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Effects of Electrical and Electronic Waste Contaminated Soil on Biochemical and Haematological Parameters in Wistar

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Abstract

The production of electronic waste (e-waste) continues to increase every day, especially in developing countries. This study investigated the subacute toxicity of e-waste contaminated soils on male *Wistar* rats by evaluating selected biochemical and haematological parameters. Six groups of five adult rats were exposed for 28 days through bedding contact to 1 kg of soils from collection, repair and dismantling e-waste sites, composite mixture soil, commercial soil (*Fontainebleau sand*), and control soil (Bambilor, no e-waste activity). Soil analysis revealed elevated concentrations of lead (637.2 ppm) and cadmium (6.31 ppm) in dismantling soil, copper (442.58 ppm) and chromium (99 ppm) in composite soil, exceeding control levels (lead: 0.31 ppm, cadmium: 0.44 ppm, copper: 4.14 ppm and chromium: 0.81 ppm) ($p<0.05$). Biochemical assays showed no-significant increases in hepatic (AST: 237.20 ± 66.69 U/L; ALT: 117.60 ± 28.38 U/L) and renal markers (urea : 143.40 ± 20.51 mg/dl) in dismantling group compared to controls (AST: 170.40 ± 15.58 U/L; ALT: 97.80 ± 9.07 U/L ; urea : 128.00 ± 11.90 mg/dl) ($p<0.05$). Haematological analysis also revealed non-significant elevations in white blood cells, red blood cells in all exposure groups compared to the control group. These results demonstrate that e-waste contaminated soils, in particular dismantling sites, may induce significant toxicity linked to lead, cadmium and copper bioaccumulation. The results underscore the urgent need for regulated e-waste management in developing regions to mitigate health risks for exposure populations.

Major Findings: The study found that Wistar rats exposed to e-waste contaminated soil, particularly dismantling site with high lead and cadmium levels, showed significant increases in liver and kidney toxicity markers. These results demonstrate that e-waste pollution poses a serious health risk, underscoring the urgent need for regulated e-waste management in developing regions.

Keywords: Biochemical, Blood, Electronic Waste, Heavy Metals, Haematological

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1. Introduction

Electronic waste (e-waste) is one of the main sources of environmental pollution, especially in developing countries with receive more than 60% of end of life electrical and electronic equipment in informal, unregulated settings each year[1,2]. The informal management of this waste, often due to the lack of adequate infrastructure and financial resources, leads to the uncontrolled release of toxic heavy metals such as mercury (Hg), lead (Pb), cadmium (Cd), copper (Cu) and Chromium (Cr), which constitute a growing health and environmental problem[3,4]. Previous studies have identified these metals in the soils surrounding informal e-waste treatment sites, with potential consequences for workers and nearby populations[3,5]. Chronic exposure to contaminated soil occurs mainly by dermal contact, ingestion, or inhalation, especially among workers in the informal recycling sectors[6].

Classified by the IARC as human carcinogens (Cd compounds, Cr (VI)) or probable carcinogens (inorganic Pb)[7,8], these metals affect multiple biological systems, particularly disrupting hematopoietic, and damage hepatocytes and renal tissue, manifesting as altered red and/or white blood cell counts, haemoglobin levels, and increased ALT, AST levels in the exposed population[9-11]. In animal models, exposure to these metals has shown alterations in red blood cell count, haemoglobin, and liver enzymes, which make them suitable for toxicological assessments[9-12].

Despite the large number of studies on individual heavy metal toxicity, few studies have evaluated occupational exposure through an environmentally realistic route, such as direct contact with contaminated soil from e-waste, using an animal model that mimics real-life exposure scenarios. However, experimental studies evaluating the toxic effects of soil samples directly from e-waste sites on haematological and biochemical parameters remain scarce. This study aims to fill this gap by assessing the short-term toxic effects of soils contaminated by informal e-waste activities on Wistar rats. We hypothesise that soils from e-waste sites, exhibiting the highest bioavailable heavy metal fraction, will induce the greatest perturbations in physiological, haematological and biochemical markers, indicating systemic toxicity and organ dysfunction. This work provides novelty, exposure to multiple soil types and the integrated assessment of exposure, bioaccumulation and early effects indicator.

