and cadmium speciation were carried following the sequential extraction method and determined using MP- AES.

Step 1 (Water soluble fraction): In a 50 ml polypropylene centrifuge tube, one gram of air-dried soil sample was weighed and 25 ml of double distilled water was added. It was shaken for 2 hours at 25°C in an end-over-end shaker. The tubes were then centrifuged for 10 minutes at 8000 rpm and filtered using Whatmann No. 42 filter paper. The amount of soluble Cr and Cd in the water extract was calculated.

Step 2 (Exchangeable fraction): 25 ml of 0.5 M KNO₃ was added to the residue from step 1 and agitated for 16 hours. As described in step 1, centrifugation, filtering, and measurement were carried out.

Step 3 (Organic fractions): 0.5 M NaOH was added to the residue from step 2 and agitated for 16 hours. As described in step 1, centrifugation, filtering, and measurement were carried out.

Step 4 (Organic plus iron – oxide bound fraction): 0.05 M Na₂EDTA was added to the step 3 residue and agitated for 6 hours. As described in step 1, centrifugation, filtering, and measurement were carried out.

Step 5 (Residual fraction): Using a jet of water, the soil residue from step 4 was placed into a 100 mL conical flask and dried in an oven. The contents were digested at 1100° C after 10 mL of strong nitric acid was added. The contents were diluted and filtered using Whatmann No. 4 filter paper after digestion.

Before and after extraction, the tube and contents were weighed to determine the amount of entrapped solution and heavy metal transfer between extractants. The quantity of Cr and Cd extracted by each extractant was estimated independently using the following equation.

$$\text{Cr and Cd extracted } (\mu\text{g g}^{-1}) = C \times (E+M) - (C' \times M) / \text{weight of soil}$$

Where,

C – Concentration of heavy metal in the extraction solution

Table 2. MRM acquisition parameters for the detection of PFOA in LC/MS.

Compound	Precursor (<i>m/z</i>)	Fragment ion (<i>m/z</i>)	Fragment voltage (V)	Collision energy (V)	Dwell time (ms)
PFOA	413	369*	80	1	30
		169	80	12	30

M – Mass (g) of the entrained solution carried over from previous extraction

C' – Concentration of the heavy metal in the extraction solution proceeding step of the sequence

E – Mass (g) of the extractant

2.5.2.2 Perfluorooctanoic acid estimation

PFOA (Perfluorooctanoic acid) was determined using LC/MS (Liquid Chromatography – Mass Spectrometer) – SHIMADZU LC/MS/MS 8040. PFOA was purchased from Sigma Aldrich with 95% purity. The standards were prepared at concentrations of 50, 40, 20, 10, 5, 2, 1 ppb (parts per billion) and the linearity curve arrived. The soil sample were prepared as done by Bugsel and Zwiener [13]. In a 50-mL polypropylene (PP) tube, five grams of soil samples were weighed, and 10 mL MeOH was added. The mixture was vortexed for 2 minutes, sonicated for 10 minutes, and then shaken horizontally for 24 hours. The supernatant was transferred to a 20-mL PP jar using a glass pipette after centrifugation (10 min, 4000 rotation per minute (rpm)). As specified, the extraction was repeated with 10 mL MeOH. The supernatants were mixed, heated to 40 °C, and evaporated with a moderate stream of nitrogen to less than 1 mL. To make the volume 1 mL, pure MeOH was utilised. prior to analysis, the concentrate was placed into a PP vial and centrifuged (10 min, 4000 rpm). Table 2 gives details about the MRM acquisition parameters for the detection of PFOA.

2.5.3 Biological properties of soil

Soil enzyme activity: Urease, phosphatase and dehydrogenase of the soil were determined. For determination of urease Tabatabai and Bremner, 1972 method [14] was adopted. Dehydrogenase was determined using Chendrayan et al. 1980 method [15]. For the determination of phosphatase Tabatabai and Bremner, 1969 method [16] was adopted.

3. RESULTS AND DISCUSSION

The results emanated from the study is discussed here.

3.1 Characteristics of Experimental Soil and Amendment

Before spiking the soil with contaminants (Cr, Cd and PFOA) along with the amendments (Biochar and humic acid), the initial characteristics of soil were analysed (Table 3). From the table, it was evident that the soil and amendments were not contaminated by chromium, cadmium nor PFOA. These contaminants not exceeded the permissible limit and were in below detectable limit. Hence the soil was suitable for incubation experiment.

