Environ Monit Assess (2025) 197:515
https://doi.org/10.1007/s10661-025-13945-3

RESEARCH

Variation of nickel accumulation in some broad-leaved plants by traffic density

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Received: 6 January 2025 / Accepted: 26 March 2025 / Published online: 5 April 2025

Abstract Urban areas with intense industrial activity and heavy traffic are among those most affected by increasing pollution levels. These areas experience a rise in air pollution, containing a complex mix of pollutants including particulate matter and potentially toxic elements. Trees located along urban and rural roadsides are used as environmentally sustainable tools for tracking and reducing air pollution impacts. In this study, the aim was to determine the variation of nickel (Ni) concentrations in the species *Nerium oleander* L., *Salix babylonica* L., *Magnolia grandiflora* L., *Prunus laurocerasus* L., *Cercis siliquastrum* L., *Robinia pseudoacacia* L., *Aesculus hippocastanum* L., *Platanus orientalis* L., and *Acer negundo* L. based on plant organs and traffic density. In this study, plant materials collected from the city center of Trabzon/Türkiye were used. The results indicate significant variations in Ni accumulation among species under different traffic densities based on average values. Differences in element concentrations have been observed both among the studied species and within the organs of the same species. Generally, the lowest Ni concentrations were observed in *N. oleander* (766.2 ppb), *S. babylonica* (935.7 ppb), and *M. grandiflora* (632.9 ppb), while the highest concentrations were recorded in *R. pseudoacacia* (3217.9 ppb) and *A. negundo* (3111.9 ppb). Therefore, *R. pseudoacacia* and *A. negundo* are considered suitable as bioindicator for Ni metal. These findings underscore the potential of plants to monitor heavy metal pollution from traffic and suggest that these species should be considered in environmental protection efforts.

Keywords Heavy metal · Biomonitoring · Nickel · Air pollution

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Introduction

While industrialization and urbanization provide numerous benefits, they also release various pollutants into the environment, leading to increased pollution levels, particularly in urban areas with intense industrial activity and heavy traffic (Liu et al., 2019; Luo et al., 2019; Masresha et al., 2023; Sage, 2020). These areas experience a rise in air pollution, containing a complex mix of pollutants including particulate matter (PM) and potentially toxic elements (PTEs) or heavy metals (HM). These pollutants represent the primary sources of air pollution (Nematollahi et al., 2020; Southerland et al., 2022). A significant proportion of HMs arise from various activities, including fossil fuel combustion, heavy traffic, transportation, vehicle exhaust, metal processing and smelting, industrial emissions, and agriculture (Chen et al., 2019; Istanbullu et al., 2023; Özel et al., 2024). The pollution resulting from increased concentrations of HMs poses serious concerns, especially in urban areas, due to threats to both human health and the environment (Şevik et al., 2024; Tan et al., 2021; Wang et al., 2020).

Plants are considered biological filters capable of mitigating atmospheric HM pollution (Pace et al., 2021; Sulhan et al., 2023). HMs can directly enter plant tissues through leaves from the air, roots from the soil, and stem sections with the assistance of particulate matter. Among these pathways, the uptake of HMs from the soil via roots is primarily related to the anatomical structure of the plant, and only a very small fraction of the HMs present in the soil is transported to the leaves (Cobanoglu et al., 2023; Pulatoglu et al., 2025). Studies have shown that HMs accumulating in leaves and bark are largely associated with airborne HM pollution. The accumulation of HMs in the woody part of the plant, however, is significantly more limited due to the lack of direct contact with the air and is also largely influenced by airborne HM concentrations (Koç et al., 2024; Sevik et al., 2024). Therefore, it has been suggested that HM concentrations in leaves and bark serve as important indicators of airborne HM pollution (Koç et al., 2024).

Numerous scientific studies have demonstrated that tree leaves can function as air filters and that trees can serve as bioindicators for monitoring HM pollution (Badawy et al., 2022; Key et al., 2023; Koç et al., 2024). Trees located along urban and rural roadsides are used as environmentally sustainable tools for tracking and reducing air pollution impacts. Using various tree organs, such as leaves, branches, and wood, as biomonitors for metal accumulation has become significant due to its accessibility and cost-effectiveness (Yalaltdinova et al., 2018). The capacity of plants to accumulate particulates varies significantly by species depending on characteristics of the leaf surface such as grooves, trichomes, stomatal density, roughness, and the amount of epicuticular wax (Zhang et al., 2022).

