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Impact of Bushfire on Soil Heavy Metals in Oil Palm Plantations in Edo State, Nigeria

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HIGHLIGHTS

- Bushfire is a significant environmental disturbance in oil palm plantations.
- Bushfire has significant positive impacts on the heavy metals.
- The concentrations of the heavy metals were enhanced in the burnt oil palm plantation.
- Further studies on the ecological risks of heavy metals in oil palm plantations affected by bushfires are needed.

Abstract

The research examined the impact of bushfires on soil heavy metals in oil palm plantations in Edo State, Nigeria. The objectives of the study were to determine the concentration levels of heavy metals in the unburnt and burnt oil palm plantations, analyze significant differences in the soil heavy metals between both sites, and find out if bushfire has significant positive or negative impacts on the heavy metals. Soil samples were collected from the topsoil of the unburnt and burnt oil palm plantations, and were analyzed for lead (Pb), cadmium (Cd), cobalt (Co), chromium (Cr), nickel (Ni), arsenic (As), and vanadium (V). Data were analyzed using descriptive (range, mean, standard deviation, and coefficient of variation) and inferential (Student t-test) statistics. The impact of bushfires was statistically tested by comparing each heavy metal in unburnt and burnt oil palm plantations. The findings revealed that the concentrations of Pb (15.15 mg kg^{-1}), Cd (0.20 mg kg^{-1}), Co (5.09 mg kg^{-1}), Cr (6.52 mg kg^{-1}), Ni (5.42 mg kg^{-1}), As (3.19 mg kg^{-1}), and V (2.12 mg kg^{-1}) were higher in the burnt oil palm plantation. Statistically significant differences in heavy metal concentrations were observed between both sites, and the findings also indicated that bushfires have significant positive impacts on Pb, Cd, Co, Cr, Ni, As, and V. Overall, bushfire enhanced the concentrations of heavy metals in oil palm plantations. These findings can aid in the formulation of soil quality management strategies for tropical oil palm plantations affected by bushfires.

Keywords: Fire; heavy metals; oil palm plantations; soil quality

1. Introduction

Bushfires are major environmental disturbances in many ecosystems around the world (Carrión-Paladines et al. 2022). The increase in bushfire incidents over the last ten years and its impending danger will have overwhelming ecological consequences (Fennema 2021). Bushfire is regarded as one of the most damaging

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disorders in flora biomes that affect soil quality properties and ecosystem fitness (Dhungana et al. 2024). Bushfires severely affect vegetation ecosystems due to the elimination of the undergrowth and changes in soil quality indicators (Lucas-Borja et al. 2022). Bushfire may leave short-term effects on soil fertility indicators or cause enduring and irremediable changes in soil quality (Ershad et al. 2013). The concept of soil quality can be defined as the ability of a particular soil type, after disturbance in a natural or managed biome, to sustain flora and fauna efficiency, boost water and air quality, and support human health and dwelling (Xifré-Salvadó et al. 2021). Soils can be affected by bushfire through ash deposition, combustion of flora and soil cover, or post-fire erosion (Fernandez-Marcos 2022). However, bushfires may impact particular soil properties contrarily having positive, negative, or neutral effects (Dhungana et al. 2024).

The majority of studies have investigated the impact of bushfires on soil heavy metals in different ecosystems and climates. De Marco et al. (2005) reported that Cd and Pb had significantly increased higher in burnt soils. Bogacz et al. (2011) observed higher contents of Cu, Pb, Ni and Cr in soils affected by bushfires in Lower Silesia (Poland). Stankov Jovanovic et al. (2011) noted that Pb contents were higher in burnt soils comparative to unburnt soils from Vidlic Mountain in Serbia. In *Eucalyptus globulus Labill*. and *Pinus pinaster Ait.* Plantations, Campos et al. (2016) observed significantly higher contents of V, Ni, Cd, and Pb in burnt soils compared to unburnt soils. In the Lviv region (Ukraine), Popovych and Gapalo (2021) reported significant accumulation of Cd in edaphic horizons. Baieta et al. (2022) observed that there was a significant accumulation of Pb in the topsoil. In Naples (Southern Italy), high V contents in forest and bushfire forest soils were reported by Panico et al. (2023). Despite the large and growing body of literature on the impacts of bushfire on heavy metals, the response of heavy metals such as Pb, Cd, Co, Cr, Ni, As, and V to bushfire in oil palm plantations in the tropics is not well known because specific investigations are lacking.