3.2 Effect of Contaminants and Amendments on Soil pH and EC during Incubation Period

The pH of the soil in the treatments from T₁ to T₄ for 60 days of incubation period was moreover in a stable state. The pH was gradually increased in the treatments T₅ to T₁₀ when compared with T₁ to T₄. This was due to addition of amendments to the soil. Since biochar and humic acid homogenized with the soil, it influenced the chemical properties of the soil.

The EC of the soil when compared with the 15th and 60th showed varied difference. During the initial analysis of the soil, EC of all treatments were similar. After course of time the EC got decreased to 62.5 per cent due to the influence of the contaminants and amendments.

3.3 Effect of Contaminants and Amendments on Soil Organic Carbon on 0th and 60th day of Incubation Period

Comparing the results from 0th and 60th day of soil organic carbon analysis, the organic carbon reduced tremendously for the treatments T₅ to T₁₀, comparing with the treatments T₁ to T₄, when comparing with their initial and final values. The treatments from T₁ to T₄ does not have any of the amendments, hence doesn't showed any variations. The treatments from T₅ to T₁₀ showed huge variation due to the addition of amendments. Collectively, the organic carbon of

the soil was reduced to about 66.37 per cent. Hence this result confirms that the contaminants along with the amendments biochar [17] and humic acid have effect on soil organic carbon.

3.4 Effect of Biochar and Humic acid on Water Soluble Fraction (H₂O Fraction) of Chromium and Cadmium in Soil at Different Incubation Period (mg kg⁻¹)

The concentration of chromium and cadmium had reduced in every treatment. Comparing the treatments with amendments plus contaminants and treatments with only contaminants, the treatments with amendments plus contaminants have reduced in their chromium and cadmium concentration to 38 per cent and 34.5 per cent respectively. This could be as a result of the surface complexation and/or adsorption just on soil particles converting the soluble form of Cr and Cd into insoluble ones [18].

3.5 Effect of Biochar and Humic Acid on Organic Fraction (NaOH Fraction) of chromium and Cadmium in Soil at Different Incubation Period (mg kg⁻¹)

The NaOH – Cr and Cd concentration was observed to steadily decrease over the course of 60 days of incubation. The many physicochemical interactions between Cr, Cd and soil, such as complexation, adsorption, and precipitation, may be too responsible for this drop in concentration [19].

3.6 Effect of Biochar and Humic Acid on Residual Fraction (HNO₃ Fraction) of Chromium and Cadmium in Soil at Different Incubation Period (mg kg⁻¹)

Comparing with the initial and final values taken at 60 days of incubation period, the residual fraction had increased in both chromium and cadmium. The fact that Cr and Cd is immobile may be the cause of its persistence in soil. The sorption of Cr and Cd may have significantly increased the residual proportion of Cr and Cd respectively. Chromium is mostly concentrated in residual fractions [20].

3.7 Effect of Biochar and Humic Acid on Availability of Trivalent Chromium (Cr (III)) and Divalent Cadmium (Cd (II))

Comparing all the treatments, T₇ and T₁₀ had significantly reduced the availability of cadmium and chromium in soil respectively. The humic acid in T₇ which contains mixed contaminants, had specifically decreased cadmium [21] to lower concentration than chromium. The biochar in T₁₀ which contains mixed contaminants, had specifically decreased chromium to lower concentration than cadmium. But both the biochar and humic acid had a great influence in reducing the chromium and cadmium in the soil. This may be due to reduced mobility and transport of heavy metals in the soil influenced by organic amendments [22]. The concentration of chromium and cadmium was reduced to 31.5 and 27.5 per cent respectively.

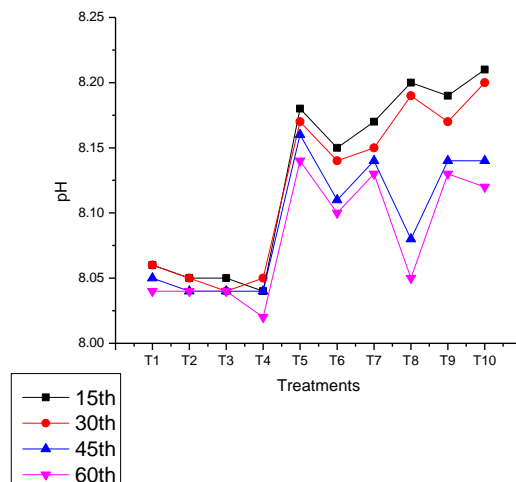


Fig. 1. Effect of contaminants and amendments on soil pH during incubation period