HM accumulation is more pronounced in areas close to highways (Cobanoglu et al., 2023). The increasing number of motor vehicles has intensified traffic congestion, leading to a visible density of pollution around main transportation routes due to the elevated emissions from vehicle exhaust. Measuring the amounts of HMs in bioavailable forms is crucial for identifying environmental pollution and the toxic effects of these metals (Isinkaralar et al., 2024; Sevik et al., 2024).

Nickel, the focus element of this study, is used in coal, petroleum, steel, alloy production, galvanization, and electronics industries (Aricak et al., 2019). According to the Agency for Toxic Substances and Disease Registry (ATSDR), Ni is listed among priority pollutants with potential adverse effects on human health and the environment. The Environmental Protection Agency (EPA) also includes Ni on its list of 13 priority pollutant metals. Research has suggested a possible association between Ni exposure and the development of diabetes (Nie et al., 2022; Wang et al., 2022). The toxic effects in humans of Ni can arise not only from high-level exposure but also from continuous, low-level exposure.

This study investigates Ni concentrations to evaluate air quality in areas with varying traffic densities, focusing on HM pollution in the study area. Numerous studies have reported a strong correlation between traffic density and Ni levels (Grigoratos & Martini, 2015; Martins et al., 2021). Przybysz et al. (2014) reported that HM accumulation was highest in *Taxus baccata*, *Hedera helix*, and *Pinus sylvestris* exposed to traffic-related pollution and lowest in rural areas.

This study aims to determine the concentrations of Ni in leaf, wood, and bark samples from various plant species in Trabzon/Türkiye, examining the relationship between HM levels in plants and their distance from highways. This research will assess the potential of these plant species as biomonitors for this element. The selected species are commonly found in both parks and roadside areas of the study site, making them suitable for this research. Understanding the relationship between traffic density and HM accumulation in plants is an important indicator for monitoring the extent of environmental pollution and is crucial for pollution management. Such studies can provide guidance in selecting bioindicator plant species for monitoring similar pollution levels in the future.

Material and method

In this study, plant materials collected from the city center of Trabzon/Türkiye were used. First, areas with high, low, and no traffic (areas without vehicle access within at least 50 m) were identified. For this reason, the Black Sea Coastal Road, which has a high traffic volume and is also busy with both urban and intercity traffic, has been chosen as a high-traffic area (as a divided road carrying both intercity and urban traffic loads, it experiences near-continuous traffic congestion throughout the entire 24-h period). Soğuksu Neighborhood, which is far from the city center, has been selected as a low traffic (an urban road with traffic congestion occurring primarily during early morning and afternoon hours). The samples used in the study were collected from trees located in the central median of the road, specifically from branches approximately 2 m above the ground, while Botanic Park has been chosen as an area with no traffic (there are no roads open to vehicular traffic within at least 50 m of the sampling locations) (Fig. 1). Leaf and branch samples from the following species were collected in these areas: *Nerium oleander* L., *Salix babylonica* L., *Magnolia grandiflora* L., *Prunus laurocerasus* L., *Cercis siliquastrum* L., *Robinia pseudoacacia* L., *Aesculus hippocastanum* L., *Platanus orientalis* L., and *Acer negundo* L. The samples were collected in the last week of September, near the end of the vegetation season. The plant species examined in this study are not evergreen; therefore, their leaves emerge in early spring (late March) and are exposed to traffic-related pollution for approximately 6 months. In the study, branches were cut from the basal sections of the current year's shoots using sterile steel knives to ensure that leaves, bark, and wood from the same branch were utilized. All samples were collected on the same day. Each sample was individually labeled, placed in plastic bags, and kept strictly separated throughout the study to prevent contamination, maintaining a designated distance between them.