Annually, bushfire occurrences are prevalent in most parts of Nigeria, mainly during the dry season (Orobator and Odjugo 2023), and it has been a significant part of the evolutionary history of most savannah and woodland biomes (Orobator, 2022; Orobator and Ugwa, 2023). Oil palm plantations in Nigeria are major ecosystems affected by bushfires, primarily caused by human agricultural burning. Orobator and Odjugo (2024) reported that the locals carry out bush burning as a customary pre-planting farming practice. In addition to affecting the physicochemical and biological properties of soil, bushfires can produce or discharge heavy metals in the soil (Fernandez-Marcos 2022). After a bushfire, the remained ash comprises variable quantities of heavy metals (Pitman 2006). Furthermore, various studies (Burton et al. 2016; Kristensen et al. 2014; Odigie and Flegal 2011, 2014, etc.) have stated that bushfires have the capacity to release heavy metals from their sequestered stages in soil. The incidence in soil of heavy metals causes a decline in soil quality and establishes a risk to the health of the soil ecosystem when the soil becomes contaminated (Fernandez-Marcos, 2022). Knowledge on the response of heavy metals to bushfire is valuable to comprehend their role in the post-fire restoration of the soil quality of oil palm plantations. The lack of empirical data makes it challenging to comprehend and predict the bushfire impact on soil heavy metals in oil palm plantations. Empirical investigations are required to cover this research gap. To achieve this, the present study examined the impacts of bushfires on the heavy metals of soil in oil palm plantations in Edo State, Nigeria.

The research specifically aims to achieve three key objectives. Firstly, it seeks to determine the concentration levels of Pb, Cd, Co, Cr, Ni, As, and V in both unburnt and burnt oil palm plantations. Secondly, it aims to examine whether there are significant differences in soil heavy metal concentrations between the unburnt and burnt plantations. Lastly, the study intends to assess whether bushfires have significant positive or negative impacts on the levels of these heavy metals (Pb, Cd, Co, Cr, Ni, As, and V).

The research hypothesized that there are no significant differences in Pb, Cd, Co, Cr, Ni, As, and V between the unburnt and burnt oil palm plantations. The novelty of the current study is that it exemplifies a first attempt to examine the impact of bushfire on soil heavy metals in oil palm plantations. The outcomes should give agriculturists, environmentalists, biogeographers, fire ecologists, and soil scientists insights about the expected impacts of bushfire on soil heavy metals in oil palm plantations. Furthermore, the research culminations should be beneficial for initiating policies and collaborating on strategies for improved management of oil palm plantation ecosystems affected by bushfire. The outcomes of the study will significantly support achieving the following Sustainable Development Goals (SDG's): i. SDG 2 (Zero Hunger), soil contaminated with heavy metals affects the safety and yield of oil palm plantations, which are vital for the production of food and livelihood; ii. SDG 3 (Good Health and Well-being), higher concentrations of heavy metals in soils caused by bushfires pose health risks via food chains or groundwater pollution, and iii. SDG 12 (Responsible Consumption and Production) emphasizes the connection between the accumulation of heavy metals in the soil and chemical safety and ecological stewardship, ensuring that agricultural practices are both sustainable and safe.

2. Materials and Methods

2.1. Study area

The study was carried out in Okunuvbe community, Ovia North East Local Government, Edo State, Nigeria, and it is located within Latitudes 6° 37' 5.24'' N - 6° 36' 46.97'' N and Longitudes 5° 45' 53.88'' E - 5° 45' 49.16'' E (Figure 1). Okunuvbe community is spatially bounded by Odiguete village to the north and Igbakhue village to the southwest, and is approximately 37 km from the capital city of Benin. The study area belongs to the Af category of Koppen's climatic classification. The climate is tropical, characterized by relatively wet and dry seasons. The soils are the coastal plain sands, which are extensive red yellow, weathered, and loose, ill-sorted sands overlying the Bendel-Ameki group (Fagbami and Fapohunda, 1986). The topography of Okunuvbe is relatively flat, with an average elevation of 44 m above sea level, and it is drained by River Okhuo, a tributary to the Ovia River, which is the largest and longest river in Edo State. Oil palm (*Elaeis guineeensis*) and rubber trees (*Hevea brasiliensis*) are the major perennial tree crops cultivated in the study area. Trees such as Mahogany (*Swietenia macrophylla*) and Iroko (*Milicia excelsa*) are also scattered within the area. *Andropogon spp, Pennisetum spp* and *Chromolaena odoranta* are the prevalent grass species in the Okunuvbe community.