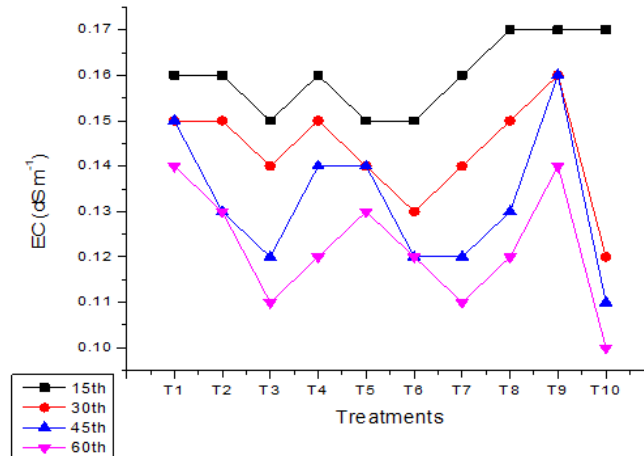


Fig. 2. Effect of contaminants and amendments on soil EC during incubation period

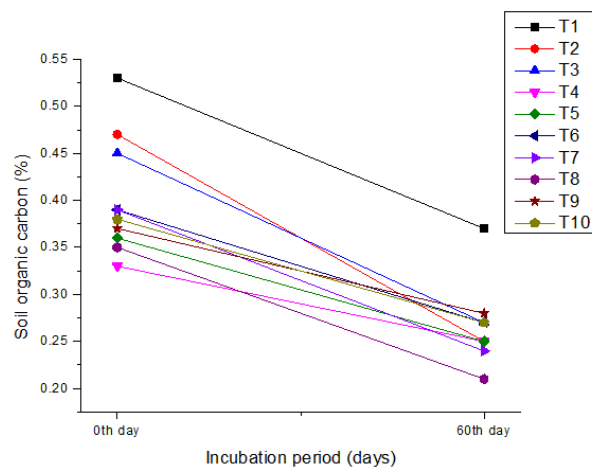


Fig. 3. Effect of contaminants and amendments on soil organic carbon on 0th and 60th day of incubation period

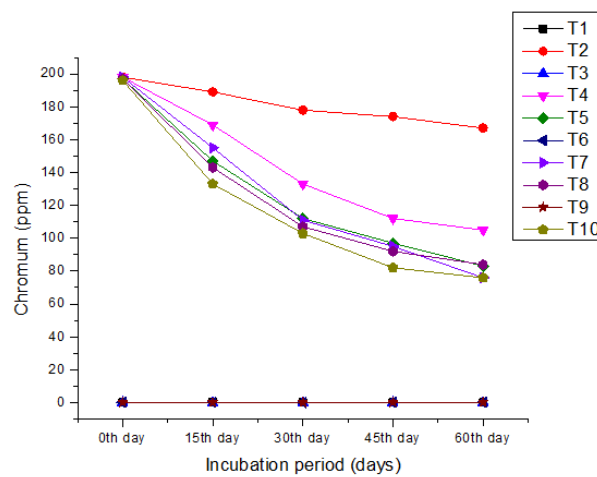


Fig. 4. Effect of biochar and humic acid on water soluble fraction (H₂O fraction) of chromium in soil at different incubation period (mg kg⁻¹)

