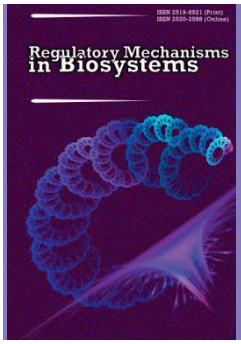

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Influence of lead on the distribution of macro- and microelements and biochemical parameters in the organs of rats

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Heavy metals, entering the environment, accumulate in various organisms, disrupting metabolic pathways and are potentially dangerous for human health. Therefore, it is important to determine the mechanism of disturbances in some mammalian systems due to long-term exposure to a heavy metal such as lead. Therefore, there is a need for careful research, analysis and investigation of the consequences of the accumulation of heavy metals in organisms and further development of strategies to mitigate their effects. The purpose of this study was to study the influence of exposure to lead (II) on the distribution of macro- and microelements and biochemical indicators in the organs of rats. The total time of the experiment was 8 days, it was conducted on sixteen 3-month-old male rats of the Wistar line, which were divided into two groups: control and experimental. The experimental group was irradiated with a sublethal dose of lead acetate, while the control group remained unirradiated. After seven days of exposure, the rats were euthanized and samples of their hearts, kidneys and livers were analyzed for certain metals, including lead, calcium, zinc, iron, magnesium and cadmium. Blood samples were also collected and analyzed for lipid metabolism, aminotransferase activity, and glutathione levels. The results of this study showed significant accumulation of lead in the liver and kidneys of the exposed rats. In addition, changes in the concentrations of calcium, zinc, iron, magnesium, and cadmium were observed in various organs, suggesting that exposure to lead may disrupt the normal distribution of these essential nutrients. The study also found reduced levels of reduced glutathione and levels of sulfhydryl groups, suggesting increased use of thiol compounds for detoxification and antioxidant defense in response to lead exposure. It should be noted that the activity of liver aminotransferase was significantly impaired, which emphasizes the sensitivity of this enzyme to the influence of lead. Thus, this study provides valuable information on the toxic effects of heavy metals, particularly lead, on the distribution of essential nutrients and biochemical parameters in rat organs. These findings highlight the importance of understanding the toxicity of heavy metals and their effects on biological systems. In addition, the study highlights the need for the development of functional foods that can help mitigate the effects of xenobiotic intoxication, which can have significant consequences for human health, as well as further research into ways to remove heavy metals from the body.

Keywords: metabolic pathways; heavy metals; heavy metal removal; lipid metabolism; lead distribution; xenobiotic intoxication.

Introduction

In recent decades, the escalation of the level of anthropogenic pollution has caused a growing concern about the environment and public health. The modern functioning of the national economy is accompanied by an increase in man-made load. Anthropogenic activities contribute to the dispersal of a significant number of chemical elements involved in the migration process (Sanders et al., 2014; Çiğdem et al., 2022). A serious environmental problem is also growing due to pollution and water shortage, and limited availability of water is increasing due to the devastation of natural water reserves. During the last 50 years, industrialization has spread at a rapid pace, increasing the need for indiscriminate exploitation of the Earth's natural resources and exacerbating the global problem of environmental pollution (Reddy et al., 2015; Kenston et al., 2018). Toxins, such as organic and inorganic pollutants, organometallic compounds, radioactive isotopes, and gaseous pollutants, severely pollute the aquatic environment (Bortey-Sam et al., 2016; Khalil et al., 2018).