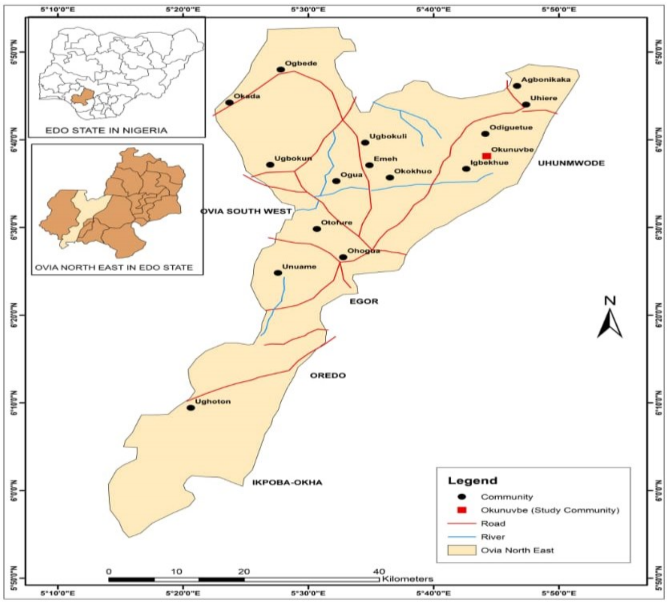

Figure 1. Location of study area

2.2. Fieldwork

Two oil palm plantations (unburnt and burnt) located next to each other and situated in the Okunuvbe community were adopted for the study. The choice of unburnt and burnt oil palm plantations enabled comparisons of Pb, Cd, Co, Cr, Ni, As, and V between the two study sites. Using a grid sampling design, a sampled area measuring 100 × 100 m was mapped out for the collection of disturbed soil samples from both the unburnt and burnt oil palm plantations, respectively (Figure 2). Adopting the systematic random methodology, the soil samples were collected at a distance of 15 m apart from each sampling point with the aid of a soil auger at a depth of 0 -15 cm (topsoil). It is well known that the burning process can affect soil properties down to 15 cm soil depth (Terzano et al. 2021). Ten (10) soil samples were collected, each from the burnt and unburnt oil palm plantations. Consequently, a total of twenty (20) soil samples were collected for the purpose of the study. The soil samples collected from the unburnt oil palm plantation served as the control soil samples, while the soil samples collected from the burnt oil palm plantation were the treatment samples. The number of soil samples collected is based on the similarity of soil type, vegetation, and climatic characteristics of the control and treatment plots (Ozgeldinova et al. 2025).

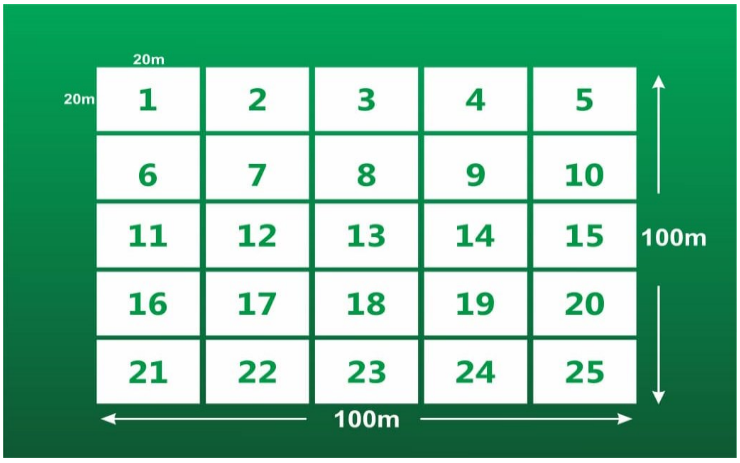

Figure 2. Grid sampling design; Sample area (100 m x 100 m) and plot size (20 m x 20 m) within each oil palm plantation