In the laboratory, bark and leaf samples were first fragmented and classified. Subsequently, leaves and bark were divided into two groups, one of which underwent a washing procedure. Particulate matter adhering to plant organs influences the accumulation of heavy metal concentrations within these organs. Several studies have demonstrated that the washing process with water can remove heavy metal accumulation in plant organs, depending on the type of metal. If the particulate matter is contaminated with heavy metals, unwashed samples generally exhibit higher heavy metal concentrations (Cesur et al., 2022; Kuzmina et al., 2023). In this study, plant organs were subjected to a washing process to observe the effect of particulate matter on heavy metal accumulation. The washing process was conducted using intensive water and a brush, followed by rinsing with pure water. No metal tools were used during these procedures. Once washing was completed, all samples were transferred to labeled glass containers. The samples were left to dry at room temperature for 15 days and then oven-dried at 45 °C for 1 week. The dried samples were ground, and 0.5 g portions were weighed and placed into tubes designed for microwave processing. Then, 10 ml of 65% HNO_3 was added to each sample. This process was carried out in a fume hood. The prepared samples were then processed in a microwave oven at 280 PSI pressure and 180 °C for 20 min. After these steps, the samples were removed from the microwave and left to cool (room temperature, 23–25 °C). Deionized water was added to each cooled sample

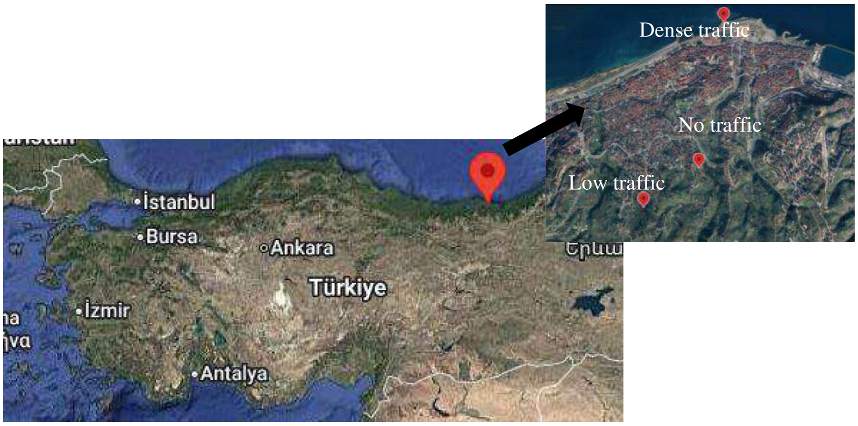

Fig. 1 Location of the study area

to reach a final volume of 50 ml. The prepared samples were filtered through a filter paper and analyzed for Ni using a GBC Integra XL-SDS-270 ICP-OES device. In total, data from 9 plant species × 3 different areas × 5 organs (Unwashed Leaf, Washed Leaf, Washed Bark, Unwashed Bark, Branch) × 10 replications = 1350 measurements were obtained and evaluated. The collected data were analyzed using SPSS 22.0 software with variance analysis and the Duncan test, and the results were interpreted. This methodology is commonly used in similar studies (Ghoma et al., 2022; Isinkaralar et al., 2022; Koç et al., 2024).

Results

As shown in Table 1, the variation in Ni concentration by species is statistically significant at the 99.9% confidence level across all traffic densities as well as the average values. Upon examining the values, it is generally observed that the lowest Ni concentrations are found in *N. oleander*, *S. babylonica*, and *M. grandiflora*, while the highest Ni concentrations are generally recorded in *R. pseudoacacia* and *A. negundo*.

In *N. oleander*, the variation in Ni concentration across all organs with traffic density, and across all traffic densities by organ, was found to be statistically significant (Table 2). However, the variation in Ni concentration by organ alone was not statistically significant at the average values level ($p > 0.05$). Generally, the highest values were obtained in high-traffic conditions, and according to the Duncan test on the average values, two groups were formed: high traffic was classified in the second group, while the values from other traffic densities were placed in the first group.

The variation in Ni concentration in *S. babylonica* is presented in Table 2. As shown in Table 2, the variation in Ni concentration across all organs with traffic density and across all traffic densities by organ in *S. babylonica* is statistically significant. Generally, the highest values were obtained in high-traffic conditions, and according to the Duncan test on the average values, the values obtained in high traffic were classified in the second group. By organ, the highest values were found in the leaves.

The variation in Ni concentration in *M. grandiflora* is presented in Table 2. In *M. grandiflora*, the variation in Ni concentration across all organs by traffic density, and across all traffic densities by organ, was also found to be statistically significant. When evaluated by organ, two groups were formed based on average values: washed leaves, where the highest values were recorded, were placed in the second group, while all other organs were included in the first group. Generally, the highest values were obtained under high-traffic conditions, and according to the Duncan test on average values, two groups were formed, with high traffic categorized in the second group and values from other traffic densities in the first group. The variation of Ni concentration in *P. laurocerasus* is presented in Table 3.