Among the chemical factors of environmental pollution, one of the first places is occupied by salts of heavy metals, which have high toxicity and can affect living organisms even in small concentrations (Kim et al., 2015; Zulaikhah et al., 2019; Paithankar et al., 2021). The frequency and severity of ecologically related diseases arising as a result of anthropogenic pollution of the biosphere indicates the relevance of this problem (Lu, 2018). It is heavy metals that are the main pollutants of atmospheric air, water bodies and soils on a global and regional scale. Due to their high migration ability, propensity for bioaccumulation and polytropy, metals pose a danger to humans not only with direct exposure, but also due to the negative impact on sanitary and hygienic indicators of environmental objects (Saghazadeh et al., 2017; Gazwi et al., 2020; Rusin et al., 2021). Among various pollutants, heavy metals stand out as particularly harmful due to their toxicity to all living organisms. Heavy metals such as lead (II) are persistent pollutants that do not undergo transformation, leading to their accumulation and migration in ecosystems (Yessimsiitova et al., 2019; Hernández et al., 2015). As these toxic metals enter the environment, they pose a significant risk to living organisms, especially when they become part of the food chain. Therefore, the growing pollution of the environment by heavy metals has become one of the most important problems of our time. The impact of heavy metals on biological systems is profound. In high concentrations, these metals disrupt the most important metabolic pathways in the body, which leads to many pathological processes. Ultimately, this disruption can significantly affect human health, making the study of heavy metal toxicity a critical area of research (Ohta et al., 2020). The human body relies on a delicate balance of macro- and micronutrients to maintain stability in its internal environment. Enzyme systems play a key role in mediating metabolic processes that maintain body balance (Andrade et al., 2017; Zhushan et al., 2020). This en-

zymatic activity, in turn, is regulated by various macro- and microelements. Any imbalance in the availability of these nutrients can significantly affect metabolic processes in the body, potentially leading to negative health consequences (Zeid et al., 2022). In previous studies, we established that the body's ability to accumulate heavy metals operates at different levels, from cellular to tissue and organ. Accumulation of these metals in various tissues and organs is due to both their inherent affinity with certain biological structures and the existence of protective mechanisms that limit their migration in the body (Andreiko et al., 2018; Proshad et al., 2020).

Taking into account the complex interaction between the influence of heavy metals, nutrients and biochemical parameters in living organisms, there is a need to shed light on and improve our understanding of the complex mechanisms underlying heavy metal toxicity and their potential effects on metabolic processes and provide a basis for the development of strategies, such as functional foods, aimed at mitigating the adverse effects of heavy metal exposure on living organisms. In particular, we aim to investigate the effect of exposure to lead (II) on the distribution of macro- and microelements in the organs of rats, namely the heart, kidneys and liver, as well as changes in basic biochemical parameters (Maiuolo et al., 2020).

Materials and methods

When performing the experiment, we observed the principles of the European Convention on the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (ETS No. 123, Strasbourg, 1986) and the Law of Ukraine "On the Protection of Animals from Cruel Treatment" (No. 3447-IV dated 21.06. 2018) /2006). Procedures with the rats were carried out following the ethical rules for manipulations with experimental animals and were allowed by the local Ethical Committee.

Experimental research was carried out in the vivarium of Kharkiv National University named after V. N. Karazin on white male Wistar rats. For this purpose, 16 individuals aged 100 days and weighing 192–276 g were selected and divided into two groups (7 individuals – then intact (control) group and the second (9 individuals) – the experimental group. The parameters of the microclimate in the vivarium corresponded to all established standards for keeping rats. The animals were housed in standard plastic cages with no more than 3–5 individuals in each. Temperature was maintained at 25 ± 2 °C and the rats were exposed to 12 h of natural daylight per day. The animals were fed once a day with a balanced standard vivarium diet, with constant access to water. Rats from the control and experimental groups were kept in the same conditions. The experimental rats were kept in the vivarium in accordance with generally accepted recommendations, requirements and provisions for the care of laboratory animals. Before the start of the experiment, all rats were examined, weighed, their age, motor activity, and skin condition were recorded. There were no sick animals were included in the experiment.

The animals of the experimental group were injected once intramuscularly (in the thigh) with a solution of lead acetate (PbAc) ($Pb(CH_3COO)_2 \times 3H_2O$) with an equivalent amount of lead of 62.5 mg per 1 kg of rat weight (62.5 μ/kg), which is less than ¼ LD_{50}. After the introduction of lead acetate solution for 7 days, the animals were not subjected to other manipulations, after which on the 8th day they were euthanized under chloroform-inhalation anesthesia, by complete exsanguination (blood serum was obtained by the generally accepted method). Organs (heart, kidneys, liver) and blood serum were collected.

