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Original article

Assessment of Some Heavy Metals in *Arbutus pavarii* Pamp. Fruits in Relation to Roadside Exposure in Al-Jabal Al-Akhdar, Libya

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Abstract
Road traffic represents a potential source of metal contamination in roadside environments, particularly through exhaust and non-exhaust emissions. This study investigated the concentrations of selected heavy metals in Arbutus pavarii Pamp. fruits collected from three locations in Al-Jabal Al-Akhdar, Libya, situated at different distances from the road: Lamluda (5 m), Taret (10 m), and Dabousiya (50 m). Iron (Fe), copper (Cu), and nickel (Ni) were determined using atomic absorption spectrophotometry (AAS), and differences among locations were evaluated by one-way ANOVA followed by Fisher's LSD test. Fe concentrations ranged from 6.395 to 14.830 mg/kg, Cu from 4.848 to 9.562 mg/kg, and Ni from 1.279 to 2.963 mg/kg dry weight. Fe differed significantly among locations (p = 0.0044), with the highest concentration recorded in Taret and the lowest in Dabousiya, whereas differences in Cu and Ni were not statistically significant (p > 0.05). Although some of the higher metal concentrations occurred at the more road-exposed sites, no consistent distance-dependent pattern was observed across all three elements. The findings therefore indicate spatial variation and possible traffic-associated metal enrichment, but do not provide definitive evidence of hazardous heavy-metal contamination or of accumulation exclusively derived from traffic. Further investigation incorporating soil and road-dust analysis is recommended to clarify the sources of metal accumulation in A. pavarii fruits.
Keywords. *Arbutus pavarii, Heavy Metals, Traffic Pollution, Atomic Absorption Spectrophotometry, Roadside Contamination, Al-Jabal Al-Akhdar.*

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Introduction

Heavy metal contamination is an important environmental concern because of the persistence of metals in the environment and their potential accumulation in soils and biological tissues. Road traffic represents a significant anthropogenic source of metal-containing particulate matter in roadside environments. In addition to vehicle exhaust, non-exhaust emissions originating from brake and tire wear, road-surface abrasion, and the resuspension of deposited road dust can contribute substantially to traffic-related particulate pollution [1,2]. With increasingly stringent controls on exhaust emissions, non-exhaust sources have become an increasingly important component of traffic-related particulate matter. Traffic-derived particulate matter may contain a variety of metallic elements that can accumulate in roadside environments. Brake wear is particularly relevant because brake components and wear particles contain substantial amounts of metals, including Fe and Cu, while Ni and several other trace metals may also occur in brake-derived particles [3].

Recent evidence has further demonstrated that Fe and Cu are among the major metals released through vehicular brake-lining wear [4]. Nevertheless, these elements are not exclusively derived from traffic; natural soil composition, mineral dust, and other anthropogenic sources may also contribute to their occurrence in roadside environments. Vegetation growing near roads can be exposed to traffic-associated metals through the deposition of airborne particles on plant surfaces and through uptake from contaminated roadside soils. Consequently, analysis of metal concentrations in roadside vegetation can provide useful information about spatial patterns of environmental contamination. The interaction between vehicular emissions, roadside soils, and associated vegetation is complex and is influenced by factors such as distance from the road, traffic intensity, soil characteristics, plant species, and local environmental conditions [5]. Recent studies have further shown that traffic-associated metals can migrate from road dust into edible vegetables and tree tissues, while traffic volume and distance from the road can influence Fe, Cu, Ni, and other element concentrations in roadside vegetation [6,7].

Assessment of metal contamination is particularly relevant when the exposed plant produces edible fruits, because the presence of metals in edible tissues may represent a potential route of human exposure. However, the detection of metals in plant tissues alone does not necessarily demonstrate traffic-derived contamination, since many metals occur naturally in soils and are essential or naturally present in plants. Therefore, spatial comparisons among sampling locations with different degrees of roadside exposure can provide more meaningful evidence regarding the potential influence of vehicular activity. *Arbutus pavarii* Pamp., locally known as Shmari, is an endemic shrub or small tree belonging to the family Ericaceae and is naturally distributed in the Al-Jabal Al-Akhdar mountainous region of northeastern Libya. Ecological investigations have confirmed its restricted distribution and conservation importance within this region [8]. The species produces edible fruits that are locally consumed, making assessment of their potential exposure to

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environmental contaminants particularly relevant. Recent investigations have also demonstrated scientific interest in the chemical, mineral, and bioactive composition of *A. pavarii* fruits and other plant tissues [9].

