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Research Article

From Environmental Monitoring to Biological Risk - A New Paradigm for Managing Heavy Metal Contamination.

Innocente Cataldo Galeandro, Andrea Del Buono, Luca Rastrelli, Armando D'Orta, Vincenzo Lettieri, Luciano Martucci.

1 Medical technological division of TECNOPOLIS, the Science and Technology Park of the University of Bari.
2 Department of Pharmacy, University of Salerno.
3 XRF-200 Beauty and Healthcare Technician at Homae srls;
4 Global Research Foundation, Taranto.

Abstract

This study introduces a new paradigm for managing heavy metal contamination, integrating widespread environmental monitoring with individual-level biological risk assessment. Through the analysis of hair mineralograms and their correlation with systemic inflammatory markers derived from blood counts, we highlight heterogeneous, patchy environmental contamination and its direct impact on the induction of a silent, chronic inflammatory state in exposed populations. This holistic approach provides crucial tools for identifying contamination hotspots, guiding targeted remediation interventions and implementing proactive public health strategies based on early biomarkers of damage.

Keywords : Heavy Metals, Environmental Monitoring, Biological Risk, Systemic Inflammation, Mineralogram, XRF, NLR, PLR, SII, Land of Fires.

INTRODUCTION

Environmental contamination by heavy metals represents a global challenge for public health and ecosystems. Elements such as lead, mercury, cadmium, arsenic, and chromium, even at low concentrations, can accumulate in living organisms and induce long-term toxic effects [1,2]. Traditionally, risk management has relied on large-scale environmental monitoring, which is often insufficient to capture the complexity and heterogeneity of pollutant distribution and their direct biological impact.

This study aims to overcome this limitation by integrating an advanced biomonitoring strategy based on hair analysis with the assessment of biomarkers of biological damage at the individual level. The goal is to develop a new paradigm that allows for the correlation of environmental exposures with the systemic inflammatory response, providing a more accurate picture of risk and supporting more effective interventions.

OBJECTIVE

The primary objective of this study is to assess the environmental and biological impact of heavy metals. Specifically, it aims to map the distribution of heavy metals in areas known to be affected by spills and compare them with uncontaminated areas, in order to delineate the relationship between environmental exposure and potential health effects.

To achieve this goal, the study will focus on two main aspects:

Assessment of Environmental Risk Biomarkers: The presence of toxic metals and nutritional metal deficiency will be analysed as indicators of environmental and health risk.

Analysis of Biological Damage in the Exposed Population: In a randomly selected subgroup with a complete blood count (CBC) previously performed for health screening and no more than 90 days old, the relationship between environmental contamination by toxic metals and measurable biological damage was explored. This will be done by analyzing known systemic inflammatory markers derived from white blood cell and platelet counts.

***Corresponding Author:** **Luciano Martucci,** Global Research Foundation, Taranto. **Email :** luciano.martucci11@gmail.com.
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ENVIRONMENTAL AND BIOLOGICAL RISK INDICATORS

Key systemic inflammatory risk indicators that will be calculated and analyzed include:

- NLR (Neutrophil-to-Lymphocyte Ratio): Ratio between the number of neutrophils and lymphocytes. o Formula: NLR=Absolute Lymphocyte CountAbsolute Neutrophil Count
- PLR (Platelet-to-Lymphocyte Ratio): Ratio between the number of platelets and lymphocytes. Formula: PLR=Absolute Lymphocyte CountPlatelet Count
- SII (Systemic Inflammation Index): Aggregate index that combines platelets, neutrophils and lymphocytes, considered more sensitive [3].

Formula: SII=Absolute Lymphocyte Count/Platelet Count × Absolute Neutrophil Count

This dual-track approach will allow us to better understand the impact of heavy metal contamination on the environment and human health, providing useful data for future mitigation and prevention strategies.

MATERIALS AND METHODS

Analysis Of The Distribution Of Metals On Organic Matrix (Hair) As A Strategy For Monitoring And Identification Of Contamination Sources

The present study focuses on the analysis of mineralograms of biological matrices (hair), using heavy metals as biomarkers of environmental exposure and toxicological risk [4]. The primary hypothesis of this study is the correlation between the concentration of metals in hair samples and residence in geographical areas characterized by a high and documented anthropogenic impact, such as the "Land of Fires", known for the illicit disposal of industrial and urban waste.

Use Of The Xrf-200 Analyzer For The Elemental Analysis Of Metals

For this large-scale investigation, an X-ray fluorescence (XRF) analyzer, model XRF-200, was used. The choice of this instrumentation was motivated by:

- Non-destructive analysis: The sample is not altered, allowing for further analysis.
- Speed: Each analysis takes only a few minutes, allowing for the processing of a large low-cost sample volume.
- Minimal preparation: Unlike other techniques, it requires minimal preparation or sample zero, reducing time, costs and contamination risks.
- Multielemental Analysis: Simultaneously detects and quantifies a wide range of elements in a single measurement [5,6].

Analytical Validation And Instrumental Performance

From a performance point of view, the tool guarantees:

• Certain identification: Each element has a unique energetic "fingerprint", ensuring unambiguous identification.

• Adequate sensitivity: Detects metals at the parts per million (ppm) level, sufficient for biomonitoring studies with toxicological relevance.

• Accuracy and reproducibility: Rigorous calibration with certified reference materials ensures precise and reliable results.