To determine the elemental composition of the selected organ samples, preliminary sample preparation was carried out by the method of dry ashing with subsequent dissolution of the residue in a mixture of concentrated nitric and 10% trichloroacetic acids. The obtained samples were analyzed according to the standard method by the method of atomic absorption spectrometry on the S-115M1 device (Selmi, Ukraine, 2002) using lamps with hollow cathodes. Concentr ations of Ma E (Calcium and Magnesium) and ME: Zinc, Lead and Cadmium were determined on the basis of micrograms per gram of wet tissue (Alemasova, 2003). Determination of the content of SH-groups in homogenates of heart and liver was carried out by the spectrophotometric method with Ellman's reagent (Alfa Aesar, USA), (Ellman, 1959). LDH studies were performed using standard kits (Filicit-Diagnostics, Ukraine). AST was determined from blood serum using kits (Genrui Biotech, China) and ALT (High Technology, USA). The results of the study were statistically analyzed in ANOVA. Data in text and tables are presented as means with standard deviation (x ± SD). Differences between groups were considered statistically significant at $P < 0.05$ (taking into account the Bonferroni correction).

Results

The amount of lead in the liver of rats after the introduction of lead acetate was 18.61 times more than in the intact group (x ± SD, n = 16, Table 1).

Table 1
Concentrations of elements (Pb, Ca, Zn, Fe, Mg, Cd) in the internal organs of white male rats (μg/g) after administration of lead acetate

Elements		Intact group	Group with introduced lead acetate
Pb	liver	1.70 ± 0.20	19.43 ± 5.30***
	kidneys	3.10 ± 0.19	55.47 ± 13.82**
	heart	3.29 ± 0.24	9.52 ± 6.73
Ca	liver	3.17 ± 0.27	4.50 ± 0.24
	kidneys	4.86 ± 0.27	12.93 ± 0.71***
	heart	6.64 ± 1.33	6.41 ± 0.54
Zn	liver	14.56 ± 0.53	97.35 ± 3.40***
	kidneys	12.53 ± 0.31	14.29 ± 0.57
	heart	14.35 ± 1.05	11.57 ± 1.47
Fe	liver	14.42 ± 0.38	16.45 ± 2.03
	kidneys	13.84 ± 0.56	8.15 ± 0.54***
	heart	17.69 ± 0.90	11.57 ± 1.47***
Mg	liver	77.43 ± 1.46	155.14 ± 19.00***
	kidneys	65.89 ± 3.52	157.8 ± 12.51***
	heart	144.8 ± 2.12	91.49 ± 6.27
Cd	liver	7.78 ± 0.71	77.43 ± 1.46***
	kidneys	2.08 ± 0.33	2.01± 0.09
	heart	0.30 ± 0.12	1.07 ± 0.16**

Note:* – $P < 0.05$, ** – $P < 0.01$, *** – $P < 0.001$ compared to the control group of animals using ANOVA.

Lead accumulation occurred in the liver, where its concentration was 11.42 times higher than in the intact group ($F = 3.34$, $P = 5.292*10^{-3}$). Lead in the kidneys was 17.77 times more than in the control group. There were significant indicators of increase in kidneys by 2.89 times ($F = 3.79$, $P = 2.254*10^{-3}$). When examining the calcium content, it was found that it was 29.6% more in the liver compared to the control group. The indicators of the amount of lead in the heart were almost the same in both groups. In the experimental group of rats, a significant increase in the concentration of calcium in the kidneys was observed (by 2.66 times, $F = 10.62$, $P = 10^{-5}$). In the study group, 6.68 times more zinc was found in the liver than in the intact group ($F = 24.06$, $P = 10^{-6}$). But in the kidneys and heart, the amount in the control group does not differ significantly from the experimental one. In the kidneys, there was only 1.14 times more zinc than in intact ones. In the heart, the concentration of zinc in the intact group was 1.24 times higher compared to the experimental group.