2.3 Laboratory analysis

Laboratory analysis was undertaken to determine the concentrations of lead (Pb), cadmium (Cd), cobalt (Co), chromium (Cr), nickel (Ni), arsenic (As), and vanadium (V) in the soils of the unburnt and burnt oil palm plantations. The soil samples were air-dried in the laboratory for 72 hours. 5 g of the dried sieved soil from the soil samples was digested with HNO_3-HCl according to USEPA method 3050B to extract the metals (Orobator et al. 2019). The concentrations of Pb, Cd, Co, Cr, Ni, As, and V were measured by Perkin-Elmer Analyst 300 Atomic Absorption 6 Spectrophotometer (AAS), and amounts obtained were reported in mg kg-1 (Khodadoust et al. 2004).

2.4. Statistical analysis

Data of Pb, Cd, Co, Cr, Ni, As, and V contents were analyzed by means of PC applications for the Statistical Package for Social Sciences and Excel. To achieve the objectives of the research, both the descriptive (range, mean, standard deviation and coefficient of variation) and inferential (Student t-test) statistics were adopted. Descriptive statistics revealed that substantial variation exists in the contents of the studied soil parameters between sampling locations (Budak, 2018). Student t-test was used to identify statistically significant differences in heavy metal concentrations between the unburnt and burnt oil palm plantations. This was achieved by comparing the means of each heavy metal between the unburnt and burnt oil palm plantations. The outcomes aided in determining the significant positive or negative impacts of bushfires on heavy metals. Significant levels were designated as significant ($p < 0.05$) and non-significant ($p > 0.05$), respectively.

3. Results and Discussion

3.1. Lead (Pb)

Lead (Pb), a naturally occurring chemical element in the carbon group, is also a heavy metal (Niu et al., 2023). In the burnt oil palm plantation, the Pb values ranged from 10.41 to 22.40 mg kg^{-1} with a mean of 15.15

mg kg^{-1} and a standard deviation of 4.09, while in the unburnt oil palm plantation, it ranged from 10.38 to 14.04 mg kg^{-1}, with a mean of 11.87 mg kg^{-1} and a standard deviation of 1.37 (Table 1).

The results showed that Pb concentrations were higher in the burnt oil palm plantation (15.15 mg kg-1) than the unburnt oil palm plantation (11.87 mg kg^{-1}). Oil palm plantation floor is characterized by a blend of organic materials, and the higher Pb contents in the burnt oil palm plantation soils may be due to mineralization of the organic materials caused by the bushfire (Santorufo et al. 2021). Similarly, the presence of ash in the soils of the burnt oil palm plantation may also account for higher Pb contents. The accretion of Pb in soils through ash deposition on soil due to bushfire is predictable (Stankov Jovanovic et al. 2011). Solid wastes from palm oil mills are empty fruit bunches (EFB), which can be utilized as mulch on oil palm plantation soils. The mulch and inorganic fertilizer used can contain Pb (Winarko et al., 2024). This may account for the occurrence of Pb in the unburnt oil palm plantation. The detected values of Pd in both oil palm plantations were below the WHO permissible limit of 85.00 mg kg^{-1}. This inferred that Pb concentrations in the soils are not toxic. The response of Pb in this study mirrors the findings of Bartkowiak and Lemanowicz (2017), who reported higher Pb concentrations in burnt soils. Our results also accord with a previous study of Bogacz et al. (2011), who reported higher levels of Pb in both topsoil and subsoil. However, the outcomes of the research contradicted Panico et al., (2023), who reported lower levels of Pb in burnt forest (2.6 mg kg-1) compared to forest (4.1 mg kg^{-1}) and urban (14.9 mg kg^{-1}) areas. The higher Pb contents in the burnt oil palm plantation diminish the positive impacts of bushfire on Pb in the oil palm plantation. The significant difference ($p < 0.05$) in Pb contents between both oil palm plantations inferred that Pb was considerably higher in burnt oil palm plantations, and the positive impact of bushfire on Pb was significant. Pb also showed significant changes in the standard deviation values when comparing the two oil palm plantations (1.37to 4.09). In agreement with the research, Rao et al. (2024) reported that Pb concentration was significantly higher ($p < 0.05$).

