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Insect- Heavy Metal Dynamics in Pristine Anatolian Waters

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Abstract

Heavy metals (HMs) in aquatic environments pose a potential risk to the survival of aquatic insects. These metals are common pollutants in water bodies and tend to sink and accumulate in sediments. This study examined the distribution of aquatic insects and their correlation with HMs concentrations in the waters of Ardahan, Kars and Iğdır provinces in Northeast Anatolia (Türkiye), bordering the Caucasus mountain range. In this region, HMs pollution is generally low because of minimal motorized traffic and limited industrial activity. Correlation analysis revealed positive relationships between insects abundance and Mo ($r=0.55$), Co ($r=0.49$), Ni ($r=0.42$), and Fe ($r=0.41$). In contrast, As (arsenic) showed a weak correlation ($r=+0.08$), while Si ($r=-0.13$) and Hg ($r=-0.12$) exhibited slight negative associations. Silicon dominates in Ardahan due to siliceous volcanic sedimentary geology with Cd and Pb largely absent, Kars exhibits extremely high Al and Fe with localized As enrichment from basaltic volcanic and hydrothermal inputs and Iğdır shows moderate overall levels with the exception of extreme Fe and As linked to Mount Ağrı's volcanism and alluvial sediment transport. These patterns suggest a complex, nonlinear ecological response to varying element levels. Principal component analysis (PCA) indicated that sufficient insect samples were obtained from sites with relatively low HMs concentrations. These findings provide valuable insights into the dynamics of HMs in minimally industrialized freshwater systems and can inform future monitoring and assessments in both natural and industrial areas.

Keywords: Aquatic insects, Freshwaters, Heavy metal, PCA, Pollution indicators.

1. Introduction

It is widely acknowledged that rivers, lakes and other bodies of fresh water represent some of the most vital ecosystems on our planet (Mishra 2023). One of the most striking features of these areas is the richness of their aquatic insect fauna. The fauna of the country plays a central role in ecological and economic terms and represents a valuable resource in these areas. In addition, the diverse topographical structure contributes to this biodiversity (Ministry of Environment and Urbanization A, B

2025). The loss of biodiversity in freshwater ecosystems is a growing phenomenon (Abell 2002). The removal or loss of aquatic insects can have a negative impact on the stability and diversity of ecosystems (Krishnan et al. 1988).

Within the animal kingdom, insects belong to Arthropoda and class Insecta. With over one million identified species, Insect is the most diverse and richest in biomass on earth (Harvey et al. 2025). Coleoptera are the most numerous group of insects on earth. The majority of existing insects (40 %) are assigned to this group (Bektaş 2015). Within the study of order Hemiptera in Türkiye, especially during the 19th and 20th centuries, a significant amount of work was carried out by domestic and foreign researchers. By 2005, the total number of subspecies belonging to 40 different families had been recorded (Usinger 1956, Yang 2004, Topkara et al. 2011; Bektaş and Tepe 2024).

Wildlife, humans and livestock rely on river ecosystems in arid and semi-arid areas as primary water sources (Christine et al. 2017). Metal pollution is a considerable threat to ecosystems and public health, which underscores the necessity for effective monitoring instruments (Benner et al. 2025). A variety of heavy metals (HMs) are present in the ecosystems inhabited by insects and have negative effects on the health of these organisms (Singh et al. 2022). It is widely accepted that HMs are considered environmental pollutants (Yazkan et al. 2002), these pollutants are regarded as those which have been demonstrated to present a considerable threat to the stability of ecosystems. (Bat et al. 1999; Förstner and Wittmann 1983). HMs are widely distributed in the aquatic environment includes sediments (Scheuhammer 1987). Aquatic insects differ from other insects by their tolerance to pollution, which is an important adaptation for survival (Nehring 1976). Statistical studies conducted in regions characterized by elevated HM loads have demonstrated that the distribution of HMs exerts a detrimental influence on aquatic insect assemblages. This is attributable to the prevalence of aquatic insects and their interconnectedness within wetland ecosystems. Furthermore, the interaction between HMs and ecological dynamics within wetlands has been shown to have a deleterious effect on aquatic biota (Girgin et al. 2010; Brix et al. 2011; Azam et al. 2015; Bouchelouche and Arab 2020; Mebane et al. 2020; Tabassum et al. 2024; Gori et al. 2025).

