Effect of Urbanization on Terrestrial Ecosystem in Europe (Vienna) and in Asia (Pakistan)

Thesis for the Degree of Doctor of Philosophy (PhD)

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Debrecen, 2026

Hereby, I declare that I prepared this thesis within the Doctoral Council of Natural Sciences and Engineering, Juhász-Nagy Pál Doctoral School, University of Debrecen in order to obtain a PhD Degree in Natural Sciences at Debrecen University.

The results published in the thesis are not reported in any other PhD thesis.

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Hereby, I confirm that Dina Bibi candidate conducted her studies with my supervision within the Quantitative and Terrestrial Ecology Doctoral Program of the Juhász-Nagy Pál Doctoral School between 2022 and 2026. The independent studies and research work of the candidate significantly contributed to the results.

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Dissertation submitted in partial fulfilment of the requirements for the doctoral (PhD) degree in Environmental Science

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List of Abbreviations

AAC	Ascorbic acid content
ANOVA	Analysis of variance
APTI	Air Pollution Tolerance Index
BAF	Bioaccumulation factor
BAT	Best available techniques
CDA	Canonical discriminant analysis
CRM	Certified reference material
DW	Dry weight
FW	Fresh weight of individual leaves
GIS	Geographical information system
ICP-OES	Inductively coupled plasma optical emission spectrometer
IBM	International Business Machines.
LOI	Loss of ignition
NOx	Nitrogen oxide
OM	Organic matter
PAH	Polycyclic aromatic hydrocarbons
PCA	Principal component analysis
PI	Pollution Index
PM	Particulate Matter
RWC	Relative water content
SPSS	Statistical Package for the Social Sciences
SOX	Sulphur oxides
TChl	Total chlorophyll content
TW	Turgid weight
WHO	World Health Organization

1. INTRODUCTION

The urbanization includes urban the growth of developed areas and the urban areas now make up 3-4% of the most productive regions (Svirejeva-Hopkins & Schellnhuber, 2008). Approximately 0.5% of the world's geographical area is made up of heavily expanded areas (Schneider et al., 2010) Until the middle of the 20th century only the 17.8% of people lived in cities in the growing world. But the percentage has risen to almost 40% after 1950 in the 50 years. Based on the prediction in developing countries nearly 60% of people will live in cities by 2030 (Xing, 2016).

Urbanization has a direct impact on ecosystem productivity, biodiversity, watershed discharge characteristics, and biogeochemical cycles (McDonnell et al., 1997), diversity of alien species (Airola & Buchholz, 1984), and such abiotic environmental factors including soil characteristic, temperature, and atmospheric chemistry (Pouyat et al., 2002). As cities expand, the potential carbon sink on land decreases due to the replacement of vegetated land with impermeable materials such as building, highways, and parking lot. Traffic in Europe accounts for around 70% of nitrogen dioxide emissions, primarily from populated regions (Nieuwenhuijsen, 2020). Urban growth may significantly impact the carbon cycle, causing irreparable harm to surrounding ecosystems. According to Poggio et al. (2008), the urban environment is crucial as it houses the majority of the world’s population and has a direct impact on soil health.

Soil is a natural resource for plant growth and development, consisting of organic and mineral components in gaseous, aqueous and solid forms. Soils vary in both genetic and environmental factor, but they serve as water and nutrient reservoirs for plant roots and microbes to thrive (Ndiaye et al., 2000). Soil acts as a pollution absorber because it may hold onto several types of pollutants, pesticides, heavy metals, and PAH’s (polycyclic aromatic hydrocarbons). They aid in the food chains contamination, which can also endanger people’s health. Among all the xenobiotics found in soil, pesticides are the most widespread pollutants (Riffaldi et al., 2006).

Soil quality refers to the soil's capacity to perform ecological tasks, provide ecosystem services, sustain biological production, enhance environmental quality, and improve plant and animal health (Joimel et al., 2017). Integrating several elements, including physical, chemical, biological and enzymatic activity, can result in a more precise and superior soil evaluation (Liao et al., 2014). These elements need to be combined as indicators of soil quality evaluation (Liao et al., 2014). Chemical and physical properties including soil texture, soil moisture, pH, and organic matter are all out of balance because of natural disturbances and agricultural activities like

harvesting, irrigation, burning, fertilizers and pesticide application (Vallejo et al., 2012). Additionally, organic matter is an important indicator of soil health and fertility (Obalum et al., 2017). The presence of heavy metals content of soil is currently one of the most serious environmental problem heavy metals are regarded as potentially hazards compounds generated by anthropogenic activity which represents a danger to human health and the environment according to several types of scientific environmental studies (Al-Swadi et al., 2022) The risk to the health of humans and the environment is increasing due to the higher levels of heavy metal pollution in environmental components; toxic and harmful substances contaminating the soil cause some soil functions to be lost or destroyed. Anthropogenic activities have a negative impact and soil because of their close correlation with other environmental compartments, such as the atmosphere and water. One of the most damaging effects of human activities on terrestrial and aquatic ecosystems is the extensive mobilization and dispersal of pollutants from their natural reservoirs into the atmosphere and water (Driscoll et al., 2013; Karimi Nezhad et al., 2014; Wang & Qin, 2007).