3.2. Cadmium (Cd)

Cadmium (Cd) is a malleable metal that appears as a bluish or silvery-white powder (Charkiewicz et al. 2023). Among all non-essential heavy metals, cadmium (Cd) is likely the one that has garnered the most attention in soil science and plant nutrition, owing to its potential toxicity to humans and its relatively high mobility within the soil-plant system (McLaughlin and Singh 1999). In the burnt oil palm plantation, the Cd values ranged from 0.15 to 0.33 mg kg-1 with a mean of 0.20 mg kg-1 and a standard deviation of 0.06, while in the unburnt oil palm plantation, it ranged from 0.08 to 0.19 mg kg-1, with a mean of 0.15 mg kg-1 and a standard deviation of 0.03 (Table 1). The results revealed that Cd contents were higher in the burnt oil palm plantation (0.20 mg kg-1) than the unburnt oil palm plantation (0.15 mg kg-1). The observed higher Cd may be as a result of the vertical migration nature of Cd in the soil ecosystem, consequent on ash subsidence in the burnt biome (Smith et al. 2011). Cd increases in soils are associated with the burning of biomass involved in bushfires (Pacifico et al., 2023). Cd concentrations in the environment can be caused by bushfires, and bushfire-induced increases in the concentrations of Cd in soils and ashes have been noted by Demeyer et al. (2001) and Campos et al. (2016). The incidence of Cd in the unburnt oil palm plantation may be due to the application of fertilizers on the soil. Superphosphate fertilizer is a significant anthropogenic source of Cd (Oyedele et al. 2016). The observed values of Cd in both oil palm plantations were below the WHO permissible limit of 0.80 mg kg^{-1}. This deduced that Cd concentrations in the soils are not toxic. The outcome of our study agreed with Rao et al. (2024), who reported higher Cd concentrations in burnt soils. In both beech and oak forests on the Vesuvian slopes, Demirbas (2003) reported higher levels of Cd. Upsurges of total concentrations of Cd were also detected by Abraham et al. (2018b). In the post-fire areas of forests and meadows, Bogacz et al. (2011) reported that Cd increased on surface horizons. In contrast to the findings of the study, Stankov Jovanovic et al. (2011) noted that Cd levels were low in all post-fire areas of *A. genevensis, L. galeobdolon, T. chamaedrys and A. alpinus* for all soil samples. The higher Cd concentrations in the burnt oil palm plantation infer the positive impacts of bushfire on Cd. The significant difference ($p < 0.05$) in Cd between both oil palm plantations suggested that Cd was substantially higher in burnt oil palm plantations, and that the positive impact of bushfire on Cd was significant. Similarly, compared to unburned soils, Campos et al. (2016) reported significantly higher value of Cd in burnt soils. Also, Cd indicated changes in the standard deviation values when comparing the two oil palm plantations (0.03 to 0.06).

Table 1. Concentrations of Pb, Cd, Co, Cr, Ni, As, and V in the soils.

Soil Parameter	Depth (cm)	Unburnt oil palm plantation				Burnt oil palm plantation				*p*-value	WHO Limits
		Range	Mean	Std.	CV (%)	Range	Mean	Std.	CV (%)		
Pb (mg kg^{-1})	0 - 15	10.38 - 14.04	11.87	1.37	11.51	10.41 - 22.40	15.15	4.09	27.03	0.01*	85.00
Cd (mg kg^{-1})	0 - 15	0.08 - 0.19	0.15	0.03	21.94	0.15 - 0.33	0.20	0.06	28.91	0.00*	0.80
Co (mg kg^{-1})	0 - 15	2.05 - 4.61	3.63	0.77	21.28	3.72 - 8.20	5.09	1.48	29.07	0.00*	24.00
Cr (mg kg^{-1})	0 – 15	2.61 - 5.89	4.62	0.97	21.02	4.70 - 10.50	6.52	1.90	29.19	0.00*	100.00
Ni (mg kg^{-1})	0 - 15	2.20 - 4.98	3.93	0.83	21.16	4.01 - 8.50	5.42	1.54	28.45	0.00*	35.00
As (mg kg^{-1})	0 - 15	1.28 - 2.87	2.26	0.47	21.20	2.30 - 5.12	3.19	0.95	29.79	0.00*	0.8.00
V (mg kg^{-1})	0 - 15	0.85 - 2.01	1.52	0.34	22.13	1.55 - 3.42	2.12	0.62	29.26	0.00*	Not specified