Principal component analysis (PCA) is a method that simplifies complex data sets. This approach reduces dimensionality while preserving as much variance as possible (Souza 2025). According to the results of PCA HMs concentration and soil pollution assessment are of great importance for the development of agriculture, as is the accurate measurement of HMs content (Cui et al. 2024). Furthermore, statistical analyses (e.g. PCA) have been conducted to evaluate the impact of treatments on insect diversity and to ascertain the primary habitats and variables that influence it. (Kruess & Tschardtke 2002; Lestari et al. 2025; Zafar et al. 2025)

The studies have shown that to detect and halt biodiversity decline, it is also necessary to explore intact biodiversity areas and ecologically intact areas (Allan et al. 2022; Palomo et al. 2025, Reedman 2025). Intact areas have been shown to be comparatively less exposed to the deleterious effects of industrialization and population decline, which are recognized as the principal causes of biodiversity loss (Rodríguez-Rodríguez et al. 2021, Cafaro et al. 2022). Furthermore, the biological diversity of the Caucasus water basins, which have remained undisturbed due to their low human population density, has been the subject of scientific study in comparison with undisturbed areas in other regions. (Naseka 2010, Chertoprud et al. 2016;

Abbasov et al. 2022; Cherchesova et al. 2023; Barkhalov et al. 2023; Eпитashvili et al. 2025). In this study, it has been focused on the provinces of Ardahan, Kars and Iğdır, which are located in the Caucasus region of north-eastern Anatolia in TÜRKİYE. The presence of HMs in areas of low pollution in aquatic environments (Motta et al. 2025; Yu et al. 2025), even in areas with minimal pollution, represents one aspect of the impact of global pollution on such environments (Al Naggat et al. 2018; Timothy and Williams 2019). Recent studies have shown that insect populations are declining even in an intact zone (Bektaş 2023), due to the interregional displacement of industrial areas (Sun et al. 2023). The research to be conducted here will provide valuable data on the use of insects as indicators when comparing industrial zones of influence in the coming years. Aquatic insects are essential for the functioning of freshwater ecosystems and play a central role in maintaining biodiversity and network dynamics (Dijkstra et al. 2014). Due to their sensitivity to pollutants, including HMs, aquatic insects are often used as bio-indicators of the status of freshwater ecosystems (Kumari and Paul 2020). Freshwater systems in low-polluted and sparsely populated areas provide a unique opportunity to investigate for aquatic insect communities and their relationship to HMs enrichment (Ouma et al. 2022). This study focuses on the faunal distribution of aquatic insects and the HM content in different habitats, including lakes, rivers, streams and ponds. Statistical analyses, in particular tests such as PCA tests (Szentgyörgyi et al. 2017; Trett et al. 2000; Pastorino et al. 2020; Soliman et al. 2022; Khan et al. 2023), were performed to identify significant differences in HMs accumulation between different habitats and insect population.

2. Materials and Methods

2.1 Study area and sampling of insects

Aquatic insects (Coleoptera and Hemiptera) were collected from freshwater springs in Ardahan, Kars and Iğdır (northern Anatolia, Türkiye, Caucasus region). The region's topography is characterized by a diverse array of geographical features, including mountains, plateaus, plains and rivers, with altitudes ranging from 805 meters in the Dilucu Plain to a maximum of 5137 meters at Mount Ağrı (Demirel and Çamlıca 2021). Ardahan, Kars, and Iğdır are located on the border of Armenia, Iran, and Nakhichevan, and have only a limited degree of industrialization (Fig. 1). Sampling was conducted on a monthly basis between April and October (2019–2021) in a variety of water bodies, including lakes, springs, streams, puddles and warm water reservoirs. The collected specimens were conducted utilizing sieves, scoops and nets with a pore size of 1–3 mm. The specimens were then preserved in 70% ethanol, labelled and stored for further analysis.

2.2 Aquatic insect analysis

Due to the unfeasibility of collecting samples during the winter months, the laboratory work was conducted during this period. Laboratory processing of the specimens involved a series of steps including cleaning, drying and rehydrating. The identification of the specimen was conducted at the family, genus and species level utilising stereomicroscopy and conventional taxonomic keys (Hansen 1987; Bektaş 2015; Darilmaz and Incekara 2011; Fery et al. 2001; Fery and Erman 2009). The following diagnostic features were examined: aedeagophores (prepared with 10% KOH and mounted in glycerol), elytral and pronotal structures, maxillary palps,

abdominal segments, femoral setae and thoracic morphology. Body measurements were averaged across 10 individuals (5 males, 5 females) when available. The specimens were then subjected to a rigorous protocol of labelling, photographing and sexing (Fig. 2).

2.3 Surface water sampling and HMs analysis

Water samples were collected at each station from both the surface and the benthic zones (at a depth of approximately 30 centimetres) using glass bottles that had been meticulously cleaned. The samples were preserved and analysed at the Eastern Anatolia High Technology Application and Research Centre (DAYTAM, Atatürk University). Heavy metal concentrations (Al, Cr, Fe, Co, Ni, Cu, Mo, Zn, Ag, Cd, Hg, Pb, Si and As) were determined by ICP-MS, following external calibration, LOD/LOQ validation, and quality control with blanks and certified standards (Wu et al. 2017; Llaver et al. 2021).