Upon examining Table 3, it is evident that the variation in Ni concentration in *P. laurocerasus* across all organs by traffic density, as well as across all traffic densities by organ, is statistically significant. According to the average values, the lowest concentrations were observed in the leaves, while the highest

Table 1 Variation of Ni concentration (ppb) by species and traffic density

Species	Traffic density			Average
	No traffic	Low-density traffic	Dense traffic	
N. oleander	509.7 a	461.9 a	1327.0 a	766.2 a
S. babylonica	946.8 ab	624.2 a	1302.9 a	935.7 ab
M. grandiflora	381.2 a	378.4 a	1139.3 a	632.9 a
P. laurocerasus	2432.1 d	1098.0 b	1021.1 a	1517.1 c
C. siliquastrum	1930.0 cd	2668.6 d	2407.2 b	2335.3 d
R. pseudoacacia	4457.4 e	2533.6 cd	2662.8 b	3217.9 e
A. hippocastanum	1552.9 bc	1198.2 b	1030.1 a	1260.4 bc
P. orientalis	1836.0 cd	1066.2 b	1634.8 a	1512.4 c
A. negundo	3759.9 e	2270.7 c	3304.9 c	3111.9 e
F-value	23.309***	76.345***	16.174***	47.617***

According to Duncan test results, lowercase letters (a, b) show differences among traffic. It is statistically different from the values contained in different groups, starting with the letter a numerical value grows. Significant levels such as ns = $p > 0.05$, *$p < 0.05$; **$p < 0.01$; **$p < 0.001$

Table 2 Variation of Ni concentration (ppb) in *N. oleander, S. babylonica,* and *M. grandiflora* by organ and traffic density

Species	Organ	Traffic density			*F*-value	Average
		No traffic	Low-density traffic	Dense traffic		
N. oleander	Unwashed leaf	330.4 abA	481.63 dB	622.56 cC	2098.2***	478.2
	Washed leaf	519.7 bA	796.63 eB	2535.46 dC	23,539.1***	1283.9
	Washed bark	521.9 bB	347.63 bA	567.13 bC	1039.1***	478.8
	Unwashed bark	1027.5 cA	411.80 cA	2688.13 eB	17.7**	1375.8
	Branch	149.2 aA	272.13 aC	222.00 aB	78.6***	214.4
	F-value	35.7***	5049.970***	6695.538***		5.831 ns
	Average	509.7 A	461.9 A	1327.0 B	7.441**	
S. babylonica	Unwashed leaf	1261.43 cA	1322.89 cA	2323.93 cB	1072.1***	1636.0 b
	Washed leaf	1461.96 cB	858.69 bA	2673.06 dC	7157.9***	1664.5 b
	Washed bark	748.86 bC	372.76 aA	586.73 bB	791.1***	569.4 a
	Unwashed bark	437.06 aA	491.66 aC	463.56 aB	74.6***	464.1 a
	Branch	344.44 aB	294.7 aAB	49.4 A	5.4*	344.5 a
	F-value	26.442 ***	18.165***	29,707.563 ***		18.689***
	Average	946.8 AB	624.2 A	1302.9 B	3.655*	
M. grandiflora	Unwashed leaf	388.26 bB	362.16 bA	431.50 bC	38.3***	393.9 a
	Washed leaf	418.93 cA	554.69 dB	2951.33 eC	7015.3***	1308.3 b
	Washed bark	331.26 aA	362.86 bA	967.50 cB	1387.8***	553.8 a
	Unwashed bark	430.00 cB	398.09 cA	1264.03 dC	4528.7***	697.3 a
	Branch	337.70 aC	214.20 aB	82.33 aA	873.1***	211.4 a
	F-value	150.123***	392.785***	5147.477***		4.351**
	Average	381.2 A	378.4 A	1139.3 B	8.049**	

According to Duncan test results, lowercase letters (a, b) show differences among traffic, while uppercase letters (A, B) show differences among organs. Significant levels such as ns = $p > 0.05$, *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

concentrations were found in the unwashed bark. In terms of traffic density, the results of the Duncan test indicated that the values obtained in areas with no traffic were categorized in the second group, while the values from other traffic densities were included in the first group.