3.3. Cobalt (Co)

Cobalt (Co) is a heavy metal in soil, found in comparatively low concentrations in the Earth's crust, and is known for its role in plant metabolism (Srivastava et al. 2022). In the burnt oil palm plantation, the Co values ranged from 3.72 to 8.20 mg kg^{-1} with a mean of 5.09 mg kg^{-1} and a standard deviation of 1.48, while in the unburnt oil palm plantation, it ranged from 2.05 to 4.61mg kg^{-1}, with a mean of 3.63 mg kg^{-1} and a standard deviation of 0.77 (Table 1). The results indicated that Co contents were higher in the burnt oil palm plantation (5.09 mg kg-1) than in the unburnt oil palm plantation (3.63 mg kg^{-1}). The experiential higher Co signifies that it is less soluble and mobile in soil and persists in the soil, while it is efficiently transformed from ash to soil (Campos et al. 2016). The prevalence of Co in the soils of the unburnt oil palm plantation may be due to micronutrient supplement application. As an agricultural input, micronutrient mixtures used in perennial agricultural systems contain Co. Also, plant litter decomposition may lead to incidences of Co on unburnt soils**.** Co taken up by plants (together with weeds and understory flora) is reverted to the soil through leaf litter, decaying roots, or pruning residues (Kabata-Pendias 2011). The observed values of Co in both oil palm plantations were below the WHO permissible limit of 24.00 mg kg^{-1}. This suggests that Co concentrations in the soils are not toxic. The findings of the investigation aligned with Campos et al. (2016), who reported a higher level of Co owing to bushfires in eucalypt and pine forest plantations. Similarly, in both Ilside Site and Vesuvian area of the Campania region in Southern Italy, Pacifico et al. (2023) stated that Co values increased due to bushfire. In the forest soils of the Lviv region (Ukraine), Popovych and Gapalo (2012) observed that Co (up to 0.9 mg kg^{-1}) was slightly higher. Conversely, in surface forest soils in Victoria (Australia), Abraham et al. (2018a) reported a lower range of Co values (3–16 mg kg^{-1}) in burnt soils compared to unburnt soils (4–25 mg kg^{-1}). The decrease in Co concentrations may be ascribed to volatilization. The higher Co contents in the burnt oil palm plantation constitute the positive impacts of bushfire on Co in the oil palm plantation. The significant difference ($p < 0.05$) in Co contents between both oil palm plantations suggested that Co was substantially higher in burnt oil palm plantations, and that the positive impact of bushfire on Co was significant. Correspondingly, in the Vesuvian area, compared to unburnt soils, Pacifico et al. (2023) reported significantly higher value of Co in burnt soils. Co also showed significant changes in the standard deviation values when comparing the two oil palm plantations (0.77 to 1.48).

3.4. Chromium (Cr)

Chromium (Cr) is the 17th most abundant element in the Earth's mantle (Dwivedi et al. 2023). It is a highly mobile heavy metal within the transition metals group (Chen et al. 2024) and usually occurs in soils (Adel and Norman 2003). In the burnt oil palm plantation, the Cr values ranged from 4.70 - 10.50 mg kg^{-1} with a mean of 6.52 mg kg^{-1} and a standard deviation of 1.90, while in the unburnt oil palm plantation, it ranged from 2.61 - 5.89 mg kg^{-1}, with a mean of 4.62 mg kg^{-1} and a standard deviation of 0.97 (Table 1). The results revealed that Cr contents were higher in the burnt oil palm plantation (6.52 mg kg^{-1}) than in the unburnt oil palm plantation (4.62 mg kg^{-1}). The higher Cr content in burnt oil palm plantation may be due to the extremely caustic character of ash produced during bushfires (Yusiharni and Gilkes 2012). The accelerated migration and transformation of Cr on the topsoil may also account for the increase (Rao et al. 2024). In addition, Cr has a low leaching or volatilization rate (Terzano et al. 2021). The burnt vegetation in the oil palm plantation may also account for the higher contents of Cr. Soil enrichment by Cr was demonstrated to stem also from the burning of the flora (Panichev et al. 2008). Phosphate-based fertilizers, generally used in the cultivation of oil palm, usually contain Cr (Eze et al. 2020). This may account for the prevalence of Cr in the unburnt oil palm plantation. The observed values of Cr in both oil palm plantations were below the WHO permissible limit of 100.00 mg kg^{-1}. This suggests that Cr concentrations in the soils are not toxic. The results of the study agreed with Pacifico et al. (2023), who observed that Cr values increased due to bushfire in both the Ilside site (23.5 to 24.9 mg kg-1) and the Vesuvian area (10.9 to 12.9 mg kg^{-1}), respectively. The higher Cr contents in the burnt oil palm plantation imply the positive impacts of bushfire on Cr in the oil palm plantation. The significant difference ($p < 0.05$) in Cr contents between both oil palm plantations demonstrated that Cr was significantly higher in burnt oil palm plantations, and that the positive impact of bushfire on Cr was significant. However, in the Mediterranean region, Santorufo et al. (2021) reported that the concentration of Cr did not significantly change. Cr indicated significant changes in the standard deviation values when comparing the two oil palm plantations (0.97 to 1.90).