2. Materials and Methods

2.1 Soil Samples

Soil samples were collected from 17 e-waste handling sites identified in the Dakar region. Site selection was conducted using snowball sampling, a link-tracking recruitment strategy. First, an initial group of e-waste handlers was identified as the seed sample. These participants were then asked to nominate other handlers and e-waste processing sites, and this referral process was repeated iteratively[5]. The sites were distributed in such a way that there were five sites specialising in collection, five in reparation, and 7 in dismantling e-waste. The sampling criteria were described in a previous study. The collection sites were used as storage points for the waste collected on the city streets. Reparation sites were the sites where electronic waste was sorted, and materials that could be reused were recovered and transferred to other devices or sold to the highest bidder. Dismantling sites were those where the e-waste was broken down, shredded, or burned for its components. For each category (collection, recycling, dismantling), a final composite sample of approximately 20 kg was collected, and rats were exposed to these contaminated soils via bedding contact, simulating occupational exposure pathways, dermal contact during normal cage activities, incidental ingestion during grooming behaviour leading to soil particle ingestion and inhalation risk during movement. An uncontaminated commercial soil, "*Sable de Fontainebleau*", obtained from the *HUMEAU* laboratory, was used as the blank control. An unpolluted soil was obtained in the locality of Bambilor, in the Dakar region, in a site far from any industrial activity or the recycling, collection, and dismantling of electrical and electronic waste[4]. For this study, the "*Sable de Fontainebleau*" represents an uncontaminated environment, and the Bambilor soil is considered here as a local control site.

Once in the laboratory, the soil samples were removed by sieving metal debris, stones, and fine parts with a particle size of 100 µm were used for analysis.

2.2 Characterisation of the Bioavailable Fraction in Soils

The determination of the bioavailable fraction was carried out according to the method of Kubová J *et al.*, 2008. For each of the composite samples collected at each site, 1 g of soil was stirred in 0.5 mol.L^{-1} of HCl (purity grade>37%)

in a 20: 1 ratio (v: m) for 1 h. The suspensions obtained after stirring were centrifuged (2500 rpm) for 20 min, and the supernatant was filtered before being stored at 4°C until analysis using the flame absorption spectrometer[13]. Solutions of 1000 mg/L (Agilent, Meck) of lead, copper, cadmium, and chromium were used for the preparation of the calibration curves.

All equipment used was thoroughly washed and then soaked in a 10% nitric acid solution (v:v) for 24 hours before being rinsed with double-distilled water.

2.3 Experimental Model Design

The experimental exposure of the rats was performed according to the method modified and described by Fouchecourt[14]. Briefly, thirty healthy adult male Wistar rats weighing 179 ± 20 g were used in this study in the animal facility of the Toxicology and Hydrology Laboratory of the Department of Chemistry of the Cheikh Anta Diop University of Dakar. They were acclimatised for 7 days in polypropylene cages and maintained at an average ambient temperature between 22 and 25°C with a relative humidity of 60% and a 12-h day/night cycle. All animals were fed a normal commercial pellet diet, and water was administered ad libitum. After the acclimatisation period, the rats were weighed, recorded and randomly divided into six groups of five rats each. Throughout the 28 days correspond to the experimental period, the bedding was replaced weekly to maintain consistent exposure levels. The exposure model chosen for our study is semi-controlled by contact between the food and the litter, by air dispersion of the pollutants present in the litter and by contact of the rats' fur with the litter. To limit the risk of further contamination of the soil samples, the collected samples were sealed in self-sealing bags and stored in a standard room at a constant temperature of 25°C for subsequent testing. At the end of the experiment, the equipment used for sacrifice, blood, and organ collection was sterile, and the material used was free of trace metals. The rats were extracted from their housing, then cleaned to remove as many metal particles as possible, before being sedated and the blood sample taken from the heart.

The groups of rats were divided as follows:

Group 1: 1 kg of uncontaminated soil '*Sable de Fontainebleau*' from the *HUMEAU* laboratory.

Group 2: 1 kg of soil from the collection sites.

Group 3: 1 kg of soil from e-waste recycling sites.

Group 4: 1 kg of soil from e-waste dismantling sites.

Group 5: 1 kg of a mixture of different polluted soils (collection, recycling, dismantling).

Group 6: 1 kg of soil from Bambilor localities around the Dakar region.