The potential of aquatic insect species as bio indicators was assessed by means of an analysis of HMs accumulation, with PCA applied to evaluate interspecies and habitat variations. The infographic (Fig. 3 b–d) illustrates the taxonomic distribution and abundance of insects, organised by order, family, and genus, with color coding and bar charts employed to enhance visualisation. A scatter plot (Fig. 3 a) was employed to analyse the relationship between altitude and specimen counts across 32 sites, revealing no significant correlation. Ardahan exhibited a slight increase in specimen counts with altitude, while Kars and Iğdır demonstrated slight decreases.

2.4 Statistical analysis

A comprehensive analysis was conducted on heavy metal data from 32 localities, employing PCA to assess spatial variations across habitats, including lakes, streams, rivers and ponds, and to ascertain associations with various insect taxa. The dataset comprised 14 elements (Al, Cr, Fe, Co, Ni, Cu, Mo, Zn, Ag, Cd, Hg, Pb, Si and As), 13 families and 78 species of Coleoptera and Hemiptera. Prior to analysis, the data were standardized in order to mitigate the potential for elements with elevated concentrations, such as Si and Fe, to exert undue influence on the results. A correlational analysis was conducted between the total number of insects collected at each site and their corresponding elemental concentrations (Chen et al. 2016). This analysis enabled the potential ecological impacts of these elements to be inferred (Llaver et al. 2021).

3. Results

Functional feeding groups have been identified comprising collectors (856 individuals: Hydrophilidae, Helophoridae, Corixiidae, Micronectidae), predators (214 individuals: Dytiscidae, Noteridae, Hydraenidae, Nepidae), and scrapers (4 individuals: Haliplidae, Hydrochiidae) (Birara 2020). The presence of detritus-rich environments, along with the prevalence of predators in specific fast-flowing or structured sites (e.g., L₂, L₆, L₁₈), and the rarity of scrapers in certain habitats, all serve to indicate collector dominance (L₅, L₂₆).

The PCA results (Fig. 4 a and b) on 14 elements revealed that PC1 and PC2 explain

52.3% of the variance. The locations exhibited a high degree of similarity in their chemical profiles, while the outliers (L₄, L₉) demonstrated elevated levels of arsenic. A strong correlation was identified between Fe, Ni, Co, and Mo, while a moderate correlation was observed between As and Mo, as well as Cu. In contrast, Si exhibited negative correlations with Fe–Ni–Co. The results of the heatmap analysis confirmed these associations, highlighting Fe–Ni–Co as lithogenic metals and Si as indicative of distinct geological input.

The geologic and geographic context of Ardahan, Kars and Iğdir exerts a significant influence on the distribution of HMs in aquatic systems. Ardahan and Kars are distinguished by their high-altitude plateaus and volcanic–andesitic geology, which are indicative of elevated levels of Fe, Co and Ni. These levels are consistent with natural lithogenic inputs from mineral-rich bedrock. In contrast, Iğdir, with its low-altitude alluvial plains and proximity to Mount Ararat's volcanic deposits, exhibits higher As and Mo, reflecting both geochemical weathering and sediment transport processes (Demirel and Çamlıca 2021; Motta et al. 2025). In Ardahan (L₁–L₁₄), silica (Si) was consistently dominant, reflecting the siliceous volcanic and sedimentary geology of its high-altitude plateaus, while heavy metals such as Cd and Pb were largely absent. In Kars (L₁₅–L₂₄), remarkably elevated aluminum (Al) and iron (Fe) values (e.g., L₁₅, L₂₃) signify lithogenic inputs from basaltic and volcanic rocks, with localized arsenic (As) enrichment (L₂₂, L₂₄) presumably associated with hydrothermal or mineralized zones. In Iğdir (L₂₅–L₃₂), although overall metal levels were moderate, extreme Fe and As concentrations (e.g., L₃₀) suggest contributions from volcanic deposits of Mount Ağrı and sediment transport across the alluvial lowlands (Fig. 5).

The analysis was conducted on the concentrations of 14 elements across the 32 sampling locations provided in the ICP-MS results (Table 1). The initial two principal components (PC1 and PC2) were extracted from the biplot. PC1 accounted for 33.6% of the total variance in the data. PC2 accounted for 18.7% of the total variance in the data. The two axes of the subsequent plot represented 52.3% of the total information contained in the original dataset (Fig. 4 a and b). The provided graphic (Table 1) offers a comprehensive visual overview of the concentrations of 14 different elements (Al, Cr, Fe, Co, Ni, Cu, Zn, As, Mo, Ag, Cd, Hg, Pb and Si) at 32 distinct sampling locations (L₁–L₃₂). Conversely, Silicon (Si) and Mercury (Hg) show weak negative correlations $r = -0.13$ and $r = -0.12$ respectively, suggesting that their presence may slightly inhibit biological density or that their geological distribution follows a different environmental logic than the heavy metals associated with toxicity (Table 2). Regional analysis demonstrates a clear gradient of heavy metal accumulation across the provinces of Ardahan, Kars and Iğdir. While Ardahan remains characterized by a "Low" pollution level dominated by natural silicic volcanic–sedimentary geology, Kars and Iğdir exhibit "Medium to Locally High" pollution levels (Table 3).