As can be seen from the table, when lead acetate was administered, the distribution of iron was as follows: in the liver of rats, the content increased by 1.14 times compared to the intact group. In the kidneys, there was a decrease in the experimental group by 69.8% compared to the intact group ($F = 7.31$, $P = 6*10^{-6}$). An increase in iron by 52.9% compared to the control was also observed in the heart ($F = 3.55$, $P = 3.552*10^{-3}$). In the kidneys of the experimental group, magnesium concentration was 2.39 times higher than in the intact group ($F = 7.07$ $P = 8*10^{-6}$). In the liver, the difference in the experimental one was 2.00 times greater than in the intact one ($F = 4.08$ $P = 1.306*10^{-3}$). In the heart, on the contrary, in the intact group, these indicators exceed 52.9% of the experimental value ($F = 8.05$ $P = 2*10^{-3}$). The concentration of cadmium ions fluctuated within the intact group only in the kidneys, while an increase in its concentration was found in the rest of the samples: in the liver – by 9.95 times ($F = 42.90$, $P = 1*10^{-3}$), in the heart – by 3.5 times ($F = 3.85$, $P = 2.008*10^{-3}$).

Regarding the activity of LDH, its changes were not detected under the influence of lead acetate. However, the introduction of lead acetate affected the activity of one of the LDH fractions (decreased by 44.4% compared to the intact group). As a result, the distribution of LDH fractions has changed. If in animals of the intact group the urea-stable fraction of LDH was 58.8%, in the experimental group of lead acetate it was 32.5%. (Table 2). In contrast, in the heart there was an increase in LDH activity by 57.0% compared with control (Table 2). At the same time, the distribution between the factions remains unchanged.

The results of studies on the effect of lead acetate on a number of biochemical parameters of serum and organs of experimental rats are shown in Tables 2–6.

In the intact group, the concentration of metallothionein per gram of tissue in the liver was 8.05% higher than in the experimental group. The concentration of metallothionein per gram of protein in the liver in the control group was 2.02 times higher than in the research group ($F = 9.77$, $P = 1*10^{-7}$). In the liver of the control group animals, the concentration of SH-groups was 3.75 times higher than in the research group. In the heart, there was a 3.12 times increase in the concentration of SH in the group with the introduction of lead acetate compared to the intact group ($F = 27.46$, $P = 1*10^{-7}$). The concentration of GSH in the liver in the control group was 2.27 times higher than in the research group (Table 2).

Table 2
Change in indicators of SH-groups and metallothione in the liver and heart of experimental rats after administration of lead acetate (x ± SD, n = 16)

Organ	Indication	Intact group	Group with introduced lead acetate
Liver	Metallothionein, nmol/g tissue	65.70 ± 4.65	60.80 ± 3.04
	Metallothionein, nmol/mg protein	160.64 ± 6.17	79.48 ± 5.56***
	SH-groups, mmol/L	1.35 ± 0.03	0.36 ± 0.02***
	GSH, mmol/L	0.41 ± 0.08	0.18 ± 0.08
Heart	SH-groups, mmol/L	0.95 ± 0.12	2.96 ± 1.02

Note:* – P < 0.05, ** – P < 0.01, *** – P < 0.001 compared to the control group of animals using ANOVA.

Under the influence of lead acetate there was a slight decrease in the activity of both total LDH (by 26.6%) and its urea-stable fraction (by 22.5%). The percentage of urea-stable fraction of LDH did not change (in the intact group – 26.7%, in the experimental group – 28.2%).

In the liver there was a decrease in the content of SH-groups by 73.3% in the group with the introduction of lead acetate (Table 2). This may indicate the intensive use of thiol compounds in the mechanisms of detoxification and antioxidant protection of the body.

In the experimental rats due to the introduction of lead acetate, there was a dynamic: the activity of specific proteins of metalloteoneins – inhibits the synthesis of these proteins. Thus, the concentration of metallothioneins in the liver of rats loaded with lead acetate decreased by 7.5% (Table 2). In the blood serum of experimental animals in the model of lead intoxication, ALT activity increased compared with the intact group by 69.5% (Table 3).