The variation in Ni concentration in *C. siliquastrum* is presented in Table 3. As shown in Table 3, the variation in Ni concentration in *C. siliquastrum* across all organs by traffic density, as well as across all traffic densities by organ, is statistically significant. Generally, the highest values were obtained under high or moderate traffic conditions, and according to the Duncan test on average values, the values recorded in high and moderate traffic constituted the second group. By organ, the highest values were found in the unwashed bark.

The variation in Ni concentration in *R. pseudoacacia* is presented in Table 3. In *R. pseudoacacia*, the variation in Ni concentration across all organs by traffic density and across all traffic densities by organ was found to be statistically significant. However, the variation in Ni concentration by organ alone was not statistically significant according to the average values ($p > 0.05$). Generally, the highest values were obtained in areas with no traffic, and based on the Duncan test results on average values, two groups were formed: the values recorded in areas without traffic were classified in the second group, while those obtained in other traffic densities were included in the first group. The variation in Ni concentration in *A. hippocastanum* is presented in Table 4.

Upon examining Table 4, it is evident that the variation in Ni concentration is statistically significant based solely on traffic density in leaves and wood. In contrast, the variation by organ across all traffic densities is statistically significant. However, the variation in Ni concentration by organ alone is not statistically significant according to the average values ($p > 0.05$). Generally, the highest values

Table 3 Variation of Ni concentration (ppb) in *P. laurocerasus, C. siliquastrum,* and *R. pseudo-acacia* by organ and traffic density

Species	Organ	Traffic density			*F*-value	Average
		No traffic	Low-density traffic	Dense traffic		
P. laurocerasus	Unwashed leaf	3159.73 dC	177.10 aA	627.00 aB	1256.9***	1321.2 ab
	Washed leaf	633.23 aC	438.63 bA	495.16 aB	692.4***	522.3 a
	Washed bark	3775.06 eB	1765.60 eA	1814.26 bA	112.4***	2451.6 c
	Unwashed bark	1731.46 bB	1674.13 dB	681.00 aA	8.7**	1362.2 ab
	Branch	2861.20 cB	1434.66 cA	1488.53 bA	1648.9***	1928.1 b
	F-value	185.255 ***	4821.690***	14.649***		6.191**
	Average	2432.1 B	1098.0 A	1021.1 A	13.040***	
C. siliquastrum	Unwashed leaf	1925.60 cA	2582.13 bB	1978.53 aA	276.0***	2162.0 a
	Washed leaf	1804.80 bA	2548.53 aC	2024.26 aB	786.7***	2125.8 a
	Washed bark	2485.86 eA	2629.06 bB	2970.79 dC	126.3***	2695.2 b
	Unwashed bark	1058.66 aA	2848.26 dC	2629.73 cB	2501.5***	2178.8 a
	Branch	2375.20 dA	2735.33 cB	2432.93 bA	57.3***	2514.4 ab
	F-value	517.142***	55.209***	412.618***		2.914*
	Average	1930.0 A	2668.6 B	2407.2 B	14.344***	
R. pseudo-acacia	Unwashed leaf	4253.73 cC	2387.46 aA	3011.06 dB	876.7***	3217.4
	Washed leaf	3522.40 aC	2681.46 cB	2454.39 bA	2841.6***	2886.0
	Washed bark	3955.19 bC	2642.66 cB	2149.73 aA	1410.1***	2915.8
	Unwashed bark	5150.53 dC	2515.33 bA	3044.13 dB	6636.3***	3570.0
	Branch	5405.20 eC	2441.46 aA	2655.06 cB	2573.4***	3500.5
	F-value	1005.998***	33.949***	187.596***		0.897 ns
	Average	4457.4 B	2533.6 A	2662.8 A	75.818***	

According to Duncan test results, lowercase letters (a, b) show differences among traffic, while uppercase letters (A, B) show differences among organs. Significant levels such as ns = $p > 0.05$, *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

were recorded in areas with no traffic, and based on the Duncan test results on average values, two groups were formed: the values obtained in areas without traffic were classified in the second group, while those recorded in other traffic densities were included in the first group.