In conclusion, the XRF-200 was deemed the ideal tool for the study, as it offers rapid, economical and reliable screening, essential for mapping contamination, identifying high-risk areas and identifying the most exposed subjects.

RESULTS AND DISCUSSION

Mapped Areas And Collected Data

Below is a table summarizing the mapped areas, the number of mineralogical tests performed in each city using the XRF-200, and the related dates:

Città	Numero di Esami Eseguiti	Data
R Acerra	3	24/04/2025
R Afragola	9	09/12/2024
V Bracciano	11	04/12/2024
R Casandrino	21	04/03/2025; 28/04/2025; 31/03/2025
R Castel Volturno	30	07/04/2025; 14/03/2025
V Castelmadama	4	30/04/2025
V Cellole	1	20/03/2025
R Cercola	7	12/12/2024; 20/03/2025
R Cesa	2	03/04/2025
R Crispano	17	01/04/2025; 06/03/2025
V Esperia	13	02/03/2025; 14/04/2025
V Fiano Romano	26	12/04/2025; 26/04/2025
V Gaeta	3	06/12/2024

R Gricignano	4	10/03/2025
R Lusciano	1	18/04/2025
V Maddaloni	13	02/12/2024; 07/03/2025; 23/04/2025
R Ottaviano	16	16/04/2025; 19/03/2025
R Poggiomarino	1	02/04/2025
V Ragusa	11	11/11/2024
B Recale	3	04/04/2025; 05/03/2025
B San Nicola L.S	5	09/04/2025; 11/03/2025
V San Pietro Infine	13	05/03/2025; 29/04/2025
R Sant'Antonio Abate	11	11/12/2024; 27/03/2025
R Sant'Arpino	11	12/12/2024; 13/03/2025; 16/04/2025; 25/03/2025
R Sant'Elpidio	4	05/12/2024
R Saviano	6	09/12/2024; 19/03/2025
V Sessa Aurunca	9	06/12/2024; 24/03/2025
R Somma Vesuviana	6	04/03/2025; 10/04/2025
B Taranto	87	19/02/2025
R Terzigno	6	02/04/2025
V Vico Equense	7	26/03/2025
R Villaricca	22	08/04/2025; 10/12/2024; 19/11/2024
Total Exams	383	

Elemental analysis, conducted via X-ray fluorescence spectrometry (XRF) on hair samples, has allowed us to delineate distinct contamination profiles, or "elemental signatures," for each geographic area. These profiles reflect a complex interaction between local geology, industrial activities, agricultural practices, and lifestyles.[1]

In the Red Areas (See R), traditionally considered to be at higher risk, the results revealed a complex picture. While the absence of classic heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) was evident, traces of mercury (Hg), tin (Sn), chromium (Cr), and nickel (Ni) were detected sporadically but sometimes significantly. This suggests that the sources of exposure are not constant, but rather linked to specific events or localized sources. Very high levels of nutritional minerals such as calcium (Ca) and potassium (K) were found in all samples from these areas.[1]

The Green Areas (See V), designated as control zones, surprisingly revealed a nearly constant presence of Mercury (Hg) and Chromium (Cr). Concentrations of Lead (Pb), Arsenic (As), and Tin (Sn) were also found in some samples. Here, too, levels of Calcium, Potassium, Zinc (Zn), and Copper (Cu) were notable. A peculiar finding was the detection of an exceptionally high level of Selenium (Se) in a single group, an element that can be toxic in excess.[1]

The Blue Areas (See B), which include areas with a strong industrial impact such as Taranto[10], showed a profile characterised by the almost omniprescence of mercury (Hg), followed by lead and tin. In these samples, titanium (Ti) was detected in variable but constant concentrations. The most abundant nutritional minerals were calcium and zinc.[1]

A crucial aspect of these results is the complete absence of Cadmium (Cd) and Arsenic (As) in all 383 samples analyzed. [1] This "negative evidence" is a fundamental finding that challenges the classic narrative of pollution.

Industrial. These metals are canonical pollutants associated with heavy industry, mining, and pesticides of the past. Their absence, combined with the constant presence of mercury (Hg), tin (Sn), and titanium (Ti), suggests that the sources of contamination may be more specific and modern than commonly assumed. This shifts the focus from a generic "industrial pollution" to a specific cocktail of contaminants, which could arise from sources such as electronic waste (e-waste), plastics, specific chemical production, or bioaccumulation from marine sources (in the case of mercury). This recalibration of the problem has profound implications for environmental forensics and remediation strategies, which must now focus on industries and waste streams other than those traditionally monitored.

Deconstructing Contamination Patterns: The Statistical History of "Hotspots"

Statistical analysis of the aggregate data reveals that the high variability in concentrations is not background noise, but the most important scientific finding. This variability mathematically demonstrates the "hotspot" nature of contamination and invalidates the use of average values for assessing public health risks.[1]

The following table summarizes the descriptive statistics for the most significant metals detected in the study. All values are expressed in parts per million (ppm).[1]

Table 1. Summary of Elemental Concentrations and Their Variability (ppm)

Element	Mean (ppm)	Median (ppm)	Standard Deviation (ppm)
Toxic Metals			
Lead (Pb)	6.29	0.00	8.22
Mercury (Hg)	8.08	0.00	16.47
Chromium (Cr)	17.21	15.00	12.58
Tin (Sn)	46.18	68.00	34.51
Nutritional Metals			
Calcium (Ca)	3584.44	3724.00	1820.15
Potassium (K)	917.18	1000.00	410.21
Copper (Cu)	139.44	91.00	118.03
Zinc (Zn)	429.33	388.00	139.34