Table 3. Initial characteristics of experimental soil and amendments

Parameters	Soil	Biochar	Humic acid
Physical properties			
Bulk density (g cm ⁻³)	1.11	0.49	1.75
Particle density (g cm ⁻³)	2.5	0.28	1.26
Chemical properties			
pH	8.06	8.56	6.20
Electrical Conductivity (dS m ⁻¹)	0.16	0.87	1.42
Organic carbon (%)	0.54	9.49	21.0
Available nitrogen (kg ha ⁻¹)	149.7	-	-
Available phosphorus (kg ha ⁻¹)	12.1	-	-
Available potassium (kg ha ⁻¹)	226	-	-
Total nitrogen (%)	-	18	4
Total phosphorous (%)	-	2.89	1.21
Total potassium (%)	-	18	10
Exchangeable Ca (cmol (P ⁺) kg ⁻¹)	6.23	-	-
Exchangeable Mg (cmol (P ⁺) kg ⁻¹)	2.67	-	-
Exchangeable Na (cmol (P ⁺) kg ⁻¹)	1.34	-	-
Total Cadmium	BDL*	BDL*	BDL*
Total Chromium	BDL*	BDL*	BDL*
PFOA	BDL*	BDL*	BDL*
Biological properties			
Urease (µg of NH ₄ -N released g ⁻¹ of soil day ⁻¹)	13.5	-	-
Phosphatase (µg p-Nitrophenyl Phosphate g ⁻¹ of soil)	11.4	-	-
Dehydrogenase (µg triphenyl formazan g ⁻¹ of soil)	9.3	-	-

BDL* - Below detectable level

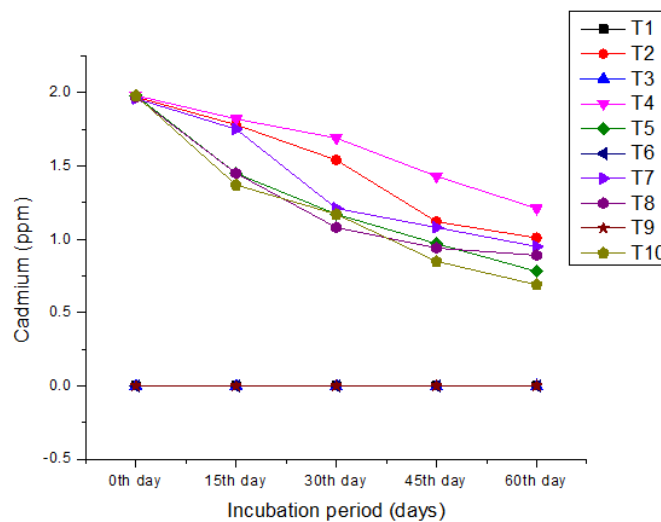


Fig. 5. Effect of biochar and humic acid on water soluble fraction (H₂O fraction) of cadmium in soil at different incubation period (mg kg⁻¹)

The exchangeable fractions and organic plus iron – oxide bound fractions of chromium and cadmium was found below detectable limit. This may be caused by the quick conversion of exchangeable Cr and Cd to organic form or by adsorption on highly maintained exchangeable

sites in the soil [23,24]. It's also possible that the Cr and Cd ions got into the pore spaces of the biochar and humic acid. The availability of chromium and cadmium thus reduced in the soil during the incubation experiment and the major influence was created by the amendments.

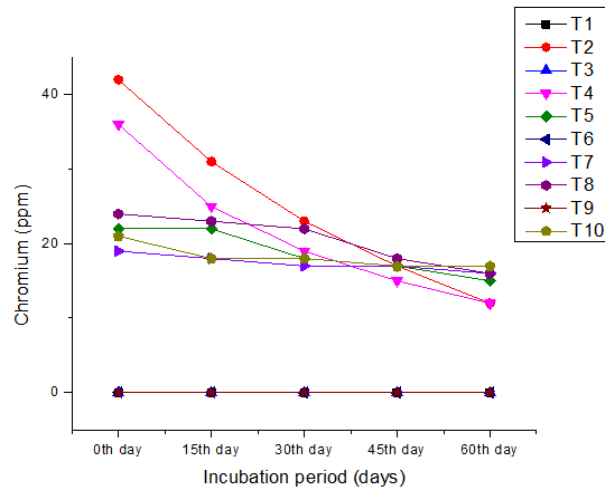


Fig. 6. Effect of biochar and humic acid on organic fraction (NaOH fraction) of chromium and in soil at different incubation period (mg kg^{-1})

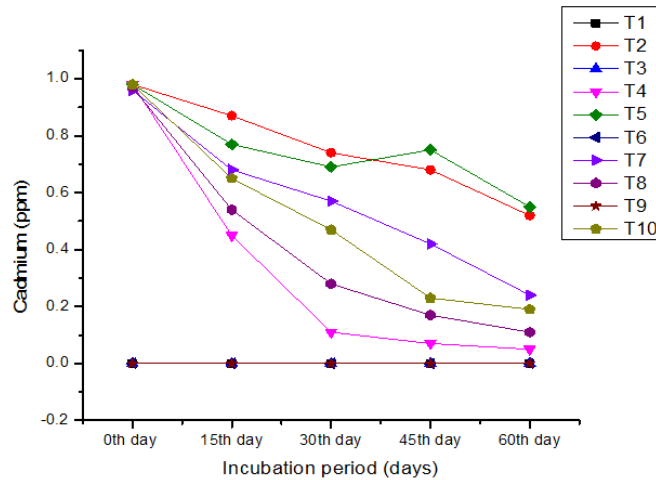


Fig. 7. Effect of biochar and humic acid on organic fraction (NaOH fraction) of cadmium and in soil at different incubation period (mg kg^{-1})