Animals in each group were weighed on the first day and then weekly. A range of clinical signs was investigated to detect not only general pharmacological and toxicological effects, but also changes in behaviour and autonomy throughout the exposure period. These signs included changes in the skin, fur, eyes and mucous membranes, the appearance of secretions and excretions, and autonomic activity such as lacrimation, pupil size and unusual respiratory activity. In addition, changes in walking style, the presence of clonic or tonic movements, excessive toileting and unusual behaviour were also investigated. Various observations of signs of toxicity were also recorded throughout the study. After 4 weeks, the animals were fasted overnight and then sacrificed under anaesthesia using a mixture of Xylazine and Clorketam (2:8) at 1 mL/kg body weight. The experiment was carried out according to the OECD guidelines and the European Directive 2010/63/EU on animal testing. The study was approved by the Ethics and Research Committee of the Faculty of Medicine, Pharmacy, and Stomatology of the Cheikh Anta Diop University of Dakar under the number 039912019/CERTCAD.

2.4 Collection of Blood Samples

Once the rats were placed under anaesthesia, the whole blood was taken by cardiac puncture and packaged in different tubes according to the analyses to be performed. Tubes containing Ethylene Diamine Tetraacetic Acid (EDTA) anticoagulant were used to draw blood for hematologic analysis. Dry tubes containing sodium fluoride citrate were used to draw blood for biochemical analysis. These were centrifuged at 3000 rpm for 15 min using the DALB DM0636 centrifuge, and the aliquots were preserved for research on the various biochemical parameters.

2.5 Organ Harvesting

The liver, lungs, and kidneys were excised and rinsed in 0.9% NaCl normal saline. After sampling, each organ was weighed to obtain the absolute weight that was used to determine the relative weight of each rat as described by Akhtar *et al.*[15]:

$$Relative\ organ\ weight = \frac{Organ\ weight(g)}{Body\ weight(g)} \times 100 \quad (1)$$

2.6 Concentration of Heavy Metals in Blood Samples

Cadmium, copper, chromium, and lead in blood were analysed using the revised method described by Robinson *et al.*[16]. Briefly, a nonionic surfactant/phosphate solution was prepared from 1.5 g of ammonium dihydrogen phosphate and 5 ml of 1% Triton X-100 solution (v / v), then diluted in 100 ml of pure water. Then 0.5 ml of blood was diluted in 5 ml of nonionic surfactant/phosphate solution[16]. Reference materials at different concentrations for blood metals were supplied by the Wadsworth Centre Laboratory, New York State Department of Health. These were used to draw the various calibration curves.

2.7 Hematological Parameters

Red Blood Cells (RBC), White Blood Cells (WBC), Haemoglobin (Hb), Hematocrit (Hct) and Platelet count (PLT), LYM %, MON % and GRA % were determined with an automated Haribo ABX-60S haematological analyser. The use of an automated analyser was based on the results of the study conducted by Messias *et al.*[17], which compared three methods for determining haematological parameters. The results of Messias *et al.*[17] show that there is no difference in the use of automated analysers and that they can be used globally.

2.8 Biochemical Parameters

Serum from tubes containing citrate fluoride was used to determine blood glucose, and dry tubes for aspartate Aminotransferase (AST), Alanine Aminotransferase (ALT), UREA (Urea), and Creatinine (Crea). Biochemical parameters (glucose, AST, ALT, creatine, urea) were determined with Biosystems diagnostic kits (Spain) using a semi-automated biochemical analyser BTS-35, Biosystems, Barcelona, according to analytical recommendations and good laboratory practice.

2.9 Data Analysis and Statistics

The parameters of the different groups were expressed as an average ± standard deviation of the number of animals used for each group. The results were analysed by unidirectional and bidirectional ANOVA, compared to rats exposed to the soil of Groups 1 and 6, who were exposed to the commercial soil and the soil of the Bambilor site. The ANOVA tests were subjected to the Tukey test to compare individual means. The pvalue<0.05 was considered statistically significant. The Shapiro-wilk normality test was performed to verify that the normality hypothesis is tolerated. Data were analysed and processed using the GraphPad Prism software version 8.00 for Windows (GraphPad Software, La Jolla, California, USA).