Source: Aggregated data from 383 mineralogical tests.1

An analysis of this table is illuminating. For key toxic metals such as lead (Pb) and mercury (Hg), the median is 0.00 ppm, while the mean is significantly higher (6.29 ppm for Pb and 8.08 ppm for Hg). This discrepancy, combined with a very high standard deviation (8.22 for Pb and 16.47 for Hg), is irrefutable statistical evidence of a highly skewed distribution. The mean value skews upward. This means that the majority of the sampled population has no detectable exposure to these specific metals, but an unfortunate minority is exposed to very high concentrations (so-called "outliers" or "peaks"), which drag down the risk of exposure to these metals. [1] However, we believe that the term "unfortunate" could be reductive if interpreted as merely coincidental. Current scientific knowledge suggests instead the existence of an individual biological susceptibility that determines greater vulnerability in some subjects. This vulnerability is the result of a complex gene-environment interaction, where key factors come into play such as:

1. genetic polymorphisms that reduce the efficiency of endogenous detoxification enzymes (e.g. glutathione transferase[20,21,22], SOD[23,24,25], catalase[26,27,28];
2. epigenetic phenomena[29,30,31,32] through which lifestyle and chronic exposure to other environmental stressors can modulate the expression of these same genes. This interaction explains why, given the same exposure, some individuals accumulate significantly higher toxin loads, resulting in altered immune-inflammatory indices. The identification of these susceptible individuals is now possible through advanced diagnostic methods, which analyse the genetic and functional profile of the detoxification pathways.

This statistical reality makes any health policy based on the "average contamination" of an area not only inaccurate, but dangerously misleading. A strategy based on averages would completely ignore the very high-risk individuals living in "hotspots." Consequently, the distribution of contaminants requires a radical change in monitoring strategy. Traditional environmental sampling (e.g., soil or water analysis) over a large area has a high probability of missing a localised hotspot, returning a false negative and creating the illusion of safety. In contrast, a human being acts as a biological integrator of their environment. Hair analysis, as used in this study, reflects chronic exposure over time from multiple sources (air, water, food).[1] Therefore, an elevated level of a toxicant in an individual's hair sample is definitive evidence of a significant exposure route, regardless of what a random soil sample might indicate. This makes individual biomonitoring not only a better method, but the only scientifically valid method for assessing the real risk to human health in a "leopard-spot" contamination scenario.

The Biological Ecology of Environmental Exposure

These data allow us to shift our focus from the "what" and "where" of contamination to the "doing," establishing a critical link between environmental data and their tangible and measurable impact on human physiology. It is here that the study's innovative contribution is fully elucidated: the connection between XRF data and hematological indices.

The Body's Silent Alarm System: Pathophysiology of Systemic Inflammation Indices

To quantify the biological damage induced by heavy metal exposure, the study used a panel of biomarkers derived from a common blood count. These indices, known as systemic inflammation indices, act as an early warning system, signaling a state of chronic physiological stress.1 The three key indicators analyzed were:

1. NLR (Neutrophil-to-Lymphocyte Ratio): The ratio between the number of neutrophils and lymphocytes.

Formula: NLR = Absolute Lymphocyte Count Absolute Neutrophil Count

This index reflects the balance between the innate immune

system (represented by neutrophils, the "front-line" cells) and the adaptive immune system (represented by lymphocytes, responsible for the specific response and immunological memory). An elevated NLR indicates a shift toward an acute inflammatory response and a relative suppression of adaptive immunity.[1]

2. PLR (Platelet-to-Lymphocyte Ratio): The ratio between the number of platelets and lymphocytes.

Formula: PLR = Absolute Lymphocyte Count Platelet Count

This index includes platelets, which are not only involved in coagulation but also actively participate in inflammatory processes by releasing pro-inflammatory mediators. An elevated PLR suggests a pro-thrombotic and pro-inflammatory state.[1]

3. SII (Systemic Inflammation Index): An aggregate index that combines platelets, neutrophils and lymphocytes, considered more sensitive and robust.

Formula: SII = Absolute Lymphocyte Count Platelet Count × Absolute Neutrophil Count

The IBS provides a more comprehensive measure of immune imbalance and systemic inflammatory status.

An elevation of these indices is widely recognized in the scientific literature as a sign of chronic low-grade inflammation, a common risk factor and a pathogenic mechanism underlying a wide range of chronic non-communicable diseases, including cardiovascular diseases, metabolic disorders such as diabetes, neurodegenerative diseases and an increased risk of cancer.[1]

The use of these indices in environmental toxicology represents a paradigm shift. It transforms a ubiquitous and low-cost clinical test, the complete blood count, into a high-throughput screening tool for environmental health. Because the complete blood count is one of the most common laboratory tests, a vast reservoir of medical data exists that could be analyzed, in an anonymous and aggregated form, for public health surveillance. Health authorities could geographically map clusters of elevated SII values to identify potential, unknown environmental exposure hotspots, leveraging existing healthcare infrastructure for proactive detection of environmental risk at minimal cost.

Making the Connection: Correlating Metal Load to Systemic Inflammation

The key point of this study is the demonstration of a direct and measurable link between toxic metals present in the hair and a state of chronic inflammation in the blood.