4. Discussion

A study was conducted to investigate the impact of mining activities on the biodiversity of aquatic insects in the Rio Doce Basin. The utilization of Ephemeroptera, Plecoptera and Trichoptera species as biological indicators, thereby demonstrating that mining activities exerted a substantial negative influence on both species richness and diversity of macroinvertebrates. (Bonfá Neto et al. 2023). These

findings emphasize the imperative for developing novel strategies for conserving freshwater ecosystems (Viana et al. 2025). The present study investigated the levels of HMs in freshwater ecosystems using an approach that included both water and aquatic insects. The present study therefore sought to ascertain the correlation between HMs and insect diversity in the even region, which is sparsely populated and pollution-free (Fig. 3). In consideration of the aforementioned data, it is posited that the region in question may be regarded as intact. However, a review of the extant literature reveals that this study is the first to conduct a comprehensive survey of HMs contamination in an aquatic environment and to assess the ecological consequences of such contamination in this particular aquatic region. Consequently, the findings of this study will assist policymakers and the government in implementing effective management strategies to reduce HMs levels in urbanized and more polluted ecosystems. PCA is a routine instrument in modern data analysis and is used in almost all scientific disciplines. The goal of PCA is to identify the most meaningful basis for re-expressing a given dataset (Kurita 2021).

The analysis of this study revealed a complex interplay in which certain elements appeared to be associated, whereas others showed little or no linear relationship. The strongest positive correlations were observed between insect abundance and Mo (correlation coefficient $r = +0.55$) and cobalt (Co) ($r = +0.49$). Furthermore, a significant positive relationship was identified for Ni ($r = +0.42$) and Fe ($r = +0.41$). This result suggests that environmental conditions conducive to higher concentrations of these metals may also be conducive to larger populations of aquatic insects, that the local fauna may have developed a tolerance to their presence. For instance, location L₂, which exhibited the highest insect count (134 individuals), also demonstrated elevated concentrations of these specific metals, corroborating the observed trend (Fig. 4 a and b).

In contrast, the analysis underscores a more nuanced relationship for known toxic elements, such as As. Contrary to the hypothesis of a robust negative correlation, the overall relationship was surprisingly weak ($r = +0.08$). This phenomenon is likely attributable to a nonlinear threshold effect. For instance, location L₄ exhibited an exceptionally elevated As concentration (213.3 mg/kg) and a comparatively low insect count, suggesting a high degree of toxicity. However, other sites, such as L₂ and L₃, have demonstrated the capacity to sustain substantial insect populations despite exhibiting moderately elevated As levels. This finding indicates that while As exhibits acute toxicity at concentrations above a certain threshold, its impact is less pronounced, albeit still elevated, as observed at some of the more populous sites. Similarly, a weak negative correlation was observed between Si and Hg ($r = -0.13$ and $r = -0.12$, respectively). This finding suggests a modest, albeit not statistically significant, tendency towards lower levels (Fig. 4 a and b).

A salient feature of these bar charts is the substantial spatial heterogeneity of the elemental concentrations. Elements such as Fe, Si and As demonstrated particularly elevated and variable concentrations, with significant peaks observed at specific locations, including L₈, L₂₃ and L₃₀ for Fe and As and various locations for Si. In contrast, elements such as Ag, Cd and Hg were found to be largely absent or present in very low, almost negligible, concentrations across most of the sampled sites. This result indicates a varied distribution of HMs within the studied area (Fig. 5 and Table 1). This detailed breakdown of elemental concentrations by location is crucial for understanding the potential environmental stressors in these habitats. Although this

graphic does not provide a direct illustration of insect diversity, the observed variations in HMs levels, particularly for elements such as As, Ni and Co, which can be toxic even at low concentrations, lay the foundation for subsequent ecological analyses. Such data are fundamental for correlating elemental profiles with insect diversity and abundance, as HMs contamination can significantly affect aquatic invertebrate communities by affecting their survival, reproduction and functional feeding group structures. Consequently, these elemental concentration maps constitute a pivotal input for evaluating the environmental health of each location and predicting its potential influence on resident insect populations.