3. Results

3.1 Characterisation of Heavy Metals in Soils

The results show significant differences (p<0.0001) in bioavailable metal concentration between soils from e-waste treatment sites (Groups 2-5) and control soils (Groups 1 and 6) for all four metals. Pb levels in contaminated soils ranged from 270. 637.2 ppm, far exceeding the WHO[18] guideline of 100 ppm, whereas control soils contained only 0.09 ppm and 0.31 ppm, with the dismantling site (Group 4) showing peak contamination. Cd concentration varied between 3.43 and 6.31 ppm, surpassing the WHO limit of 4 ppm in Groups 3, 4 and 5. Chromium concentration in e-waste soils ranged from 16.11 to 24.91 ppm, below the WHO threshold of 80 ppm but markedly higher than control values (0.52 and 0.81 ppm). Copper concentrations were much higher in Group 5 (443.58 ppm), which was a mixture of soils from collection, dismantling and recycling sites. Among contaminated soils, the lowest trace metal values were observed in Group 2 (soils of collection sites) for lead and cadmium and in Group 3 (soils of e-waste

Table 1. Concentration of bioavailable lead, cadmium, copper, and chromium in soils of the different experimental groups

	WHO	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	pvalue
Pb (ppm)	100	0.09 ±0.04	270. 85 ±0.10^{ab}	288.6 ±0.04^{ab}	637.2 ±0.13^{ab}	439.4 ±0.12^{ab}	0.31 ±0.08	<0.0001
Cd (ppm)	4	0. 42 ± 0.30	3.43 ± 0.034^{ab}	5. 48 ±0.23^{ab}	6.31 ± 0.08^{ab}	5.19 ±0.05^{ab}	0.44 ± 1.10	<0.0001
Cr (ppm)	80	0.52 ± 0.07	23.04 ±0.10^{ab}	16.11 ±0.06^{ab}	20.91 ±0.05^{ab}	24.91 ±0.05^{ab}	0.81 ±0.06	<0.0001
Cu (ppm)	84	1.37 ±0.19	262.2 ±3.72^{ab}	238.7 ±2.63^{ab}	358.15 ±0.86^{ab}	442.58 ±1.79^{ab}	4.14 ±0.82	<0.0001

The results are presented as mean and standard deviation. [a]Significant differences from Group 1 (p<0.05). [b]Significant differences from Group 6 (p<0.05).

repair sites) for chromium and copper, and the respective concentrations were 270.85, 3.43, 16.11 and 238.70 ppm (Table 1).

3.2 Weekly Average and Change in Body Weight

After 28 days of exposure, no toxic effects were recorded, and all animals were alive. The results of the weight monitoring analysis showed an increase in body weight during the study. At the end of the exposure, all rats had a gain in body weight between 32.93 and 47.61% (Table 2). No significant differences in body weight were observed compared to Groups 1 and 6 (Table 2). The lowest weight gain (32.93%) was observed in the group exposed only to dismantling soils, and the highest (47.61%) was in the group exposed to soils from collection sites.

3.3 Change in Relative Organ Weights

The liver, kidney, and lung weights of the rats were also compared to those of Groups 1 and 6. The results showed a significant increase in their relative weight to Groups 2 and 4 compared to Group 6 ($p<0.05$) (Table 3).

3.4 Distribution of Metals in the Blood

Serum Pb levels were significantly higher in Group 4 compared to Group 6 ($p<0.05$). Cr concentrations were also significantly lower in rats exposed to electronic waste and in Group 1 compared to Group 6. However, no significant differences were observed in the comparative analysis of blood copper concentrations. The results for Cd in the blood were all below 0.001 ug/L (Table 4).

3.5 Hematological Parameters

The results of the hematologic parameters are shown in Table 5. There was a nonsignificant increase in White Blood Cells (WBC) and Red Blood Cells (RBC) in all exposure groups compared to Groups 1 and 6. The red blood cell count went from 6.75 ± 0.48. $10^3/mm^3$ in the control group at a maximum value in Groups 4 (7.79 ± 1.60. $10^3/mm^3$) and 5 (7.80 ± 0.92. $10^3/mm^3$). On the