In essence, research has proven that the accumulation of toxic metals is not a harmless or inert presence in the body. Instead, these metals act as an active trigger that causes actual biological damage (oxidative stress), leading to chronic inflammation measurable through specific blood indices (NLR, PLR, SII).

A New Paradigm for Proactive Public Health and Environmental Governance

These findings guide policymakers toward targeted and strategic management, which can be implemented locally without significant financial expenditure, and to provide strategic and actionable recommendations. It moves from analysis to proposal, strongly advocating for a fundamental overhaul of how environmental contamination and public health are managed. The patchy nature of contamination makes environmental policies based on macro-areas obsolete and inefficient. The study "categorically refuted" the hypothesis of homogeneous contamination within historically defined risk zones, demonstrating the ineffectiveness of monitoring based on generalized territorial assumptions. [15]

It is therefore imperative to abandon large-scale intervention approaches in favor of a streamlined, evidence-driven approach focused on identifying and remediating specific localized "hotspots."

This new approach, based on widespread and continuous biomonitoring, is not only more environmentally effective but also more economically sustainable. It focuses limited resources precisely where the risk is highest, maximizing the impact of cleanup interventions. Furthermore, the methodology employed provides a new tool for environmental accountability. The "elementary signatures" discussed in Section 1.2 can act as fingerprints for specific pollution sources. For example, a hotspot with high levels of tin (Sn) and titanium (Ti) but low lead (Pb) indicates a different pollutant source than a lead-acid battery landfill. By systematically implementing this monitoring technique, authorities can not only identify areas requiring cleanup but also generate evidence to trace the specific industrial, agricultural, or waste disposal activities responsible. This shifts the paradigm from simply managing a widespread, anonymous problem to an environmental forensic investigation system that can enforce regulations and assign liability, creating a powerful deterrent against future pollution.

Early Diagnosis as the Cornerstone of Prevention: A New Public Health Strategy

The study's most profound public health implications are the potential for using inexpensive, readily available inflammatory markers from routine blood tests as a primary screening tool for environmental health risks. The demonstrated link between metal exposure and elevated IBS transforms the complete blood count from a simple diagnostic test to a powerful tool for proactive risk management.[18,19]

This approach allows for the identification of a state of "silent inflammation"—a measurable biological lesion—well before the clinical manifestation of a chronic disease.[18,19]

It represents a fundamental shift from a reactive healthcare model (which treats diseases after their onset) to a proactive

one (which identifies and mitigates risk factors to prevent disease onset). To operationalize this new paradigm, the following integrated surveillance protocol is proposed:

Table 2. Proposed Integrated Surveillance Protocol.

Phase	Action	Toll	Outcome
Phase 1: Extensive Surveillance	Analysis of anonymized regional blood count data to identify geographic clusters of elevated SII/NLR/PLR indices.	Existing health data (Big Data Analysis).	Mapping of areas at potential systemic inflammatory risk.
Phase 2: Targeted Biomonitoring	Offer of voluntary hair mineralogy analysis (XRF) to residents of the hotspots identified in Phase 1.	Hair analysis (XRF).	Identification of individuals with high toxic metal burden and confirmation of the source of environmental stress.
Phase 3: Environmental Forensic Investigation	In areas with confirmed high toxic loads, conduct detailed environmental sampling (soil, water, air) to identify the source of pollution.	Environmental chemical analysis.	Identification and precise location of the polluting source for remediation actions.
Fase 4: Integrated Intervention	Implementation of targeted environmental remediation and provision of personalized public health care (e.g., detoxification protocols, nutritional support) to affected individuals.	Implementation of targeted environmental remediation and provision of personalized public health care (e.g., detoxification protocols, nutritional support) to affected individuals.	Remediation interventions and clinical protocols. Reduction of environmental exposure and monitoring of the effectiveness of the intervention through the normalization of inflammatory indices (SII/NLR/PLR).

This protocol provides a clear and step-by-step roadmap for implementing the new paradigm by public health and environmental agencies, making the study's conclusions concrete and actionable.

Conclusion: The Future of Integrated Surveillance

In conclusion, this research demonstrates that effectively addressing the problem of heavy metal pollution requires a holistic approach that combines land monitoring with human health surveillance. Mapping environmental risk is no longer sufficient; measuring its biological impact is essential. The integrated approach that combines mineralogram analysis with inflammatory indices represents a next-generation governance tool, capable of transforming raw data into strategic knowledge.

Abandoning generalised risk models in favor of a detailed analysis allows for precise action, protecting ecosystems and actively promoting community health. Moving from a policy of damage tracking to a proactive strategy of prevention, ecosystem protection, and public health safeguards is not only a desirable goal, but a necessity made possible by this

A new scientific paradigm. Through the synergy between environmental and medical sciences, it is possible to build a healthier, more sustainable, and more informed future.

TABEL

Red Areas (- R-)

• Toxic Metals Detected: Traces of Chromium (Cr), Mercury (Hg), Tin (Sn) and Nickel (Ni) in some tests, while other toxic metals such as Lead (Pb), Cadmium (Cd) and Arsenic (As) were not detected.

Note: In order to display all nutritional metals on the same graph, the Y-axis (concentration) scale is very wide due to the high values of calcium (Ca) and potassium (K). This makes metals present in lower concentrations appear very low in comparison.