Despite the ecological and local importance of *A. pavarii*, information concerning the occurrence of traffic-associated metals in its fruits remains limited. In particular, little is known about whether fruits collected from areas subjected to different levels of roadside exposure exhibit significant spatial variations in metal concentrations. Investigating these variations may provide useful evidence regarding the potential influence of traffic-related pollution on this endemic species and contribute to the environmental assessment of roadside habitats in Al-Jabal Al-Akhdar. Therefore, the present study aimed to determine the concentrations of selected heavy metals in *Arbutus pavarii* Pamp. fruits collected from Dabousiya, Lamluda, and Taret in Al-Jabal Al-Akhdar, Libya, and to evaluate spatial variations in their concentrations in relation to potential exposure to traffic-related pollution. Iron (Fe), copper (Cu), and nickel (Ni) concentrations were determined using atomic absorption spectrophotometry and statistically compared among the investigated locations.

Materials and Methods

Study Area and Sample Collection

The study was conducted in the Al-Jabal Al-Akhdar region of northeastern Libya, where *Arbutus pavarii* Pamp. grows naturally. Three sampling locations were selected according to their approximate distance from the roadside: Lamluda (approximately 5 m), Taret (approximately 10 m), and Dabousiya (approximately 50 m). At each sampling location, approximately 2 kg of mature *A. pavarii* fruits were collected from different trees within the sampling area and combined to form a composite sample representative of the location. The locations of the three sampling sites are shown in (Figure 1).

After collection, the fruit samples were placed in clean polyethylene bags, appropriately labeled, and transported to the laboratory for preparation and analysis. The fruits were washed thoroughly with distilled water to remove adhering dust and surface contaminants, then dried and homogenized before acid digestion and elemental analysis.

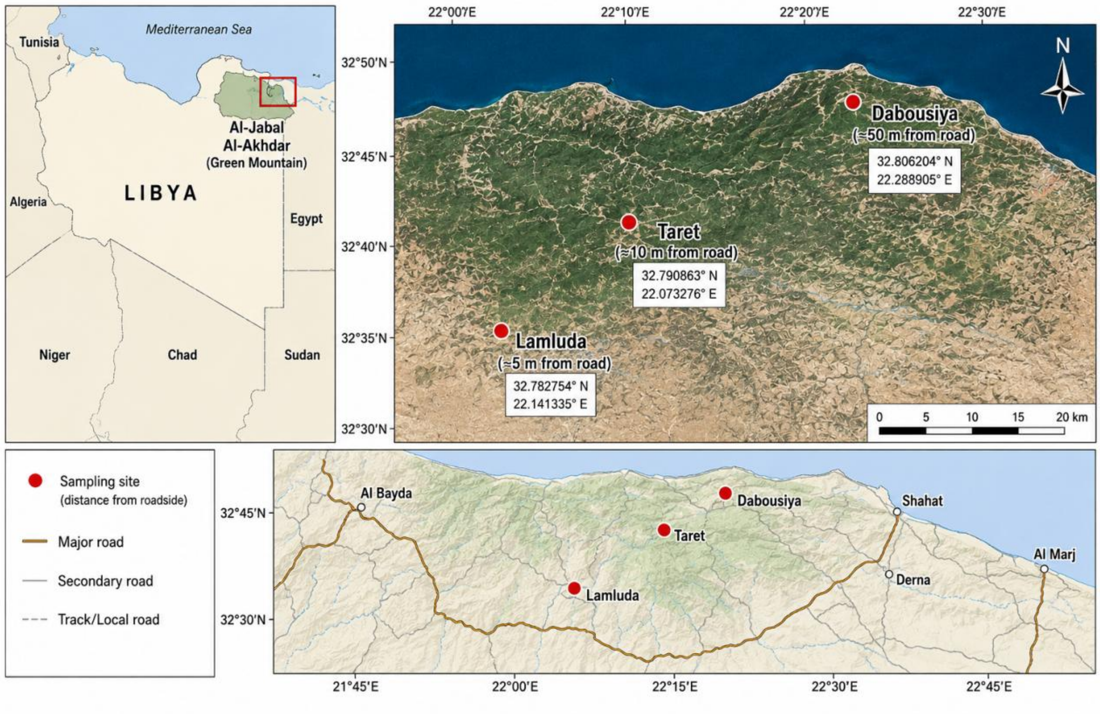

Figure 1. Location of the three sampling sites in Al-Jabal Al-Akhdar, Libya

Sample Preparation and Acid Digestion

The collected fruit samples were dried in a laboratory oven at 75°C until constant weight and subsequently ground to obtain homogeneous dry samples. For acid digestion, 0.5 g of each dried and ground sample was accurately weighed and transferred into a digestion flask. Subsequently, 5 mL of nitric acid (HNO_3) and 25 mL of distilled water were added. The samples were heated for approximately 2 h until near dryness. After cooling, the digested samples were filtered, quantitatively transferred into volumetric flasks, and diluted to a final volume of 100 mL with distilled water. Acid digestion is commonly employed for the preparation of plant materials before elemental determination by atomic absorption spectrometry (AAS) [10].