Table 2. Weekly change in mean rat body weight

Groups	Week_0	Week_1	Week_2	Week_3	Week_4	Weight gain (%)
Group 1	194.20 ±37.69	209.87 ±32.54	228.73 ±31.61	244.14 ±35.18	270.98±44.83	39.54
Group 2	179.60 ±26.02	195.52 ±27.73	219.63 ±21.56	237.97 ±29.19	265.11±29.84	47.61
Group 3	192.40 ±33.81	201.35 ±29.42	221.20 ±29.64	235.04 ±31.43	258.78±32.09	34.50
Group 4	189.72 ±15.87	203.47 ±16.07	225.61 ±14.60	255.91 ±11.19	252.20±08.67	32.93
Group 5	198.40 ±33.78	211.84 ±33.68	233.82 ±34.20	254.85 ±35.62	281.88±35.90	42.08
Group 6	179.40 ±26.37	203.38 ±26.74	205.47 ±20.24	239.56 ±24.82	258.22±24.19	43.93

Table 3. Relative organ weights (%)

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	pvalue
Kidneys	0.64 ±0.04	0.68 ±0.10	0.55 ±0.04	0.62 ±0.13	0.66 ±0.12	0.52 ±0.08	0.0582
Liver	3.15 ± 0.30	3.27 ± 0.034[a]	2.79 ±0.23	3.25 ± 0.08[a]	2.80 ±0.05	2.24 ± 1.10	0.0609
Lungs	0.58 ±0.07	0.56 ±0.10	0.47 ±0.06	0.51 ±0.05	0.49 ±0.05	0.49 ±0.06	0.250

The results are presented as mean and standard deviation. [a]Significant differences from Group 6 ($p<0.05$).

Table 4. Heavy Metal concentrations in blood rats

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	pvalue
Pb (ug/L)	24.92±2.66	31.88± 7.89b	60.98± 6.53[a]	69.38±5.29[ab]	55.03± 5.59[a]	54.77± 5.59	<0.0001
Cr (ug/L)	10.85±3.58	14.86±6.07[ab]	10.93± 2.50[b]	19.60± 3.04[a]	21.90± 2.05[a]	23.83± 4.17	<0.0001
Cu (ug/L)	4.62± 0.24	6.83± 0.00	5.94± 0.00	1.75± 0.47	1.79± 0.00	0.72± 0.00	0.0061
Cd (ug/L)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	-

The results are presented as mean and standard deviation. [a]Significant differences from Group 1 ($p<0.05$). [b]Significant differences from Group 6 ($p<0.05$).

Table 5. Variation in haematological parameters in the different experimental groups after 28 days of exposure to control and WEEE soils

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
WBC (10^3/mm^3)	6.40 ± 0.93	6.48 ± 1.99	4.60 ± 1.27	10.02 ± 3.43	10.28 ± 3.68	8.30 ± 2.49
RBC (10^3/mm^3)	6.75 ± 0.48	7.04 ± 0.33	7.36 ± 0.45	7.79 ± 1.60	7.80 ± 0.92	7.64 ± 0.40
Hb (g/dL)	12.66 ± 1.22	13.36 ± 0.54	14.34 ± 0.65	15.50 ± 2.97[a]	15.24 ± 1.98	14.48 ± 0.83
Hct (%)	41.76 ± 3.01	43.40 ± 2.32	44.68 ± 2.15	48.24 ± 10.71	47.16 ± 6.12	44.23 ± 2.32
MCV (fl)	62.00 ± 1.22	61.60 ± 1.14	60.80 ± 3.11	62.00 ± 2.00	60.40 ± 1.14	57.75 ± 0.50
MCHC (g/dL)	30.28 ± 0.88	30.82 ± 0.51	32.10 ± 0.39	32.26 ± 1.06	32.34 ± 0.59	32.70 ± 0.32
PLT (10^3/mm^3)	824.60 ± 53.32	848.20 ± 168.60	908.40 ± 101.62	846.40 ± 318.41	895.20 ± 196.63	833.75 ± 221.23
LYM %	76.70 ± 7.17	79.88 ± 9.15[a]	82.58 ± 8.81[a]	88.94 ± 5.87[ab]	90.00 ± 4.48[ab]	83.78 ± 1.54
MON %	10.68 ± 3.74	9.02 ± 2.07	10.32 ± 3.22	6.46 ± 2.24	6.58 ± 2.22	9.43 ± 0.41
GRA %	12.62 ± 7.33	11.10 ± 9.05	7.10 ± 6.07	4.60 ± 3.69	3.42 ± 2.28	6.80 ± 1.37

Results are presented as mean ± SD from groups of 5 rats. [a]significant difference with respect to Group 1 ($p<0.05$). [b]Significant differences with respect to Group 6 ($p<0.05$). Red Blood Cells (RBC), White Blood Cells (WBC), Haemoglobin (Hb), Hematocrit (Hct), Mean Corpuscular Volume (MCV), Mean Corpuscular Haemoglobin Concentration (MCHC) and Platelet Count (PLT), Lymphocyte (LYM %), Monocyte (MON %) and Basophilic Granulocyte (GRA%).