The results paint a complex and variable picture. On the one hand, a reassuring finding emerges: the absence of the most commonly feared heavy metals, such as lead, cadmium, and arsenic. On the other hand, clear exposure to specific toxic metals, such as mercury and tin, is evident in some tests, as well as very high levels of nutritional minerals, such as calcium and potassium, in all samples. The significant variability between the different tests suggests exposures that are not constant over time, but rather linked to specific sources or sporadic events. The strong variability in the results, especially for toxic metals, is the most significant element. This is not a stable picture, but a series of "snapshots" that could reflect different exposures over time. Anomalies are evident; for example, some samples contain higher levels of mercury than others, as are the same for tin and copper.

Figure 1.

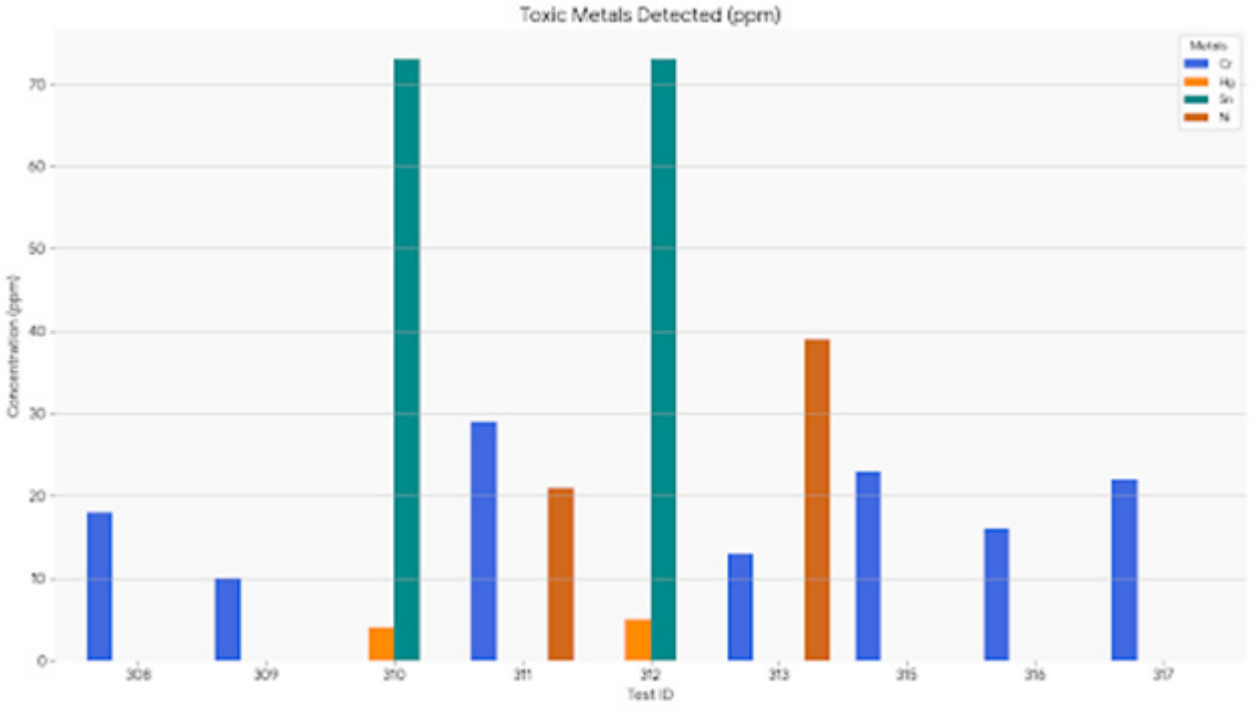
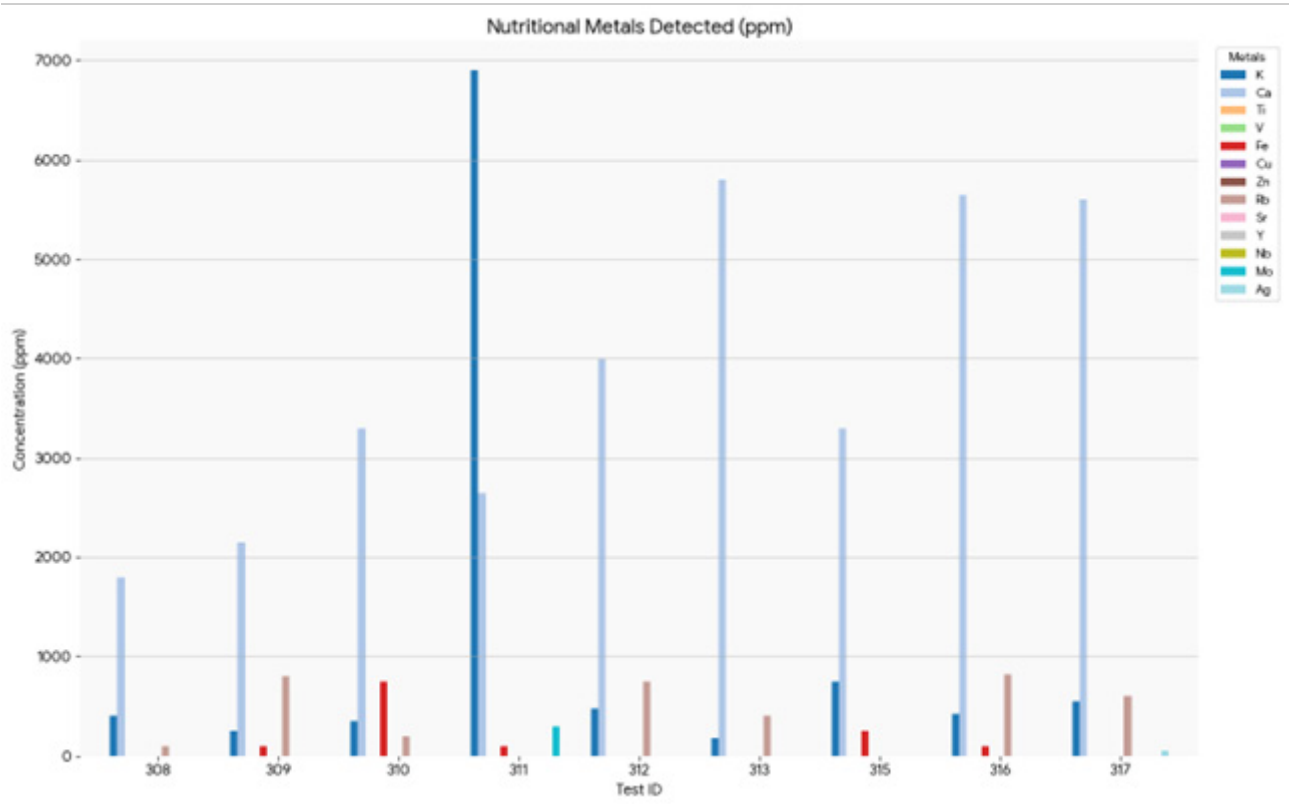