The variation in Ni concentration in *P. orientalis* is presented in Table 4. As shown in Table 4, the variation in Ni concentration in *P. orientalis* across all organs by traffic density, as well as across all traffic densities by organ, is statistically significant. According to the results of the Duncan test on average values, the organ-based values were grouped into two categories: the lowest values, found in wood and unwashed bark, were placed in the first group, while the values obtained from the other organs were included in the second group. In terms of traffic density, the values recorded under low traffic conditions were classified in the first group, while the values obtained in areas without traffic were placed in the second group, and the values from high traffic conditions were included in both groups.

The variation in Ni concentration in *A. negundo* is presented in Table 4. In *A. negundo*, the variation in Ni concentration across all organs, except for washed leaves, by traffic density and across all traffic densities by organ was found to be statistically significant. However, the variation in Ni concentration based on average values was not statistically significant ($p > 0.05$).

Discussion

The accumulation of HMs in plants can stem from soil contaminated by industrial, traffic, and household activities through roots or atmospheric deposition of particles, subsequently absorbed by leaves (Canturk et al., 2024; Kuzmina et al., 2023). Findings from this study indicate significant variations

Table 4 Variation of Ni concentration in *A. hippocastanum*, *P. orientalis*, and *A. negundo* by organ and traffic density

Species	Organ	Traffic density			*F*-value	Average
		No traffic	Low-density traffic	Dense traffic		
A. hippocastanum	Unwashed leaf	1341.53 bC	1228.86 aB	711.00 aA	382.4***	1093.8
	Washed leaf	1960.60 dC	1044.13 aA	1527.26 aB	1652.1***	1510.6
	Washed bark	1755.40 c	970.66 a	1021.00 a	2.2 ns	1249.0
	Unwashed bark	585.19 a	1581.70 a	948.19 a	2.5 ns	1038.3
	Branch	2121.86 eC	1165.86 aB	943.40 aA	3334.5***	1410.3
	F-value	1835.149***	1.073***	1.539 ***		1.415 ns
	Average	1552.9 B	1198.2 A	1030.1 A	4.651*	
P. orientalis	Unwashed leaf	2679.20 dC	1809.33 eB	1467.00 cA	2224.2***	1985.1 b
	Washed leaf	2786.40 eC	1044.46 cA	1506.53 dB	6093.2***	1779.1 b
	Washed bark	1731.13 cC	400.59 aA	889.73 bB	5374.9***	1007.1 a
	Unwashed bark	1197.06 bA	1198.73 dA	3600.73 eB	11,224.5***	1998.8 b
	Branch	786.59 aB	878.26 bC	710.40 aA	67.3***	791.7 a
	F-value	3789.913***	2744.266***	13,346.616***		5.454**
	Average	1836.0 B	1066.2 A	1634.8 AB	3.521*	
A. negundo	Unwashed leaf	2578.13 bA	2603.73 bA	3685.86 dB	818.4***	2955.9
	Washed leaf	2362.00 a	2637.86 b	3411.46 c	3.2 ns	2803.7
	Washed bark	2430.00 aB	1747.60 bA	3353.33 bC	2750.8***	2510.3
	Unwashed bark	2358.66 aA	2670.93 bB	3825.86 eC	1661.4***	2951.8
	Branch	9071.06 cC	1693.59 aA	2248.40 aB	21,978.2***	4337.6
	F-value	10,539.089***	4.613***	1688.203***		1.578 ns
	Average	3759.9	2270.7	3304.9	3.184 ns	

According to Duncan test results, lowercase letters (a, b) show differences among traffic, while uppercase letters (A, B) show differences among organs. Significant levels such as ns = $p > 0.05$, *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

in Ni concentration by species across different traffic densities, with the lowest concentrations observed in *N. oleander*, *S. babylonica*, and *M. grandiflora*, and the highest concentrations in *R. pseudoacacia* and *A. negundo*. Sevik et al. (2020) found that the concentrations of Ni and Co increased in most plant organs based on traffic density. Additionally, numerous studies have reported an increase in HM pollution associated with traffic density (Cobanoglu et al., 2023; Istanbullu et al., 2023; Zhang et al., 2022). As Ni is found in petroleum and motor oil, motor vehicles may represent a significant source of this contaminant, suggesting that higher concentrations of this metal are likely in areas with heavy traffic (Amato-Lourenco et al., 2016; Budzyńska et al., 2023).