Table 6. Variation in biochemical parameters in the serum of different experimental groups after 28 days of exposure to control and WEEE soils

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	pvalue
Glu (mg/dL)	276.2 ± 71.64	231.6 ± 94.77	199 ± 47.89	227.4 ± 22.79	199.2 ± 59.08	241.2 ± 36.31	0.1597
Urea (mg/dL)	74.40 ± 12.05	73.20 ± 16.60[b]	72.80 ± 52.77b	143.40 ± 20.51[a]	160.80 ± 16.27[a]	128.00 ± 11.90	<0.0001
Crea (mg/dL)	2.74 ± 1.20	0.83 ± 0.24	1.06 ± 0.11	0.94 ± 0.15	1.00 ± 0.16	2.52 ± 0.12	0.1996
AST (U/L)	170.20 ±95.27	235.80 ±22.51	217.20 ±51.85	237.20 ±66.69	172.20 ±17.08	170.40 ±15.58	0.0092
ALT (U/L)	92.40 ±10.67	85.60 ±8.32	110.60 ±25.89	117.60 ±28.38	77.60 ±11.31	97.80 ±9.07	0.0218

Results are presented as mean ± SD from groups of 5 rats. [a]significant difference with respect to Group 1 ($p<0.05$). [b]Significant differences with respect to Group 6 ($p<0.05$). Glu: Blood glucose; ALT: Alanine aminotransferase; AST: Aspartate aminotransferase; Crea: Creatinine.

one hand, we observed an increase in the Hb level of the different groups compared to the control group, which had a value of 12.66 ± 1.22 g/dL. The highest level of haemoglobin was observed in Group 4 (15.50 ± 2.97 g/dL), and the increase was significant compared to control Group 1 ($p<0.05$) (Table 5). On the other hand, the hematocrit rate in the control group was 41.76 ± 3.01%. This value was relatively low in this group compared to the exposed groups, and the highest values were observed in Group 4, where the hematocrit rate was 48.24 ± 10.71% and 47.16 ± 6.12% for Group 5.

A significant increase in leukocytes was also observed in Groups 2 and 3 compared to Group 1, and Groups 4 and 5 compared to Group 1 and Group 6 ($p<0.05$). In general, there were statistically significant differences in hemodynamic parameters for white blood cell count ($p=0.0054$), Lymphocytes (LYM) ($p=0.0062$) and monocytes (MON%) ($p=0.0425$).

3.6 Biochemical Parameters

The biochemical biomarker parameters were analysed, and the results are presented in Table 6. The ANOVA One-Way test shows a significant increase in urea in rats in Groups 4 and 5 compared to Group 1 ($p<0.05$), and the highest increase was observed in Group 5, where the increase was 116.12% compared to Group 1. The lowest urea value was observed in Group 3 (72.80 ± 52.77 mg/dL) (Table 6). AST activity was higher in the groups exposed to undiluted soil and decreased in each group as the soil was diluted. The highest AST activity was 237.20 U/L and was observed in Group 4, and the lowest activity was observed in Group 5 (77.60 U/L). The ALT concentration

was higher in the groups exposed to dismantling (117.6 U/L) and repair soils (110.6 U/L) (Table 6). There was also a non-significant reduction in blood glucose levels in Groups 2-5 compared to Groups 1 and 6.