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Determination of Heavy Metals
The concentrations of iron (Fe), copper (Cu), and nickel (Ni) in the digested fruit samples were determined by atomic absorption spectrophotometry (AAS) using a Varian 220 Atomic Absorption Spectrophotometer at the analytical facilities of Omar Al-Mukhtar University, Libya. Metal determination was performed according to standard atomic absorption spectrometric procedures [11]. Calibration curves were established for the investigated elements using standard solutions. The slopes of the calibration curves were 0.98 for Fe and 0.99 for both Cu and Ni. The concentration corresponding to each absorbance measurement was calculated according to the following equation:

$$c = \frac{A}{m}$$

where *C* is the metal concentration in the analyzed solution (mg/L), *A* is the measured absorbance, and *m* is the slope of the corresponding calibration curve.
The concentration of each metal in the dry fruit sample was subsequently calculated using the following equation:

$$\text{Metal concentration (mg/kg)}\}= \frac{(C\times V)}{W}$$

where *C* is the metal concentration in the digested solution (mg/L), *V* is the final volume of the digested sample (0.100 L), and *W* is the dry sample weight (0.0005 kg). The final concentrations of Fe, Cu, and Ni were expressed as mg/kg dry weight.

Statistical Analysis
Each elemental determination was performed in triplicate (n = 3), and the results were expressed as mean ± standard error (SE). Differences in Fe, Cu, and Ni concentrations among the three sampling locations were evaluated using one-way analysis of variance (ANOVA). Where appropriate, mean separation was performed using Fisher's least significant difference (LSD) test at $p \leq 0.05$.

Results
Heavy Metal Concentrations in Arbutus pavarii Fruits
All metal concentrations reported in this section and in Table 1 are expressed on a dry-weight (DW) basis. The concentrations of Fe, Cu, and Ni in *Arbutus pavarii* fruits collected from Dabousiya, Lamluda, and Taret are presented in (Table 1). Considerable spatial variation was observed among the three sampling locations. Iron was the predominant element detected in the fruit samples. The highest Fe concentration was recorded in Taret (10 m from the road), with a mean concentration of 14.830 ± 1.811 mg/kg DW, followed by Lamluda (5 m) at 9.932 ± 0.068 mg/kg DW, whereas the lowest concentration was detected in Dabousiya (50 m) at 6.395 ± 0.491 mg/kg DW. One-way ANOVA revealed a significant difference in Fe concentrations among the three sampling locations ($F = 15.265$, $p = 0.0044$). Fisher's LSD test showed that Taret had a significantly higher Fe concentration than the other sampling locations ($p \leq 0.05$). Copper concentrations ranged from 4.848 ± 0.421 mg/kg DW in Dabousiya to 9.562 ± 1.974 mg/kg DW in Lamluda. Taret showed an intermediate concentration of 6.061 ± 0.583 mg/kg DW. Although Cu was highest at the location closest to the road (Lamluda, approximately 5 m), the overall difference among locations was not statistically significant ($F = 4.074$, $p = 0.076$). Nickel concentrations were lower than those of Fe and Cu. The highest Ni concentration was observed in Taret (2.963 ± 0.526 mg/kg DW), whereas Dabousiya and Lamluda contained 1.414 ± 0.508 and 1.279 ± 0.178 mg/kg DW, respectively. The differences in Ni concentrations among the three locations did not reach statistical significance ($F = 4.632$, $p = 0.061$). Overall, the concentrations of the investigated elements followed the general order:
Fe > Cu > Ni
However, the distribution pattern varied among sampling locations. Fe and Ni reached their highest concentrations in Taret, approximately 10 m from the road, whereas Cu reached its maximum concentration in Lamluda, the site closest to the road.

Table 1. Dry-weight concentrations of selected heavy metals in Arbutus pavarii fruits collected from three locations in Al-Jabal Al-Akhdar, Libya.