3.5. Arsenic (As)

Arsenic (As) is a naturally occurring element in the Earth's crust and is widely distributed across the environment, including in the air, water, and soil (World Health Organization 2002). Soils can originate from both natural and anthropogenic sources (Kayode et al. 2020). In the burnt oil palm plantation, the values ranged from 2.30 to 5.12 mg kg^{-1} with a mean of 3.19 mg kg^{-1} and a standard deviation of 0.95, while in the unburnt oil palm plantation, it ranged from 1.28 - 2.87 mg kg^{-1}, with a mean of 2.26 mg kg^{-1} and a standard deviation of 0.47 (Table 1). The results showed that as contents were higher in the burnt oil palm plantation (3.19 mg kg-1) than in the unburnt oil palm plantation (2.26 mg kg-1). This may be ascribed to the high ash content from the burning of vegetation, as the vegetation may have absorbed it from the soil, where it was originally concentrated (Abraham et al. 2018a). In addition, soil heating from bushfires can enhance the mobilization (Johnston et al. 2019). Burton et al. (2016) stated that bushfires play a key role in mobilizing As. Furthermore, bushfires can also result in arsenic remobilization via emissions to the atmosphere, change to water-soluble arsenic compounds, and can be bound to eroded deposits in soils (Li et al. 2023). Insufficient application and inappropriate soil nutrient management can result in the accretion of heavy metals in the soil, which may account for the incidences of heavy metal contamination in the unburnt site (Eze et al. 2020; Wu et al. 2024). The observed values of in both oil palm plantations were above the WHO permissible limit of 0.80 mg kg^{-1}. This implies that concentrations in the soils are toxic. The findings of the research agreed with Abraham et al. (2018a), who reported that concentrations increased in the post-burn environment. The higher concentrations in the burnt oil palm plantation diminish the positive impacts of bushfire on As. The significant difference ($p < 0.05$) between the two oil palm plantations suggested that it was substantially higher in burnt oil palm plantations, and that the positive impact of bushfire on was significant. Consistent with the study, Abraham et al. (2018b) reported that concentrations of were significant in burnt soils. Furthermore, there were significant changes in the standard deviation values when comparing the two oil palm plantations (0.47 to 0.95).

3.6. Vanadium (V)

Vanadium is a multivalent, redox-sensitive heavy metal that is widespread in the environment (Harvey et al. 2024). In the burnt oil palm plantation, the V values ranged from 1.55 to 3.42 mg kg^{-1} with a mean of 2.12 mg kg^{-1} and a standard deviation of 0.62, while in the unburnt oil palm plantation, it ranged from 0.85 to 2.01 mg kg^{-1}, with a mean of 1.52 mg kg^{-1} and a standard deviation of 0.34 (Table 1). The results indicated that V contents were higher in the burnt oil palm plantation (2.12 mg kg^{-1}) than in the unburnt oil palm plantation (1.52 mg kg^{-1}). The higher V contents in the burnt oil palm plantation may be due to the combustion of vegetation (Terzano et al. 2021). Occurrences of V in the unburnt oil palm plantation may be attributed to the parent material of the soils. Some parent materials of soils contain V contents (Guagliardi et al. 2018). The results of the study agreed with Pacifico et al. (2023), who observed higher V values due to bushfire in the Vesuvian area (109.2 to 110.6 mg kg^{-1}). Similarly, Terzano et al. (2021) reported that the concentrations of V in the topsoil were up to 1.7 times higher than in unburnt soil. Panico et al. (2023) observed higher V contents in burned forest (9.0 mg kg^{-1}) than in forest (7.7 mg kg^{-1}) and urban areas (7.6 mg kg^{-1}). The higher V concentrations in the burnt oil palm plantation suggest that bushfires have a positive impact on V. The significant difference ($p < 0.05$) in V between both oil palm plantations suggested that V was substantially higher in burnt oil palm plantations, and that the positive impact of bushfire on V was significant. Additionally, V showed significant changes in the standard deviation values when comparing the two sites (0.34 to 0.62).