4. Discussion

Whether in their home environment or in their workplace, individuals are exposed daily to a heterogeneous mixture of metals, presenting multiple health risks[19,20]. In Senegal, electronic waste is largely managed by the informal sector, which operates outside WEEE legislation. This lack of regulation contributes to the increasing volume of e-waste and the environmental dispersion of both essential and non-essential metals. Previous studies have reported high concentrations of these metals in soils from Waste Electrical and Electronic Equipment (WEEE) sites, highlighting significant non-carcinogenic health risks associated with chronic exposure[3,4,21]. The combined presence of multiple metals is particularly concerning, as metal mixtures often exhibit greater toxicity than single compounds[22]. To assess the health impact of this exposure, we conducted and experimental study using the Wistar rats exposed to soils collected from different WEEE treatment sites, including collection, recycling and dismantling locations. The choice of male rats reflects the predominantly men workplace in Senegal's electrical and electronic waste in the informal sector [5]. We focus on four metals (Pb, Cd, Cu, Cr) whose bioavailable fractions were analysed, as these are good indicators of toxicity for these metals[23-25].

Our results on bioavailable fractions show high lead, cadmium and copper concentrations in Group 4, exposed to dismantling sites, likely due to activities such as burning and acid leaching, which release metals into the environment[3,5,26]. In contrast, groups exposed to collection (Group 2) and recycling (Group 3) soils had intermediate contamination, but still surpassed WHO limits for Pb, Cd and Cu, reflecting less intensive pollutant proportional to the activity of the site[3,5,21,24] Unlike the dismantling sites, the collection sites were mainly used for storing WEEE, while the recycling sites were used for repairing, sorting and recovering, which limits the production and dispersion of pollutants in the environment.

Following the analysis of soil contamination, the evaluation of body and organ weights allowed us to explore the early toxicology effects of exposure. Body weight variations are a simple yet informative indicator of overall toxicity[27,28]. In our study, no observable physical changes that could lead to clinical signs associated with an underlying disease, and no cases of mortality were observed, suggesting no avert acute toxicity. However, Groups 3 and 4 showed a slight reduction in body weight gain, which, though mild, may reflect subclinical toxicity. More revealing than body weight alone, organ weights and relative weights are much more sensitive indicators of toxicity[28]. The significant reduction in relative body weight in Group 4, associated with a significant alteration in the liver-to-body weight ratio, suggests hepatic involvement. Despite the increase in liver weight in this group, there was no significant difference compared to the other groups ($p>0.05$), and thus cannot definitively indicate hepatomegaly or inflammation, but it warrants closer monitoring. The same observations were made by Yuan *et al.*[29], who also found no significant toxicological changes in organ weight compared to the control group. Despite a decrease in body weight observed in some groups, the variation in relative and organ weights can be considered fortuitous and toxicologically insignificant if there is no dose dependency associated with exposure[29].

Beyond weight changes, haematological parameters are a key indicator of systemic toxicity following exposure to environmental pollutants. Traces of metals, in particular lead and cadmium, are known to accumulate in organs and tissues through the blood circulation and alter hematopoiesis by binding plasma proteins and cellular ligands[30,31].

In our study, groups exposed to dismantling and mixed soil (Groups 4 and 5) showed a non-significant increase in white blood cells, red blood cells, haemoglobin, hematocrit and platelet count compared to the controls. Although not statistically significant, these trends may suggest an inflammatory reaction or allergy, which could lead to leukocytosis. Similar increases in leukocytes have been associated with heavy metal exposure, notably lead and cadmium, with simulated leukocyte production and inhibited cell adhesion, contributing to leukocytosis[32,33]. In contrast to our results, which relate to exposure to a mixture of metals, some authors have described an unchanged status or a decrease in white blood cell count compared with the control group in experimental studies on mice or rats exposed to a single metal[34].

The rise in red blood cell count and haemoglobin in Groups 4 and 5 is similar to that of Chen *et al.*[35] who found an increase in a population living near e-waste zones, and may reflect a compensatory mechanism

in response to disrupted oxygen transport. Lead and cadmium are both known to interfere with haemoglobin synthesis by inhibiting key enzymes such as ferrochelatase and δ-aminolevulinate dehydratase (ALAD), potentially leading to anaemia [10, 36]. In this context, Hb, Hct, MCV and MCH may be important parameters for assessing anaemia in most vertebrates[37,38].

Interestingly, although typical markers like MCV, MCH, and MCHC can reveal erythropoietic dysfunction, the values observed in our study, especially their increase in exposed groups, appear to reflect an adaptive response rather than damage. Witeska *et al.*[38] interpret such changes as signs of stress adaptation, with increases promoting oxygen delivery under toxic conditions. Moreover, copper, also elevated in contaminated soils, may have mitigated some hematotoxic effects by stimulating ALAD activity and counteracting lead toxicity[39]. This interplay raises important questions about the synergistic effects of mixed metal exposure. While single metal exposure often reduces haematological parameters, combined exposure may elicit more complex physiological responses, either amplifying or mitigating toxicity[40,41].