Heavy metals are primarily deposited from a variety of sources such as fuel combustion, waste management, and transportation (car traffic, fuel composition (Guillén et al., 2011). Many toxic and poisonous elements and compounds that are designated as hazardous pollutants occur at higher quantities in a considerable percentage of soils in developed countries, and their past values exceed those in comparable new areas (Hu et al., 2013). The use of proper pollution/contamination indicators and indices, which may be thought of as a method and guide for geochemical evaluation of soil environment condition, is crucial for an effective evaluation of heavy metal pollution in soil. The mobility, bioavailability, and toxicity of metals are influenced by soil features; hence soil pollution cannot be entirely explained by heavy metal content. A more accurate assessment of contamination status and possible environmental hazards is produced by combining heavy metal levels with background values and important soil properties using soil quality and contamination indices (Kowalska et al., 2018). Pollution indices are useful in the monitoring of human activity as they aid in determining whether the buildup of heavy metals was caused by anthropogenic activities or by natural processes (Guillén et al., 2011; Karim et al., 2015). The concentration of heavy metal in soil is dependent on several factors, including the soil chemical, biochemical, and microbiological features.

In addition to contaminating soils, urbanization also degrades air quality, which can be monitored indirectly through plant responses., Industrialization, economic growth, energy use, and increasing traffic-latter, which is more common in metropolitan areas-all have an impact on air pollution (Petrova, 2011). In accordance with the World Health Organization,

(2016) air pollution is responsible for one in nine confirmed deaths annually and poses a significant threat to human health and the environment. Usually, fixed stations are used to measure the quantities of common pollutants as particulate matters, ozone, carbon monoxide, nitrogen oxide, sulfur dioxide and others. However, there are frequently not enough monitoring stations per city, and the data they offer is not typical of the entire city (Kumar et al., 2015). Trace elements have a significant influence on urban environmental pollution caused by artificial pollutants emitters, particularly industrial operations and automobile traffic. Trace elements released from soil can reach all food chain creatures and accumulate in plants, decomposers, herbivorous, and predatory organisms due to soil's ability to store pollutants (Simon et al., 2016).

The Air Pollution Tolerance Index measures how well plants can mitigate the negative impacts of air pollution (Girish et al., 2017). Therefore, the level of air pollution can be estimated using the APTI values of native plant species. APTI was initially suggested by (Singh & Rao, 1983), and landscape planners and researchers around the world have been using it more recently. Asian nations employ urban vegetation to mitigate air pollution caused by vehicle and industrial emissions, account for most reports regarding the use of APTI.

2. OBJECTIVES AND HYPOTHESIS OF THE STUDY

The aims of this study were to assess how urbanization affected the quality of soil and air pollution. Our study objectives are the following:

1. Determine the elements concentration of Vienna's soil and leaves along an urbanization gradient in urban, suburban, and rural areas.
2. Determine the elements concentration of Pakistan soil and leaves along an urbanization gradient in urban, suburban, and rural area
3. Study the sensitivity of trees to air pollution using the Air Pollution Tolerance Index (APTI).

Our hypothesis of the study is the following:

1. We hypothesized that pollutant levels increased dramatically along urbanization gradients (rural, suburban, and urban), and the pollution index is useful indicator of the ecological condition of the soil.
2. We hypothesized that the highest metal and dust concentration of leaves is in the urban area, while the lowest is in the rural area.
3. Our hypothesis is that the Pollution Index (PI) values and the elemental analysis of soil are sufficient indicators to evaluate the pollution in urban environments.
4. The tree species differ in sensitivity to air pollution, and this is reflected by their APTI values.
5. The concentration of metals in soil and Neem tree (*Azadirachta indica*) leaves is higher in urban areas than rural areas.
6. Our hypothesis is that increasing soil elements concentrations do not always result in increased plant absorption.