Compared to the other study areas, namely the provinces of Ardahan and Kars, the province of Iğdır is characterized by a lower altitude, significantly higher temperatures in the summer months and a lower amount of seasonal precipitation. In the context of ecosystem conservation and sustainability, individuals that can be easily identified as members of the same species through external observation are not exposed to disturbance, showing an increased level of sensitivity to ecological values (Fig. 3 a and f). A two-paragraph scientific commentary can be provided based on the graphic showing a correlation matrix. The image, which is a correlation heatmap, visualizes linear relationships between multiple elemental concentrations across different locations. The correlation heatmap provides a powerful visualization of the interrelationships among the 14 measured elemental concentrations. The color gradient, ranging from deep blue to deep red, quantifies the strength and direction of correlations. Strong positive correlations (approaching +1), depicted in red, indicate that elements tend to increase or decrease in concentration. For instance, the high correlation between Al and Fe indicates that they are likely to have been sourced from similar geological or anthropogenic processes, possibly from the erosion of a common mineral-rich bedrock.

The location dataset enumerates sampling sites, coordinates, altitudes, collection dates and the composition of aquatic insect species (Twardochleb et al. 2021), while the ICP-MS dataset details the concentrations of HMs in samples from these locations (Wu et al. 2017). By correlating these datasets, we can associate specific environmental conditions, such as altitude, geographic coordinates, and species diversity, with the measured elemental concentrations (e.g., Al, Cr, As, Pb). This relationship elucidates how geographic and ecological factors influence the bioaccumulation of trace elements in aquatic ecosystems, potentially identifying pollution hotspots, natural geochemical signatures, and habitat-specific contamination risks. In general, altitude exhibited only weak correlations with the concentrations of measured elements. Slight positive correlations were observed for Cr ($r \approx 0.19$), Mo ($r \approx 0.15$) and As ($r \approx 0.11$), indicating a potential slight increase in their levels with increasing elevation. Other elements, such as Co, Si, Fe, Zn and Hg, demonstrated negligible associations, whereas Ni ($r \approx -0.11$) and Co ($r \approx -0.19$) displayed small negative trends, suggesting marginally lower concentrations at greater altitudes. Pb, Al and Cd were essentially uncorrelated with elevation, the data for silver were insufficient for a correlation analysis. The application of correlation analysis yielded evidence indicative of a positive association between the abundance of insects and several trace elements. The strongest relationship was observed with molybdenum ($r = 0.55$), followed by cobalt ($r = 0.49$), nickel ($r = 0.42$), and iron ($r = 0.41$). These findings suggest that the availability of specific metals may play an influential role in shaping insect population dynamics.

The statistical correlation between insect abundance and heavy metal concentrations reveals a significant geochemical impact on the local biota. Specifically, Molybdenum (Mo) exhibits the strongest positive correlation ($r = +0.55$), indicating that higher insect populations are found in environments with elevated metal concentrations, followed by moderate positive correlations for Cobalt (Co), Nickel (Ni), and Iron (Fe). The presence of extremely high levels of Iron (Fe) and Arsenic (As) in these regions is particularly concerning. While the provided data attributes these concentrations to Mount Ağrı's volcanism and alluvial sediment transport, the recurring enrichment of toxic elements like Arsenic suggests more complex environmental stressors influencing the local ecological health. The "Medium/Locally High" heavy metal pollution levels in Iğdır raise significant questions regarding transboundary environmental hazards, specifically those originating from the Metsamor Nuclear Power Plant in neighboring Armenia. The reliance on Metsamor, an aging facility built with outdated, first-generation Soviet technology (Pashayi, 2025), poses a persistent risk of heavy metal and radioactive contamination through atmospheric deposition and transboundary water systems. Given Iğdır's geographical proximity, it is highly probable that the elevated heavy metal profiles in the region are not solely the result of natural volcanic activity but are exacerbated by industrial seepage and the structural vulnerabilities of this obsolete nuclear installation, necessitating a rigorous cross-border environmental audit (Table 3).

Conversely, strong negative correlations (shown in blue) would imply an inverse relationship, where the increase in one element corresponds to the decrease in another. Elements with values near zero (white) demonstrate the absence of a strong linear relationship. The heatmap is an efficient means of identifying these key associations, which are fundamental for inferring geochemical processes and identifying potential common sources of HMs in aquatic environments. The correlation patterns revealed by this analysis have significant implications. For instance, the identification of metals with a strong correlation facilitates the prediction of potential co-contamination issues, given that a high concentration of one element can indicate a high concentration of another toxic element. The identification of such findings is of critical importance when assessing the overall environmental risk to biological communities (Luo et al. 2022). Although the graphic does not provide direct insight into insect diversity, the identification of these elemental clusters constitutes a fundamental initial step in any ecotoxicological study. The correlation between insect assemblages and heavy metal profiles provides substantial evidence for their role as ecological sentinels in freshwater ecosystems (Fig. 4 and Table 1). The findings reported here demonstrate the efficacy of aquatic insects as bio indicators, providing an early warning system capable of detecting both natural geochemical shifts and anthropogenic pollution. Subsequent analysis will involve correlating these elemental groupings with insect diversity metrics or functional feeding group data to determine which specific combinations of HMs may be driving the observed changes in aquatic insect communities. This approach enables a more targeted and comprehensive assessment of environmental impacts.