AlAT activity in the blood serum of the experimental group of rats was 30.4% higher than the level of AlAT activity in animals of the intact group ($F = 2.45$, $P = 4.79*10^{-2}$) (Table 3). The activity of AST in the blood serum of the experimental group was almost at the same level of rats as the level of AST activity of animals of the intact group, only 2.78% more. The De Ritis coefficient (AST/ALT ratio) increased in blood serum of rats exposed to lead acetate by 40.5% compared to the intact group (Table 3).

Table 3
Serum aminotransferases activity in experimental rats after the introduction of lead acetate (x ± SD, n = 16)

Indication	Intact group	Group with introduced lead acetate
ALT, μmol/h×mL	2.65 ± 0.30	3.81 ± 0.49*
AST, μmol/h×mL	4.88 ± 0.48	5.02 ± 0.56
De Ritis coefficient, conventional units	1.84 ± 0.35	1.31 ± 0.24

Note: * – P < 0.05 compared to the control group of animals using ANOVA.

In conditions of lead intoxication, the activity of ALT in the liver (Table 4) of rats with a single injection of lead ions increased by 32.1% compared to the intact group.

Table 4
Liver aminotransferases activity in experimental rats after the introduction of lead acetate (x ± SD, n = 16)

Indication	Intact group	Group with introduced lead acetate
ALT, μmol/h×g	4.10 ± 0.06	6.04 ± 0.71*
AST, μmol/h×g	5.24 ± 0.44	5.87 ± 0.59
De Ritis coefficient, conventional units.	1.26 ± 0.16	0.97 ± 0.15

Note: * – P < 0.05 compared to the control group of animals using ANOVA.

The activity of AST in the liver homogenate of rats administered lead acetate increased by almost 10.7% (Table 4).

The De Ritis coefficient (AST/ALT ratio) decreased in the blood serum of rats exposed to lead acetate by 29.9% compared to the intact group.

Table 5
Heart aminotransferases activity in experimental rats after the introduction of lead acetate (x ± SD, n = 16)

Indication	Intact group	Group with introduced lead acetate
ALT, μmol/h×g	11.51 ± 1.13	6.23 ± 0.64**
AST, μmol/h×g	5.45 ± 0.53	5.51 ± 0.68
De Ritis coefficient, conventional units	0.47 ± 0.07	0.88 ± 0.084**

Note: ** – P < 0.01 compared to the control group of animals using ANOVA.

This indicates a shift in metabolic emphasis towards catabolism (the intensity of catabolic processes is 1.42 times higher). Significant correlations were found between changes in magnesium concentration and ACT activity in rat liver.

In conditions of lead intoxication, the activity of ALT ($F = 4.06$, $P = 1.356*10^{-3}$, Table 5) in the heart of rats with the introduction of lead acetate decreased by 84.8% compared to the intact group. The activity of AST in the homogenate of the heart of rats with a single injection of lead ions remained at the level of the intact group. The De Ritis coefficient (AST/ALT ratio) in the heart of the experimental group is 46.6% higher than in the intact group ($F = 3.75$, $P = 2.429*10^{-3}$).

Discussion

The results of this study provide valuable information on the complex interplay between lead (II) exposure, nutrient distribution, and biochemical parameters in living organisms. Understanding these interactions is critical to assessing the health and metabolic effects of heavy metal pollution (Honcharenko et al., 2012; Zhou et al., 2020).

Kenston (2018) confirmed hematological abnormality, decreased renal function, liver damage and electrolyte imbalance in rats treated with high doses of heavy metals. It is known that the liver is the main detoxifying organ in the body, and the accumulation of lead in it can be caused by its binding to metallothioneins, a significant amount of which is found in the liver (Bortey-Sam et al., 2016; Hend et al., 2018). Therefore, most of the changes in the studied parameters were detected in this organ (Jones et al., 2017).

A decrease in the content of SH-groups was observed in the liver of rats in the group with the introduction of lead acetate. This may indicate the intensive use of thiol compounds in the mechanisms of detoxification and antioxidant protection of the body (Khalil et al., 2018).