Sampling location	Fe (mg/kg DW)	Cu (mg/kg DW)	Ni (mg/kg DW)
Dabousiya	6.395 ± 0.491^{b}	4.848 ± 0.421^{a}	1.414 ± 0.508^{a}
Lamluda	9.932 ± 0.068^{b}	9.562 ± 1.974^{a}	1.279 ± 0.178^{a}
Taret	14.830 ± 1.811^{a}	6.061 ± 0.583^{a}	2.963 ± 0.526^{a}

Values are expressed as mean ± standard error (SE), n = 3. Within each column, means with different superscript letters are significantly different according to Fisher's least significant difference (LSD) test at p ≤ 0.05.

Discussion

The present study revealed spatial variation in the concentrations of Fe, Cu, and Ni in *Arbutus pavarii* fruits collected from three locations situated at different distances from the road. Overall, Fe was the most abundant of the investigated elements, followed by Cu and Ni. Differences among sampling locations were particularly evident for Fe, whereas Cu and Ni showed numerical variation that did not reach statistical significance at $p \le 0.05$. Iron concentrations ranged from 6.395 ± 0.491 mg/kg dry weight in Dabousiya, located approximately 50 m from the road, to 14.830 ± 1.811 mg/kg dry weight in Taret, approximately 10 m from the road. Lamluda, the closest location to the road (approximately 5 m), showed an intermediate Fe concentration of 9.932 ± 0.068 mg/kg dry weight. The differences among locations were statistically significant ($p = 0.0044$). The lower Fe concentration at the most distant site may indicate some influence of roadside environmental conditions.

Road traffic can contribute metal-containing particles to adjacent environments through both exhaust and non-exhaust sources, including brake and tire wear, road-surface abrasion, and resuspension of road dust [5,2,1]. Comparable roadside research has reported that Fe and Cu concentrations in plant tissues may decline with increasing distance from the road, although traffic volume and other local factors can also influence elemental accumulation [7]. However, the highest Fe concentration occurred at Taret (10 m) rather than at Lamluda (5 m), demonstrating that Fe accumulation did not follow a simple inverse relationship with distance from the road. Metal accumulation in roadside vegetation may be affected by several interacting factors, including soil properties and natural geochemical background, atmospheric deposition, traffic characteristics, resuspended dust, and plant-specific uptake processes [5]. Therefore, the Fe results indicate spatial variation but cannot be attributed exclusively to vehicular emissions. This cautious interpretation is supported by roadside orchard-soil research showing that the distribution of potentially toxic elements may reflect pedogenic and other environmental sources and that road traffic is not necessarily the dominant source for every element [12].

All experimentally determined metal concentrations in the present study are reported on a dry-weight (DW) basis. For comparison purposes only, the measured DW concentrations were mathematically converted to estimated fresh-weight (FW) concentrations using the moisture content of 68.06% reported for A. pavarii fruits [13]. These FW values are calculated estimates and do not represent direct measurements of fresh fruit samples. That study specifically investigated mature *A. pavarii* fruits collected from Al-Jabal Al-Akhdar, Libya, and reported a moisture content of 68.06 ± 1.65%. Accordingly, the estimated Fe concentrations in the present samples corresponded to approximately 2.04, 3.17, and 4.74 mg/kg fresh weight in Dabousiya, Lamluda, and Taret, respectively. Hegazy et al. [13] reported an Fe concentration of 2.57 mg/100 g fresh weight in *A. pavarii* fruits, equivalent to 25.7 mg/kg fresh weight. Thus, the estimated fresh-weight Fe concentrations obtained in the present study were substantially lower than the value previously reported for the same species. This comparison suggests that the measured Fe concentrations, despite their significant spatial variation among the three locations, do not by themselves provide evidence of unusually high Fe accumulation or hazardous Fe contamination.