Heavy metal accumulation in plants varies depending on plant species (Erdem et al., 2024; Key et al., 2022). For instance, in a study conducted in areas with high traffic density, the highest Pb levels were found in *Aesculus hippocastanum*, and the highest Cd, Ni, and Zn levels were recorded in *Salix babylonica*, with the highest Cu, Mg, Cr, Fe, and Mn levels observed in *Salix japonica* (Turkyilmaz et al., 2020). This situation is linked to various factors, including the plant's anatomical structure, the size of organelles, the interaction of organelles with the physicochemical properties of metals, morphology, surface area, surface texture, plant habitus, phenological structure, duration of HM exposure, and moisture (Shahid et al., 2017; Yucedag et al., 2019). Plants produce cell walls to protect themselves from damage caused by external sources. This protection is also provided by the semipermeable plasma membrane and cellular defense systems. Consequently, extracellular and intracellular HM concentrations vary by species (Ben et al., 2023). This study also highlights the variation in Ni accumulation across the examined species.

The research reveals differences in elemental concentration both among species and between organs of the same species. In *N. oleander* and *A. negundo*, the highest Ni concentrations were observed in leaves and bark under all traffic densities, particularly in areas of heavy traffic. In *Salix* and *Magnolia*, the highest values were recorded in all organs under heavy traffic conditions. Similarly, many studies have been conducted suggesting that HMs are retained more intensively by different organs of the same plant species (Dambiec et al., 2022). For instance, a study by Świątek et al. (2024) indicated that despite high HM concentrations in prepared substrates, there was only a slight transfer to the plant's above-ground parts, with significantly higher metal accumulation in *Betula* roots compared to *Pinus* and *Larix*.

Various plant parts, especially leaves, stems, bark, and annual rings, are also used as biomonitors in studies (Öztürk Pulatoğlu, 2024; Pulatoglu, 2024). Some researchers have reported the transfer of certain elements within trees, while others have noted a consistent concentration of other elements throughout all parts of the xylem (Cesur et al., 2021, 2022; Key et al., 2022; Zhang, 2019). Chen et al. (2021) observed that in their studies on *Pinus massoniana* annual rings, the concentrations of Ni, Cu, Cr, and Fe exhibited an increasing trend, likely due to physiological activities, rising tourism, and traffic pollution.

Some studies emphasize that there can be differences in the transport of trace elements between rainy and drought years. For instance, in a study on apple trees, high levels of As, Cd, and Cr were found, with the study noting that As and Cd were transported to apples during a high rainfall year, while under drought conditions, only Cr was taken up by the plant (Cervantes-Trejo & Leal, 2022).

In this study, a higher accumulation of Ni was observed in *P. laurocerasus*, *R. pseudoacacia*, *A. hippocastanum*, and *P. orientalis* species in areas with lower traffic density. Türkyılmaz et al. (2018) investigated the impact of HMs on traffic density in certain tree species and determined that the concentrations of Pb and Cd in *Tilia tomentosa* and Cu and Ni in *Prunus cerasifera* were higher in regions with low traffic density compared to those in high-traffic areas. Similarly, Sensula and Fagel (2023) found higher concentrations of certain elements in pine species in their research conducted away from industrial areas. Various studies have indicated that there is no significant difference in Cu content in *Pinus nigra* needles between polluted and unpolluted areas (Cindrić et al., 2019; Pavlović et al., 2017; Zsigmond et al., 2021). According to Petrova (2020), urban traffic has not affected the Cu and Zn content of *Pinus nigra* needles but has had an increasing effect on Cr and Fe content.

HMs present in the air can enter plants directly through respiration or adhere to plant organs with the help of particulate matter. Some of these metals mix with soil and water due to the effects of rain and gravity. HMs can also be absorbed by plants through their roots from water and soil. The uptake of elements by plants largely depends on the concentration, quantity, and activity of the element in the soil solution. The interaction between plants and HMs is the result of a complex mechanism arising from the mutual influence of various factors, including anatomical, morphological, genetic structures, and edaphic and climatic factors like air humidity, rainfall, and wind. After being released from the source, HMs can be transported to very distant locations, primarily through the air, but also through other pathways (Shahid et al., 2017; Türkyılmaz et al. 2020; Isinkaralar et al., 2022; Erdem et al., 2024).