3.7. Nickel (Ni)

Nickel (Ni) is typically distributed evenly throughout the soil profile, with its concentration varying widely depending on the parent rock, and its higher concentration levels in surface soils are often linked to soil-forming processes and human activities (Iyaka 2011). In the burnt oil palm plantation, the Ni values ranged from 4.01 to 8.50 mg kg^{-1} with a mean of 5.42 mg kg^{-1} and a standard deviation of 1.54, while in the unburnt oil palm plantation, it ranged from 2.20 - 4.98 mg kg^{-1}, with a mean of 3.93 mg kg^{-1} and a standard deviation of 0.83 (Table 1). The results revealed that Ni contents were higher in the burnt oil palm plantation (5.42 mg kg^{-1}) than in the unburnt oil palm plantation (3.93 mg kg^{-1}). The higher Ni contents in the burnt oil palm plantation may be attributed to the release of Ni in soil due to combustion of vegetation (Campos et al. 2016) and ash interactions with soil (Stankov Jovanovic et al. 2011). The management of palm oil plantations is characterized by extensive agrochemical use, which is a major anthropogenic source of Ni in soils (Dearlove et al. 2024). The use of pesticides and herbicides may account for the prevalence of Ni in the unburnt oil palm plantation soils. The observed values of Ni in both oil palm plantations were below the WHO permissible limit of 35.00 mg kg^{-1}. This suggests that Ni concentrations in the soils are not toxic. The outcomes of the study are consistent with Pacifico et al. (2023), who reported that Ni concentrations increased in both the Ilside site (22.9 to 23.8 mg kg^{-1}) and the Vesuvian area (15.8 to 16.8 mg kg^{-1}), respectively. The higher Ni contents in the burnt oil palm plantation indicate the positive impacts of bushfire on Ni in the oil palm plantation. The significant difference ($p < 0.05$) in Ni contents between both oil palm plantations suggested that Ni was substantially higher in burnt oil palm plantations, and that the positive impact of bushfire on Ni was significant. Equally, compared to unburned soils, Campos et al. (2016) stated that significantly higher values of Ni were detected in soils owing to bushfire. Furthermore, Ni showed significant changes in the standard deviation values when comparing the two data sets (0.83 to 1.54).

4. Conclusions

The study assessed the impacts of bushfire on heavy metals in oil palm plantations in the tropics. Higher concentrations of Pb, Cd, Co, Cr, Ni, As, and V were detected in the burnt oil palm plantation. Significant differences ($p < 0.05$) were observed among the heavy metals between the unburnt and burnt oil palm plantations. Higher As concentrations were observed in the soils of both oil palm plantations when compared with the permissible limit. The study concluded that whereas, bushfire has significant positive impacts on Pb, Cd, Co, Cr, Ni, As and V contents in oil palm plantations, the soils of both the unburnt and burnt oil palm plantations were toxic with as. The research recommended the planting fire-resistant crops such as stone plants (*Aizoaceae spp*), lavender (*Lavandula spp*), Yucca (*Yucca spp*) etc. around the oil palm plantations to act as barriers to prevent the spread of bushfire. This can also aid to reduce the intensity of fires, and constrain the release of heavy metals into the soil. The use of fern plants can be used to reduce the contents of in the soils of the oil palm plantations. The research also suggested frequent soil testing to monitor the concentration levels of Pb, Cd, Cr, Ni, and V in the soils.

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