5. Conclusion

This study provides a comprehensive analysis of the distribution of aquatic insects and their role as bio indicators of HMs pollution in low-pollution freshwater ecosystems. PCA confirmed significant variations in HMs accumulation in different

habitats and taxa, demonstrating the potential of aquatic hexapods as reliable indicators of water quality. It is recommended that in future studies, an extension of temporal variation and the inclusion of additional environmental parameters be considered to broaden the scope of bio indicators.

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Author Contributions

Mehmet Bektaş conceptualized and designed the study. All authors contributed to data collection and analysis. The first draft of the manuscript was written by Mehmet Bektaş and all authors (correspond author and second author-Yahya Tepe) commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Tables

Table 1. Heavy metal concentrations in water samples collected from each location. An average value from per location 10 separate points was obtained and presented in ppm values

Location Code	Al	Cr	Fe	Co	Ni	Cu	Zn	As	Mo	Ag	Cd	Hg	Pb	Si
L ₁	0,056	0,298	0	0,023	0,044	0,052	0,125	0,383	0,3	0	0	0,013	0	29074,31
L ₂	0,355	0,726	2,006	0,075	1,72	0,413	0	7,216	2,367	0	0	0	0	15995,05
L ₃	0,28	0,11	8,218	0,227	7,929	0,722	0,556	9,807	7,949	0	0,001	0	0	20364,31
L ₄	0,048	0,224	1,293	0,08	1,21	0,538	0	213,344	1,965	0	0	0	0	32065,79
L ₅	0,324	0,188	1,759	0,053	0,476	0,332	0,119	0,442	0,141	0	0	0	0	21522,18
L ₆	1,45	0,154	15,774	0,249	5,744	1,968	0,798	3,742	0,714	0	0	0	0	10955,87
L ₇	19,489	2,618	21,246	0,097	3,978	1,025	0	8,803	1,05	0	0	0	0	19626,54
L ₈	10,381	0,171	2344,497	8,689	11,49	0,348	12,019	5,235	1,192	0	0,007	0	0	24062,11
L ₉	0,524	0,174	4,073	0,183	4,76	1,187	0,72	127,03	40,51	0	0,024	0	0	17167,01
L ₁₀	0,746	0,203	3,443	2,533	15,773	3,675	1,66	7,287	4,781	0	0,002	0	0	7631,158
L ₁₁	1,229	0,12	4,529	0,071	1,206	0,489	0,142	7,413	0,806	0	0	0	0	6735,949
L ₁₂	0,23	0,086	0,733	0,212	0,948	0,076	0,682	17,65	0,568	0	0	0	0	80699,92
L ₁₃	0,221	0,146	5,742	0,089	1,282	0,096	0,296	2,093	0,074	0	0	0	0	0
L ₁₄	0,374	0,219	26,525	0,231	9,185	1,308	3,107	3,155	1,273	0	0	0	0	16211,66
L ₁₅	137,297	0,306	587,355	0,169	4,251	1,774	2,243	2,546	0,264	0	0	0	0,044	4288,324
L ₁₆	52,222	0,178	58,797	0,112	2,043	1,406	1,083	1,57	0,524	0	0	0	0	9485,232
L ₁₇	0,39	0,07	2,848	0,12	1,175	0,349	0,001	4,706	1,771	0	0	0	0	25768,64
L ₁₈	6,921	0,176	8,494	0,563	4,986	6,526	0,098	23,989	3,741	0	0	0	0	7106,54
L ₁₉	0,25	0,2	3,138	0,081	0,891	4,861	0,034	0,875	0,651	0	0	0	0	19204,19
L ₂₀	1,132	0,176	89,945	13,319	6,948	0,567	0,838	4,058	1,283	0	0	0	0	27289,61
L ₂₁	0,142	0,07	21,842	1,573	3,475	0,341	0,422	3,12	2,678	0	0	0	0	35901,39
L ₂₂	0,924	0,301	14,07	0,668	8,072	2,244	0,669	159,028	6,356	0	0	0	0	42351,13
L ₂₃	9,499	0,246	2934,149	1,317	1,942	0,545	2,268	2,315	0,054	0	0	0	0,065	8128,301
L ₂₄	0,486	0,477	4,198	0,214	2,804	0,49	0,814	40,133	6,91	0	0,001	0	0	29943
L ₂₅	0,764	0,093	0,65	0,066	2,318	0,662	0,28	0,829	1,048	0	0	0	0	9318,947
L ₂₆	2,133	0,147	2,481	0,068	4,158	0,984	0,034	1,624	3,003	0	0	0	0	19008,91
L ₂₇	3,619	0,383	67,299	0,143	3,689	1,448	1,079	4,785	0,59	0	0	0	0	21117,13
L ₂₈	0,762	0,088	1,766	0,198	4,018	2,314	0,09	0,959	0,517	0	0	0	0	10561,41
L ₂₉	0,379	0,036	4,886	0,151	2,628	0,261	0,08	6,768	2,383	0	0	0	0	41252,12
L ₃₀	0,501	0,074	1238,467	6,852	14,055	0,086	0,515	53,8	0,316	0	0	0	0	28964,01
L ₃₁	2,189	0,506	9,657	0,447	3,217	1,802	0,228	4,012	0,65	0	0	0	0	21867,32
L ₃₂	370,27	2,27	491,524	0,489	3,032	1,737	19,057	3,386	3,115	0	0,703	0,052	0,803	0