Biochemical serum markers provide insight into the functional state of vital organs, notably the liver and kidneys, primary targets of heavy metals. These organs play critical roles in detoxification and homeostasis by reabsorbing vital substances and excreting waste products[42-44]. They are considered key indicators of cadmium and lead exposure[35,45].

In our study, exposure to soils from dismantling sites led to marked increases in liver enzymes AST and ALT, particularly in Group 4, indicating hepatocellular damage. These enzymes, normally intracellular, leak into the bloodstream when hepatocyte membranes lose their integrity[46,47]. Previous results showed that multimetallic contamination had a significant effect on ALT and AST enzymatic activities in the liver, and could reinforce the risk of hepatic injury[34,48]. Group 4 also showed the highest blood lead levels, which may induce oxidative stress in liver cells, generating free radicals that cause lipid peroxidation and further hepatic enzyme release[49-51]. Similar patterns have been observed in occupational exposure, supporting the link between metal accumulation and liver damage[52,53].

As for kidney-related markers, blood glucose and creatinine levels decreased in all the groups exposed to WEEE treatment soils. The decrease in blood glucose may reflect increased insulin activity, enhancing glucose intake and metabolism[54,55]. According to Tazitdinova *et al.* 2018, events such as changes in the synthesis of thyroid hormones, adrenal glands or pancreatic beta cells are factors that can promote excessive insulin production[55]. However, the absence of significant disruptions suggests that blood glucose alone is not a reliable marker of liver metabolic dysfunction in this context. Decreased creatinine levels, as reported in other studies involving lead-cadmium mixtures, may indicate early renal impairment[29,56].

The assessment of renal function using blood urea and creatinine revealed specific variations in rats exposed to contaminated soils specific variations. These markers are key indicators of kidney health, with creatinine reflecting glomerular filtration and urea is also influenced by protein metabolism and liver function[45,57]. In groups exposed to dismantling and mixed soils, urea levels increased while creatinine decreased, suggesting impaired renal excretory function, possibly linked to co-exposure to metal mixture[58]. These findings align with Zhu *et al.*[58] on renal toxicity from combined lead, cadmium, and chromium exposure. In contrast, according to some authors, the administration of high doses of a mixture of metals often leads to a reduction in blood urea and creatinine, as observed in groups exposed to collection and recycling soils[19,34].

The elevated urea in Groups 4 and 5 may indicate tubular dysfunction or early kidney damage, potentially due to simultaneous exposure to lead, cadmium and chromium[57]. Meanwhile, decreased urea, as observed in Groups 2 and 3, combined with increased ALT and AST, could reflect liver dysfunction, reinforcing the link between hepatic and renal responses to toxic exposure. These changes demonstrate the kidney's particular vulnerability to heavy metals, with distinct biological profiles emerging according to exposure type. The urea and creatinine divergence in Group 4 underscores the need to interpret these markers together when assessing renal function.

5. Conclusion

This study reveals significant alterations in hepatic (ALT, AST) and renal (urea, creatinine) markers, along with haematological changes in rats exposed to soils from WEEE processing sites, especially dismantling areas. These disruptions reflect substantial biological toxicity linked to high bioavailability of lead, cadmium, copper and chromium. Combined exposure to multiple

metals appears to enhance toxicity through synergistic mechanisms. Therefore, regular medical monitoring of workers, mandatory use of personal protective equipment, and further research on metal interactions and long-term effects are strongly recommended.

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7. Author Contributions

Conceptualization, M.C. and A.T.; methodology, R.F.F., F.B and A.N.; software, R.F.F., J.C.M.P and O.O.M.; validation, M.C. and A.T.; formal analysis, R.F.F. and J.C.M.P.; investigation, R.F.F., J.C.M.P and O.O.M.; resources, A.L. and F.B.; data curation, A.S., I.S.D., A.L., and A.N.; writing—original draft preparation, R.F.F., A.T and M.C.; writing—review and editing, A.S., C.D., A.L., I.S.D. and M.F.; supervision, A.T. and M.C. All authors have read and agreed to the published version of the manuscript.

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