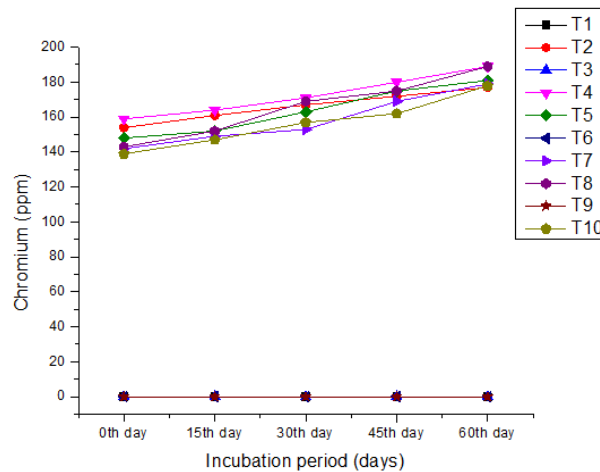


Fig. 8. Effect of biochar and humic acid on residual fraction (HNO_3 fraction) of chromium in soil at different incubation period (mg kg^{-1})

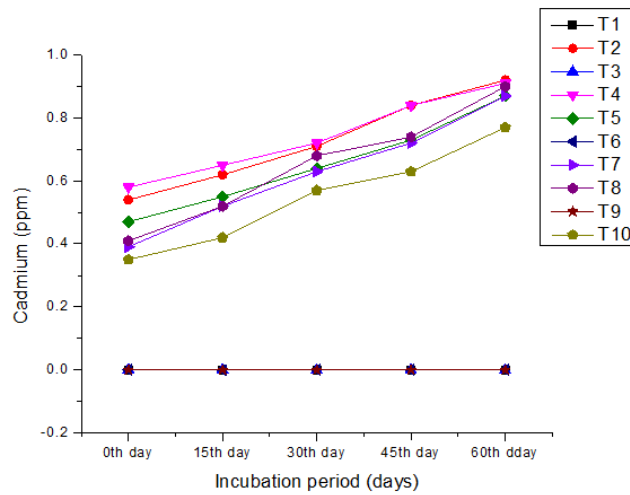


Fig. 9. Effect of biochar and humic acid on residual fraction (HNO_3 fraction) of cadmium in soil at different incubation period (mg kg^{-1})

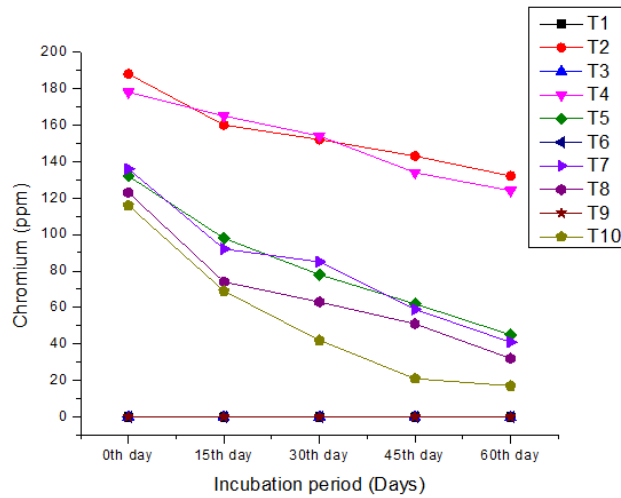


Fig. 10. Effect of biochar and humic acid on availability of trivalent chromium (Cr (III))