The results show that metabolic changes in simulated lead intoxication occur mainly in the liver. Reduced glutathione (GSH) is the most important intracellular protective agent of organs and tissues. The main organ of GSH synthesis in mammals is the liver. Under normal physiological conditions, it provides about 90.0% of all circulating glutathione in the body. Most of the GSH is contained in the cytoplasm and is renewed very quickly. The analysis of the obtained indicators of the restored concentration of glutathione in the liver homogenate revealed a statistically significant decrease in the content of GSH when loaded with lead acetate

($P < 0.01$). The following dynamics are observed in experimental rats when lead acetate is administered: the activity of specific metallothionein proteins suppresses the synthesis of these proteins. Thus, the concentration of metallothioneins in the liver of rats loaded with lead acetate decreased by 2.27 times. The increase in cardiac sulfhydryl groups may reflect increased antioxidant capacity in response to oxidative stress caused by lead exposure. Conversely, a decrease in hepatic GSH indicates increased utilization of this important antioxidant molecule, potentially making the liver more vulnerable to oxidative damage (Karri et al., 2018; Gogoi et al., 2019).

Differences in the change in MTN content when using different types of concentration calculation indicate a significant impact of lead acetate load on the function of protein synthesis in the liver compared to other types of proteins. These data indicate an increase in protein synthesis in the liver, so the numbers vary between the concentration based on crude tissue mass and the concentration of total protein (Sanders et al., 2014).

Against the background of adaptive changes in the metabolism of toxic metals, a violation of the balance of vital elements (Ca, Mg, Zn, Fe and Cd) was revealed (Soussi et al., 2018; Kucukler et al., 2021).

The concentration of cadmium ions changes within the intact group only in the kidneys, while an increase in its concentration was found in the rest of the samples: in the liver – by 4.07 times, in the heart – by 3.50 times (Lu et al., 2018).

Exposure to lead led to noticeable changes in the distribution of a number of macro- and microelements in the organs of rats. In particular, there was an increase in the concentration of calcium in the kidneys of rats receiving calcium, indicating an effect on calcium homeostasis. Conversely, only a slight increase in calcium content was observed in the liver. Such disturbances can have consequences for bone health and cellular signaling pathways (Su et al., 2017; Proshad et al., 2020).

The results indicate that changes in the distribution of nutrients in organs reveal a complex response to lead exposure. A sharp decrease in zinc levels in the liver is of concern because zinc is an important cofactor for many enzymes and plays a critical role in immune function and DNA synthesis (Wildemann et al., 2015; Samuel et al., 2021). Reduced iron content in the kidneys can affect erythropoiesis and oxygen transport. Conversely, a small increase in liver iron may indicate a response to oxidative stress. The variation in magnesium levels in different organs highlights the importance of magnesium in maintaining physiological balance with potential effects on muscle and nerve function. A significant increase in the level of cadmium in various organs emphasizes the risk of co-accumulation of various heavy metals in the body. Cadmium is known for its harmful effects on kidney function and is a strong carcinogen, making its accumulation a serious consequence of lead exposure.

Changes in LDH activity and a shift in the profile of the LDH fraction indicate adaptive changes in energy metabolism. An increase in cardiac LDH activity may indicate a shift toward aerobic energy production in response to lead exposure, whereas a decrease in hepatic ALT activity may indicate liver dysfunction. These changes may reflect the body's efforts to adapt to heavy metal stress. Thus, the effect of lead acetate on the studied enzymes and other biochemical markers was varied. The introduction of lead acetate led to a decrease in the activity of LDH in the liver of rats and an increase in cardiac activity, which indicates a more efficient aerobic energy exchange (Konovalova, 2019; Xie et al., 2023).

In conditions of adaptation to lead intoxication, instead, ALT activity increases in the liver and decreases in the heart. Thus, the effect of lead acetate on the studied enzymes and other biochemical markers was diverse. The introduction of lead acetate led to a decrease in LDH activity in the liver of rats and an increase in the heart, which indicates a more efficient aerobic energy metabolism in terms of adaptation to lead intoxication. Instead, ALT activity increases in the liver and decreases in the heart.