Table 2. Statistical correlation analysis between insect abundance and various chemical elements, utilizing the Pearson correlation coefficient (r) to categorize the strength and direction of these biological-geochemical relationships.

Correlation	Elements	Correlation Coefficient (r)	Comment
Positive	Molybdenum (Mo)	+0.55	Strong Positive (As insect abundance increases, metal concentration increases)
Positive	Cobalt (Co)	r+0.49	Moderately Positive
Positive	Nickel (Ni)	r+0.42	Moderately Positive
Positive	Iron (Fe)	r+0.41	Moderately Positive
Low/Neutral	Arsenic (As)	r+0.08	Slightly Positive
Negative	Silicon (Si)	r-0.13	Low Negative (As insect abundance increases, metal concentration decreases)
Negative	Mercury (Hg)	r-0.12	Low Negative

Table 3. A regional distribution of dominant geological elements and their primary environmental sources across the provinces of Ardahan, Kars and Iğdır, further classifying each area based on its "AM" (HMs) pollution severity.

Province	Predominant Elements and Sources	AM Pollution Level
Ardahan	Silicon (Si) - Siliceous volcanic-sedimentary geology (Cd and Pb mostly absent)	Low
Kars	Aluminum (Al) and Iron (Fe) (Extremely high). Local Arsenic (As) enrichment from basaltic-volcanic and hydrothermal inputs.	Moderate/Local High
Iğdır	Iron (Fe) and Arsenic (As) (Extremely high levels). Associated with Ağrı Mountain volcanism and alluvial sediment transport.	Moderate/Local High

Figures

Figure 1. Map of the 32 sampling locations (Ardahan, Kars and Iğdır, Türkiye) (Location code Lx).

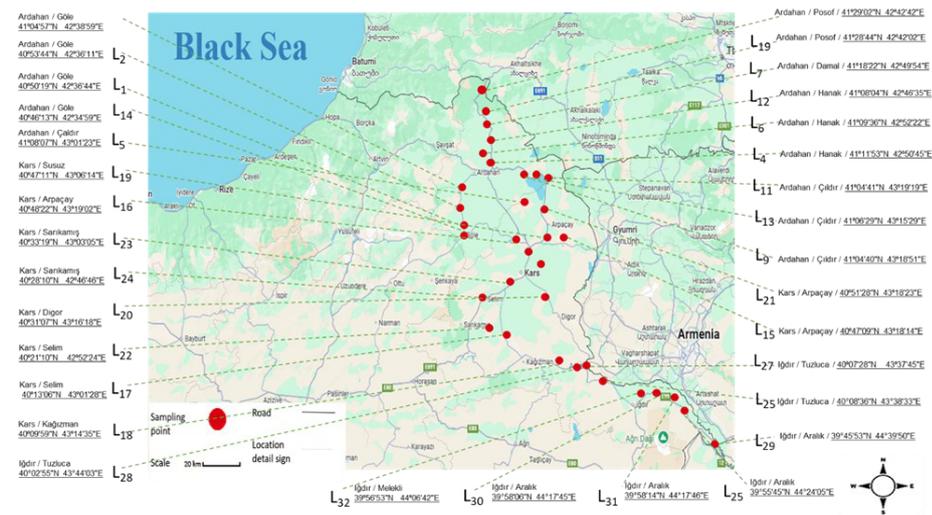


Figure 2. A): Images of some of the aquatic insects collected in the rice fields. Numbers 1-16 - Coleoptera; numbers 17-20 – Hemiptera; B): Some study area