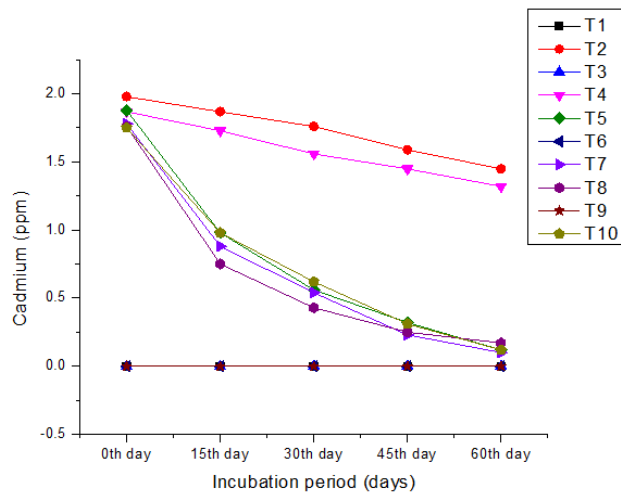


Fig. 11. Effect of biochar and humic acid on availability of divalent cadmium (Cd (II))

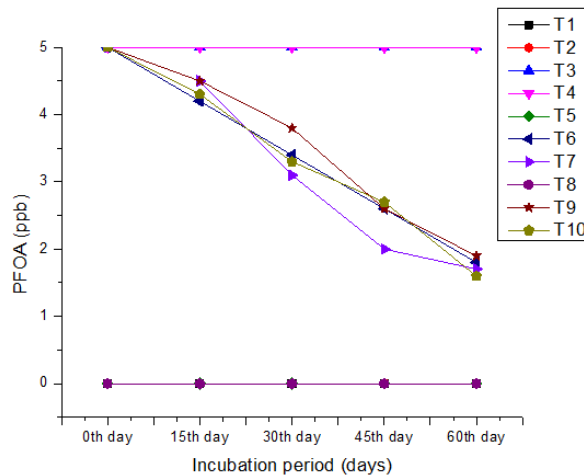


Fig. 12. Effect of biochar and humic acid on availability of Perfluorooctanoic acid (PFOA)

3.8 Effect of Biochar and Humic Acid on Availability of Perfluorooctanoic Acid (PFOA)

The treatments T₃ and T₄ doesn't show any reduction in the concentration of PFOA. Though PFOA is water soluble, it does not bind well with the soil. Hence it is extremely resistant to environmental degradation [25]. The treatments with biochar (T₉ and T₁₀) showed reduction in PFOA concentration. Biochars are considered potential sustainable sorbents to reduce the per- and polyfluoroalkyl substances (PFAS) from contaminated soils [26]. The humic acid contributes to contaminant removal individually or in combination with other mineral adsorbents [27]. The PFOA concentration was reduced to 30 per cent at the end of the incubation period. The reduction in concentration was greatly influenced by the addition of amendments.

4. CONCLUSION

The use of amendments biochar and humic acid have significantly reduced the concentration of the mixed contaminants (Cr, Cd and PFOA). The contaminants easily transported into the pore spaces of the amendments during the incubation period and the concentration reduced during incubation period. Rather than the amendment treatments, the contaminants (Cr and Cd) concentration reduced due to their degradability, solubility property in the medium (soil and water).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Abdulkadir A, Lawal AM, Muhammad TI. Climate change and its implications on human existence in Nigeria: a review. *Bayero Journal of Pure and Applied Sciences*. 2017;10(2):152-8.
2. Department of Land Resources, Government of India. Available: <https://dolr.gov.in/sites/default/files/TAMILNADU%20STATE%20PERSPECTIVE%20%26%20STRATEGIC%20PLAN.pdf>
3. Ashraf MA, Maah MJ, Yusoff I. Soil contamination, risk assessment and remediation. *Environmental Risk Assessment of Soil Contamination*. 2014 Mar 26;1:3-56.
4. Duruibe JO, Ogwuegbu MO, Ekwurugwu JN. Heavy metal pollution and human biotoxic effects. *International Journal of Physical Sciences*. 2007 May 1;2(5):112-8.
5. Kumar V, Sharma A, Kaur P, Sidhu GP, Bali AS, Bhardwaj R, Thukral AK, Cerda A. Pollution assessment of heavy metals in soils of India and ecological risk assessment: A state-of-the-art. *Chemosphere*. 2019 Feb 1;216:449-62.
6. Indian PFAS Situation Report – 2019 – IPEN.org. Available: https://ipen.org/sites/default/files/documents/india_pfas_country_situation_report_mar_2019.pdf
7. Chen L, Larson SL, Ballard JH, Ma Y, Zhang Q, Li J, Wu L, Arslan Z, Han FX. Laboratory spiking process of soil with various uranium and other heavy metals. *MethodsX*. 2019 Jan 1;6:734-9.