Unexpected results were obtained for certain species in the study. For instance, in *P. laurocerasus*, the Ni concentration in unwashed leaves from non-traffic areas was found to be 3159.73 ppb, while in washed leaves, it was 633.23 ppb. However, in high-traffic areas, the Ni concentration in unwashed leaves was 627.00 ppb, and in washed leaves, it was 495.16 ppb. The fact that the highest Ni concentrations were detected in this species in non-traffic areas suggests that these plants may have been exposed to an alternative Ni source. Although petroleum products are the primary source of nickel, it is also widely used in galvanization, electronic devices, and various industrial applications. Studies on HM pollution indicate that the major sources of contamination include mining activities, industrial facilities, traffic, urban areas, and agricultural practices (Istanbullu et al., 2023). It is possible that samples collected from non-traffic areas were exposed to pollution sources, particularly those associated with urban environments. This is because definitively identifying the exact pollution source is generally challenging in such studies. Similar findings have been reported in other studies on the subject (Isinkaralar et al., 2022; Koç et al., 2024; Turkyilmaz et al., 2020).

In all traffic densities, the average Ni concentration was highest in the bark and leaves of *N. oleander*, while in *A. negundo*, the highest concentration was found in wood. In *P. laurocerasus* and *C. siliquastrum*, the highest values were found in unwashed bark, while in *Salix*, they were found in leaves, in *M. grandiflora*, in washed leaves, and in *R. pseudoacacia*, in washed bark and wood. Some elements can easily enter leaves under wet conditions due to high stomatal conductivity (Fernández and Brown, 2013). On the other hand, wet conditions may lead to the closure of stomata and shrinkage of plant cuticles, thus preventing HM elements from entering leaves (Shahid et al., 2017). The mobility of elements among different organs of trees varies according to the element, biological characteristics, physiological processes, age of the trees, pollution sources, and environmental conditions (Cui et al., 2013). For instance, a study on *Pinus jeffreyi* reported a strong decline trend of Sr and Mn elements from the xylem to the bark, associated with metabolic processes such as photosynthesis and respiration (Kirchner et al., 2008; Marija et al., 2017). Another study indicated that in the industrial forests of Silesia, especially in areas near steel factories, trees significantly reduced their stomatal conductivity during the early 2000s (Sensula and Wilczyński, 2022). This decrease in stomatal conductivity may potentially influence the air quantity and, consequently, the elements taken up by plant leaves during respiration (Sensula and Fagel, 2023).

The study revealed that in some species, higher heavy metal concentrations were detected in washed samples, while in others, they were higher in unwashed samples. This variation is influenced by the extent to which particulate matter adhering to plant organs is contaminated with heavy metals. Specifically, if particulate matter is contaminated with heavy metals, unwashed samples tend to exhibit higher heavy metal concentrations. Conversely, if the particulate matter is not contaminated with heavy metals, washing the samples results in higher heavy metal concentrations in plant organs. This phenomenon has been reported in several studies (Cesur et al., 2022; Kuzmina et al., 2023).

Conclusion

This study presents data on Ni concentrations related to traffic density using leaf and bark samples from nine different plant species in Trabzon. In this context, the relationship between HM concentrations in plant species and their distance from the highway was assessed. The results indicate significant variations in Ni accumulation among species under different traffic densities based on average values. Generally, the lowest Ni concentrations were observed in *N. oleander*, *S. babylonica*, and *M. grandiflora*, while the highest concentrations were recorded in *R. pseudoacacia* and *A. negundo*. Therefore, *R. pseudoacacia* and *A. negundo* are considered suitable as biomonitors for Ni metal. These findings underscore the potential of plants to monitor HM pollution from traffic and suggest that these species should be considered in environmental protection efforts.

Measurable amounts of HMs in plant-available forms in polluted areas are crucial for assessing environmental pollution and detecting the toxic effects of metals. Determining the levels of HM accumulation in different parts of plants is essential for broadening the use of plants and their parts as biomonitors. To facilitate this, more research is needed on various species and metals. Expanding our understanding of how different plants interact with HMs will enhance our ability to monitor environmental health and guide remediation efforts effectively.

Author contributions A.O.P. wrote the main manuscript text.

Funding This study is supported by the Kastamonu University Scientifc Research Project Coordination Unit (Project Number is KÜ-HIZDES/2019–47).

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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