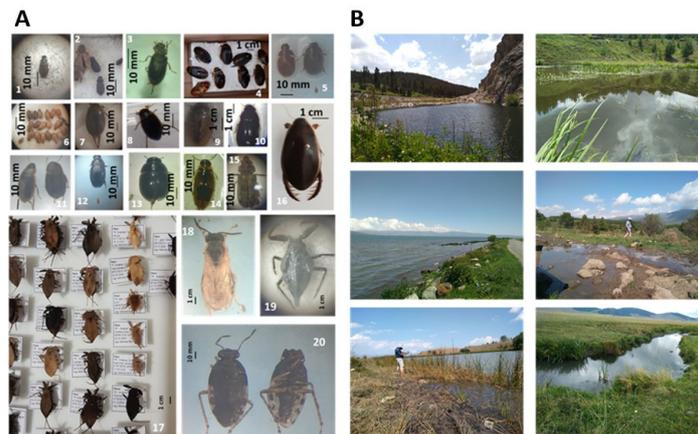


Figure 3. a. Altitude number of collected individuals by researching area); b. Number of individuals by province; c. Biodiversity of collectors, predators and scrapers; d. Distribution of the most collected aquatic Coleoptera and Hemiptera families; e. Distribution of the number of individuals per family by province; f. Number of individuals in functional feeding groups by sampling location (L₁-L₃₂) (3.a and 3.b figures built with assist of AI).

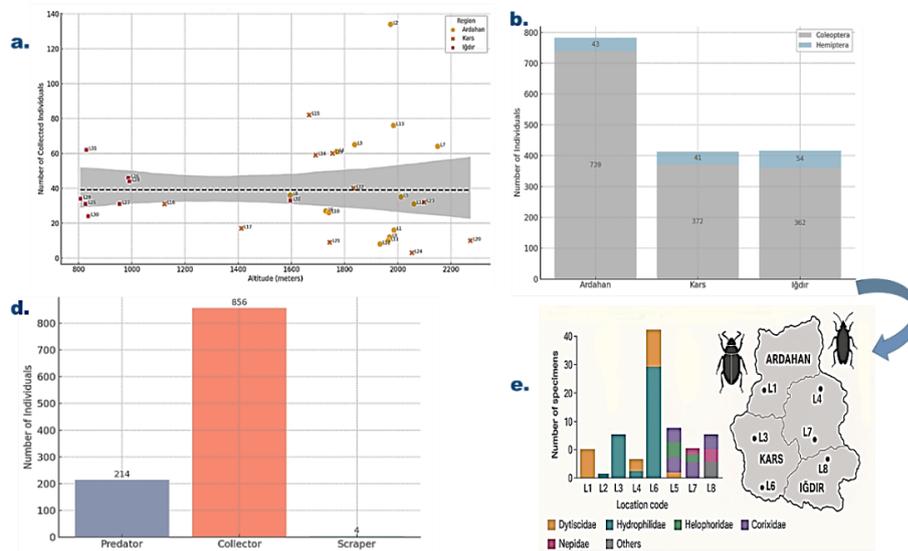


Figure 4. a) The primary focus of this study is the examination of PC1 relationships within the given dataset, with a particular emphasis on the correlation between various chemical elements; **b)** The investigation encompasses the PC2 correlations matrix of HMs concentrations (ppm), with the utilisation of artificial intelligence (AI) as a supporting methodology.

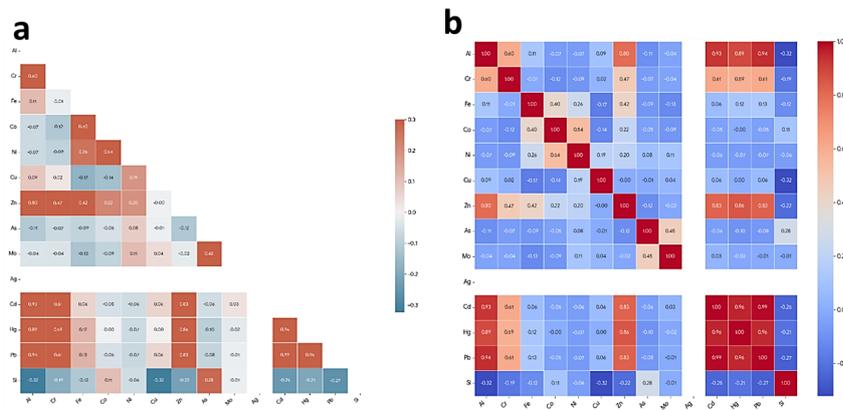


Figure 5. A comparative quantitative analysis of aquatic insect families within the orders Coleoptera and Hemiptera across the provinces of Ardahan, Iğdır and Kars, featuring both a bar chart of population counts and a detailed frequency table.