8. Piper CS. Soil and plant analysis. Scientific Publishers; 2019.
9. Jackson ML. Soil chemical analysis prentice hall of Indian Private Limited. New Delhi; 1973.
10. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*. 1934 Jan 1;37(1):29-38.
11. Ozkan A, Uygur V. Determination of Heavy Metal Concentrations in Agricultural Lands of Amik Plain with MP-AES. *Fresenius Environmental Bulletin*. 2019 Jan 1;28(1):416-25.
12. Beckett PH. The use of extractants in studies on trace metals in soils, sewage sludges, and sludge-treated soils. In *Advances in Soil Science*. Springer, New York, NY. 1989;143-176.
13. Bugsel B, Zwiener C. LC-MS screening of poly-and perfluoroalkyl substances in contaminated soil by Kendrick mass analysis. *Analytical and Bioanalytical Chemistry*. 2020 Aug;412(20):4797-805.
14. Tabatabai MA, Bremner JM. Assay of urease activity in soils. *Soil Biology and Biochemistry*. 1972 Nov 1;4(4):479-87.
15. Chendrayan K, Adhya TK, Sethunathan N. Dehydrogenase and invertase activities of flooded soils. *Soil Biology and Biochemistry*. 1980 Jan 1;12(3):271-3.
16. Tabatabai MA, Bremner JM. Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. *Soil Biology and Biochemistry*. 1969 Nov 1;1(4):301-7.
17. Steinbeiss S, Gleixner G, Antonietti M. Effect of biochar amendment on soil carbon balance and soil microbial activity. *Soil Biology and Biochemistry*. 2009 Jun 1;41(6):1301-10.
18. Bradl HB. Adsorption of heavy metal ions on soils and soils constituents. *Journal of Colloid and Interface Science*. 2004 Sep 1;277(1):1-8.
19. Caporale AG, Violante A. Chemical processes affecting the mobility of heavy metals and metalloids in soil environments. *Current Pollution Reports*. 2016 Mar;2(1):15-27.
20. Kotoky P, Bora BJ, Baruah NK, Baruah J, Baruah P, Borah GC. Chemical fractionation of heavy metals in soils around oil installations, Assam. *Chemical Speciation & Bioavailability*. 2003 Jan 1;15(4):115-26.
21. Zhao K, Yang Y, Peng H, Zhang L, Zhou Y, Zhang J, Du C, Liu J, Lin X, Wang N, Huang H. Silicon fertilizers, humic acid and their impact on physicochemical properties, availability and distribution of heavy metals in soil and soil aggregates. *Science of The Total Environment*. 2022 May 20;822:153483.
22. Sherene T. Mobility and transport of heavy metals in polluted soil environment. In *Biological forum—an international journal* 2010 (Vol. 2, No. 2, pp. 112-121).
23. Renella G, Adamo P, Bianco MR, Landi L, Violante P, Nannipieri P. Availability and speciation of cadmium added to a calcareous soil under various managements. *European Journal of Soil Science*. 2004 Mar;55(1):123-33.
24. Ogundiran MB, Osibanjo O. Mobility and speciation of heavy metals in soils impacted by hazardous waste. *Chemical Speciation & Bioavailability*. 2009 Jan 1;21(2):59-69.
25. Post GB, Cohn PD, Cooper KR. Perfluorooctanoic acid (PFOA), an emerging drinking water contaminant: a critical review of recent literature. *Environmental research*. 2012 Jul 1;116:93-117.
26. Sørmo E, Silvani L, Bjerkli N, Hagemann N, Zimmerman AR, Hale SE, Hansen CB, Hartnik T, Cornelissen G. Stabilization of PFAS-contaminated soil with activated biochar. *Science of the Total Environment*. 2021 Apr 1;763:144034.
27. Wang F, Shih K, Leckie JO. Effect of humic acid on the sorption of perfluorooctane sulfonate (PFOS) and perfluorobutane sulfonate (PFBS) on boehmite. *Chemosphere*. 2015 Jan 1;118:213-8.

© 2022 Dharani et al.; This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:

The peer review history for this paper can be accessed here:
<https://www.sdiarticle5.com/review-history/89476>