Figure 2.



Green Areas (- V -)

• Nutritional Metals: This series also confirms very high levels of Calcium (Ca) and Potassium (K) and a notable presence of Zinc (Zn) and Copper (Cu). A peculiar finding of this series is the detection of Selenium (Se) at a significant level only in group 212 (199 ppm).

• Toxic Metals Detected: almost constant presence of Mercury (Hg) and Chromium (Cr). In some specific samples, concentrations of Lead (Pb), Arsenic (As) and Tin (Sn) were also detected. An exceptionally high level of Selenium (Se), a mineral that can be toxic in excess [8], and anomalous peaks of Iron are present in group 212.

Figure 3.

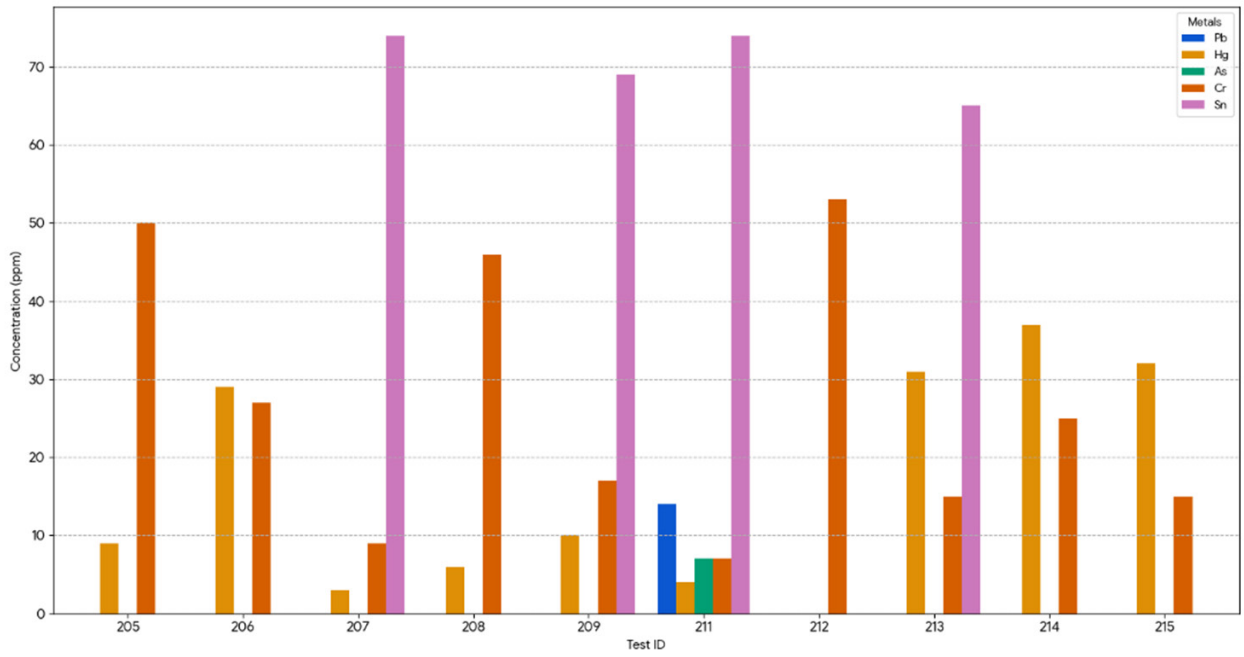
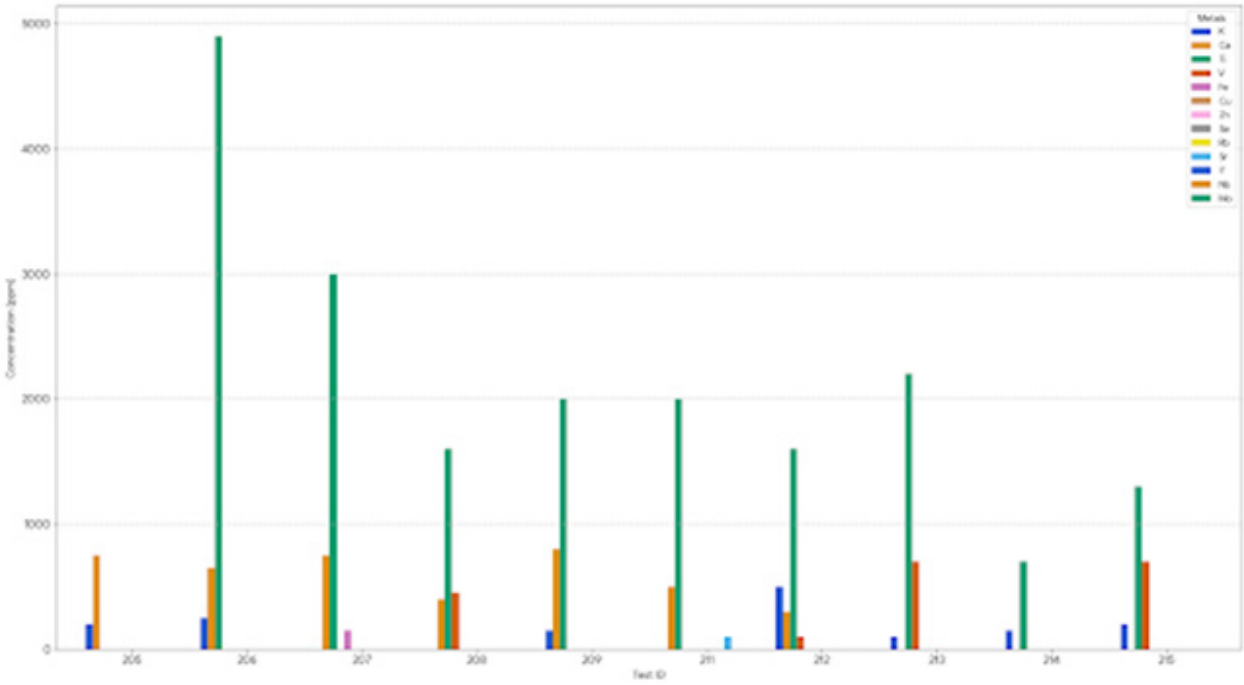