Studies of the related Mediterranean species *Arbutus unedo* L. have likewise demonstrated substantial variability in fruit mineral composition among geographical origins [14,15], supporting the possibility that local environmental and geochemical conditions contribute to the spatial differences observed in the present study. Copper concentrations ranged from 4.848 ± 0.421 mg/kg dry weight in Dabousiya to 9.562 ± 1.974 mg/kg dry weight in Lamluda, while Taret contained 6.061 ± 0.583 mg/kg dry weight. Although the highest Cu concentration occurred at Lamluda, the site closest to the road, differences among the three locations were not statistically significant ($p = 0.076$). Nevertheless, the observed numerical pattern is environmentally relevant because Cu is recognized as one of the elements associated with non-exhaust traffic emissions, particularly brake wear and road-deposited particles [2,1]. After conversion using the reported moisture content of *A. pavarii*, Cu concentrations were estimated at approximately 1.55, 3.05, and 1.94 mg/kg fresh weight in Dabousiya, Lamluda, and Taret, respectively. Hegazy et al. [13] reported 0.24 mg Cu/100 g fresh weight, equivalent to 2.4 mg/kg fresh weight, in *A. pavarii* fruits. The Cu concentrations in Dabousiya and Taret were therefore below this previously reported value, whereas that of Lamluda was moderately higher. The comparatively elevated Cu concentration at Lamluda may suggest possible roadside-associated enrichment; however, because the overall differences were not statistically significant and Cu occurs naturally in plant tissues as an essential micronutrient, this observation should not be interpreted as definitive evidence of traffic-derived contamination. Nickel showed the lowest concentrations among the investigated elements. Ni concentrations were 1.414 ± 0.508, 1.279 ± 0.178, and 2.963 ± 0.526 mg/kg dry weight in Dabousiya, Lamluda, and Taret, respectively. Although Taret showed the highest Ni concentration, differences among the three sites were not statistically significant ($p = 0.061$). After conversion to a fresh-weight basis, the corresponding concentrations were approximately 0.45, 0.41, and 0.95 mg/kg, respectively.

Unlike Fe and Cu, a direct comparison of Ni with Hegazy et al. [13] was not possible because Ni was not included among the elements determined in that study. Their mineral analysis included Na, K, Ca, Mg, Fe, Zn, Cu, and P. Consequently, the present Ni results should be interpreted cautiously. Ni may originate from both natural geochemical sources and anthropogenic activities, including road-associated emissions [5], and the absence of a consistent relationship between Ni concentration and distance from the road prevents attribution of the observed concentrations specifically to vehicular emissions. Recent analysis of Sicilian *A. unedo* fruits also detected Ni at relatively low concentrations compared with Fe and Cu and showed that geographical origin significantly affected several elements in the fruit mineral profile [15]. The findings of the present study therefore provide evidence of spatial variation and possible traffic-associated metal enrichment rather than definitive hazardous heavy-metal contamination. This interpretation is particularly supported by the relatively higher Cu concentration at the closest sampling site and the lower Fe and Cu concentrations at Dabousiya, the most distant site. Nevertheless, the lack of a consistent distance-dependent pattern across all three elements indicates that road proximity alone cannot explain the observed metal distribution. Additional factors such as soil metal concentrations, geological background, prevailing wind direction, road dust deposition, and traffic intensity should be considered in future studies [5].

A recent review of roadside food crops similarly emphasized that metal concentrations can vary with traffic density, road characteristics, geological conditions, and other local factors, underscoring the need to avoid attributing spatial differences to road proximity alone [16]. From a food-safety perspective, the measured concentrations should also be interpreted cautiously. Regulatory maximum levels are generally established for specific food–contaminant combinations and on a specified weight basis [17]; therefore, concentrations determined on a dry-weight basis should not be compared directly with regulatory limits expressed on a fresh- or wet-weight basis. For this reason, the present study does not provide sufficient evidence to classify *A. pavarii* fruits from the investigated locations as hazardous for consumption solely based on the measured Fe, Cu, and Ni concentrations. Rather, the results highlight the need for continued monitoring of roadside populations of this edible wild fruit, particularly at locations exposed to greater vehicular activity.

Conclusion

The present study demonstrated spatial variation in Fe, Cu, and Ni concentrations in *Arbutus pavarii* fruits collected from three locations at different distances from the road in Al-Jabal Al-Akhdar, Libya. Fe showed significant differences among locations, whereas variations in Cu and Ni were not statistically significant. Although the relatively higher metal concentrations at some of the more road-exposed sites may suggest possible traffic-associated enrichment, the absence of a consistent distance-dependent pattern indicates that road proximity alone cannot explain the observed variations. Overall, the findings do not provide definitive evidence of hazardous heavy-metal contamination or exclusively traffic-derived metal accumulation. Further studies incorporating soil and road-dust analysis, traffic intensity, and additional sampling sites are recommended to clarify the sources of metal accumulation in *A. pavarii* fruits.

Author Contributions

Mona Mohammad Abdalla Khanfar: Conceptualization, methodology, sample collection, investigation, data analysis, interpretation of results, writing - original draft, writing - review and editing, and approval of the final manuscript.

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Conflict of Interest

The author declares no conflict of interest.

Ethical Approval

Not applicable. This study did not involve human participants or experimental animals.

Generative AI Disclosure

ChatGPT (OpenAI) was used solely for English-language editing and improvement of clarity. The author reviewed and verified the final manuscript and takes full responsibility for its scientific content.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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