The study showed that exposure to lead infusion results in changes in aminotransferase activity in both serum and liver. Elevated serum ALT levels indicate potential liver damage, while elevated AST levels may indicate liver dysfunction, acute cardiovascular disease, muscle damage. A decrease in the De Ritis coefficient in the blood serum emphasizes the complexity of metabolic reactions to the influence of lead with a shift towards anabolic processes. The De Ritis coefficient (AST/ALT ratio) in the blood serum of rats with a load of lead acetate decreased by 71.1% compared to the intact group. This testifies to the variety of metabolic processes in the body of experimental animals under different schemes of loading with lead acetate. Thus, in the group receiving lead acetate, the peripheral link of metabolism (anabolic profile) prevails.

In general, these obtained data emphasize the multifaceted nature of heavy metal toxicity and its impact on various physiological systems. The observed changes in the distribution of nutrients, biochemical parameters and enzyme activity emphasize the need for comprehensive strategies to mitigate the adverse effects of heavy metal exposure. Further research is needed to elucidate the specific mechanisms driving these changes and to develop targeted interventions to protect against health risks caused by heavy metals. This study contributes to our understanding of the complex relationship between heavy metal exposure and metabolic processes, highlighting the importance of environmental and public health policies aimed at reducing heavy metal pollution. Analyzing the results, it can be noted that, in general, the enzyme system of the rat's body changes its activity under the influence of lead acetate, which indicates its toxic effect.

Conclusions

A comprehensive study of the effects of lead (II) on nutrient distribution, biochemical parameters, and enzymatic activity in rat organs has provided important insight into the complex nature of heavy metal toxicity. These changes, in particular, in the level of lead in the liver 19.43 ± 5.30 μg/g ($P < 0.001$) and kidneys 55.47 ± 13.82 μg/g ($P < 0.001$), in the levels of calcium in the kidneys 12.93 ± 0.71 μg/g ($P < 0.001$), zinc in the liver 97.35 ± 3.40 μg/g ($P < 0.001$), iron in the kidneys 8.15 ± 0.54 μg/g ($P < 0.001$), heart 11.57 ± 1.47 μg/g ($P < 0.05$) and magnesium in the liver 155.1 ± 19.0 μg/g ($P < 0.001$), kidneys 157.8 ± 12.5 μg/g ($P < 0.001$). Cadmium in the liver 77.43 ± 1.46 μg/g ($P < 0.001$) and heart 1.07 ± 0.16 μg/g ($P < 0.05$) indicate a potential disturbance of metabolic pathways and cellular functions with consequences for general health.

The increased level of cadmium in the liver raises concerns about the co-accumulation of various heavy metals in the body. The well-established toxic effects of cadmium underscore the importance of this discovery. Metabolic shifts, altered LDH activity, and fraction profiles indicate adaptive changes in energy metabolism in response to lead exposure. The switch to aerobic energy production in the heart and the decrease in ALT activity in the liver reflect the body's efforts to adapt to heavy metal stress.

Changes in sulfhydryl groups and reduced glutathione levels indicate different responses to oxidative stress in different organs. Although the heart increases its antioxidant capacity, the liver may become more susceptible to oxidative damage.

The observed changes in ALT and AST activity levels indicate potential liver damage and cellular distress, highlighting the complexity of metabolic responses to lead exposure. In summary, this study demonstrates a complex relationship between heavy metal exposure and metabolic and biochemical processes in the body. This reinforces the need for continued research into the toxicity of heavy metals and their health consequences. These results emphasize the importance of implementing measures to reduce environmental pollution by heavy metals and developing strategies to protect living organisms from the adverse effects of heavy metal exposure. Ultimately, the study findings provide a basis for future research and the development of interventions, such as functional foods and environmental policies, aimed at mitigating the health risks associated with heavy metal exposure. As global concern about environmental pollution and its impact on human health and the environment remains, this research contributes to our understanding of a critical issue facing society today.

The authors claim they have no conflict of interest.

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