Figure 4.



Blue Areas (- B -)

• Nutritional Metals: o Calcium (Ca) and Zinc (Zn) are by far the most abundant minerals in almost all samples.
o Potassium (K) is the third most concentrated element.
• Toxic and Potentially Toxic Metals: o Mercury (Hg) was detected in almost all samples, followed by Lead and Tin.
o Titanium (Ti) is present in almost all samples in varying concentrations.

Figure 5.

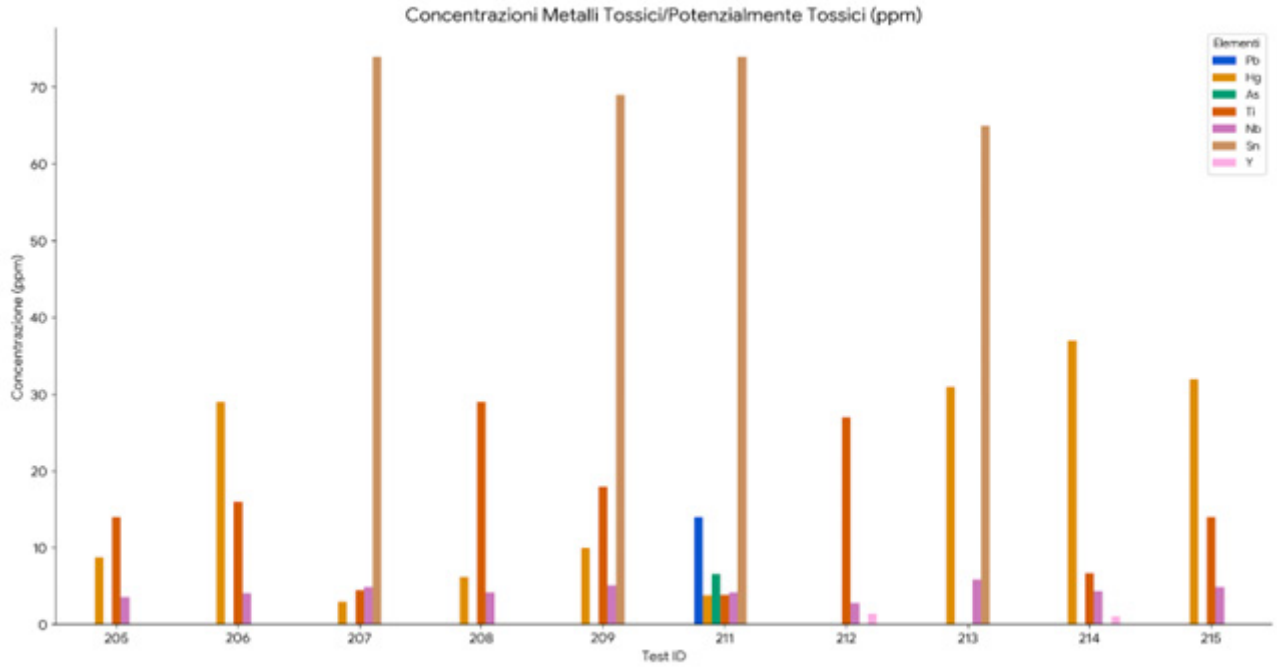
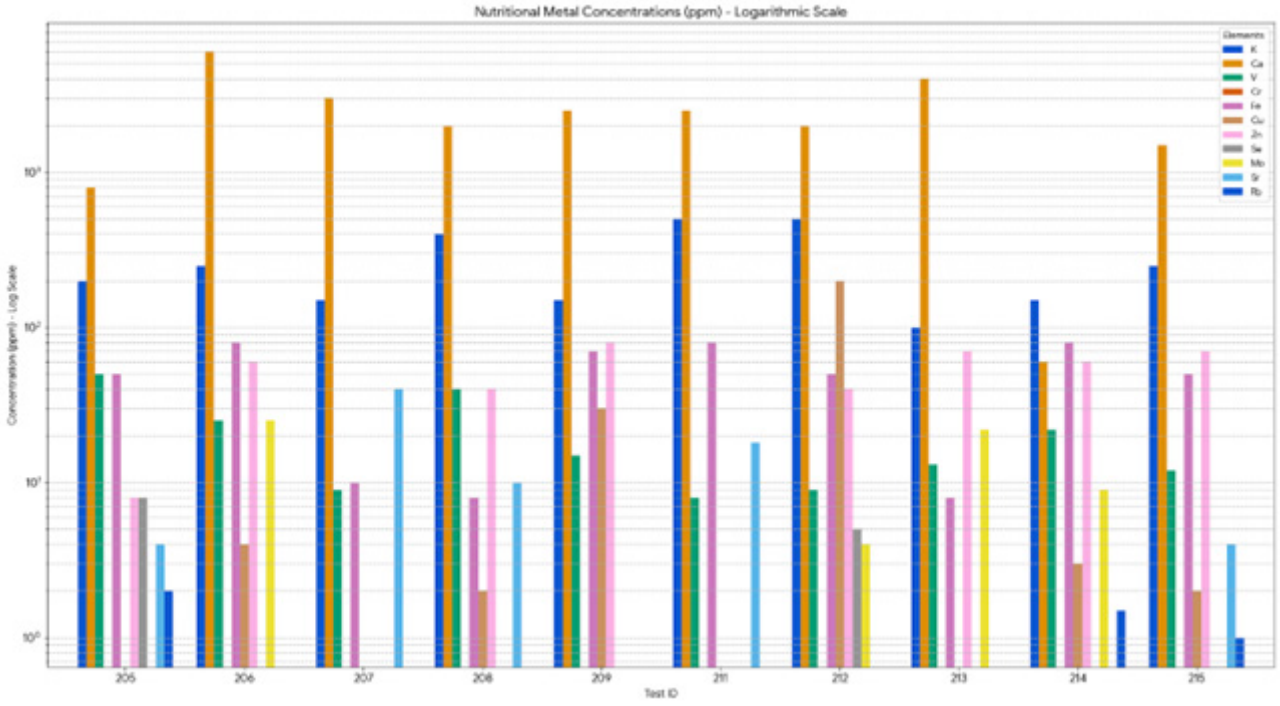


Figure 6.



Red-Green And Blue Areas: Mean, Median, Standard Deviation

The following tables summarise the data from all tests, providing an overview of the central tendencies and variability for each element. All values are in ppm (parts per million).

• Mean: The average value of the concentrations. • Median: The central value (half of the samples have a higher value and half a lower value). It is often more representative than the mean when there are outliers.

• Standard Deviation (std): A measure of how much the values deviate from the mean. A high value indicates a large variability between samples.

CONCLUSION

The discovery is fundamental for two main reasons:
1. Transform the perception of risk: We are no longer talking just about "exposure" to metals, but about active and ongoing physiological damage, which represents a concrete risk factor for the future development of chronic diseases.
2. Strengthens the value of hair analysis: The study creates a "bridge" between hair data and a recognized medical effect (inflammation). This elevates hair analysis from a simple exposure test to a valid tool for identifying at-risk individuals who are already suffering biological damage. This increases its importance and credibility for public health and legal purposes, justifying its use to guide preventative interventions.
Use:
The biological mechanism linking metal exposure to inflammation is well documented. Toxic metals such as mercury, lead, and chromium are potent inducers of oxidative stress. This persistent cellular damage triggers a chronic inflammatory response, which is precisely what the NLR, PLR, and SII indices are designed to measure.[9,10] The body recognises these metals as harmful agents, triggering a chronic immune response that leads to an increase in neutrophils and a change in lymphocyte function.[9,10]
The observation of elevated NLR, PLR, and/or SII values in this high-exposure group provides evidence of subclinical biological damage. It transforms the "presence of metals" from a mere indication of exposure to an active trigger of a harmful physiological imbalance. This finding is of fundamental importance because it confirms that the accumulation of metals is not an inert presence, but is actively causing measurable biological damage, representing a concrete risk for the future development of chronic diseases.[11,12]
This discovery provides a "mechanistic bridge" that elevates the regulatory and legal status of hair mineral analysis. Historically, some regulatory agencies have been sceptical of hair analysis, considering it a less direct measurement than blood or urine. This study does more than simply demonstrate the presence of metals in hair; it demonstrates that this presence correlates with a well-established and significant medical endpoint (systemic inflammation measured in blood).

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