3. LITERATURE REVIEW

3.1 Urbanization and Ecosystem Transformation

3.1.1 Effects of Urbanization on the Ecosystem

According to estimates, there will be 8.5-9.9 billion people on the planet by 2050 with 55-78% of them residing in cities The demand of urban land will surely rise a result of the worldwide urban population boom. In fact, urban land has already grown at a significantly quicker rate than urban population (Jiang & O'Neill, 2017; Seto et al., 2011). Despite making up approximately 0.2-2.4% of the world's total area (Potere & Schneider, 2007), urban growth has played a significant role in changing land use globally (Grimm et al., 2008), which in turn causes habitat degradation and conversion (van Vliet, 2019). According to international evaluations, compared to a naturally unaffected baseline, urban growth has resulted in a 38% decrease in the overall abundance of species and a 50% reduction in local within-site species richness (Newbold et al., 2015). At previously unseen speeds and scales, human activity is changing the terrestrial ecosystem worldwide. Currently, pastures and crops make up around 40% of the land area, which is almost equal to the amount covered by forests (Foley et al., 2005). Urbanization is the most permanent and human-dominated land use on the spectrum of anthropogenic activity: changes in land cover, hydrological systems, biochemistry, temperature, and biodiversity are all consequences of urbanization (Grimm et al., 2008). One of the main causes of habitat loss and species extinction worldwide is urbanization (Hahs et al., 2009). Prime agricultural land is being used for urban expansion in several emerging nations (Seto et al., 2000). In highlighted microplastics, urbanization and industrialization enter terrestrial ecosystems and interfere with soil-plant-systems (Fig. 1). By accumulating in soils through surface runoff and atmospheric deposition, they have the microbial communities, soil structure and transparency reducing soil fertility and generating ecological disruptions. They can also spread to aquatic environments, be absorbed by plants, and pass through the food chain, where they may be consumed by humans (Ihenetu et al., 2024).

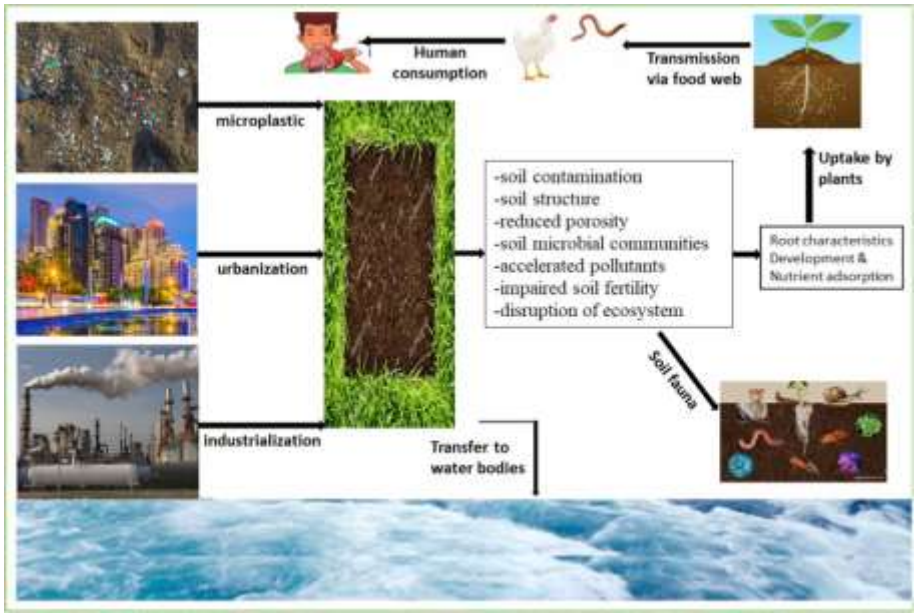

Figure 1. Schematic illustrates to the pathways from deposition → soil → plants → food web (Ihenetu et al., 2024).

3.1.2. Regional Urbanization Trends and Their Impact on the Environment

The rates of urban expansion over the research period varied significantly, according to (Seto et al., 2011), China having the highest rates and southwest Asia coming in second, Europe, North America, and Oceania have the lowest rates of urban growth. Vienna, Austria, has a population of 2,028,289 as of January 2025, with a total area of about 414.9 km², indicating that there are nearly 4,890 persons per km². Roughly 36% of Vienna's land is built-up (urban/settlement), whereas 45% is made up of parks and green space; highways and streets make up about 14.5% of the city's total surface area (Copernicus Land Monitoring Service, 2020). The Vienna urban area increased much more quickly than expected, according to data collected between 2008 and 2015. Thus, compared to the previous study period, dynamics have grown dramatically. Although Vienna's inner city is also expanding because of the positive birth rate, the urban region's overall population increase is mostly driven by internal migration and, more importantly international migration (Heikkilä & Kashinoro, 2009).

Pakistan's geographical identity is clearly established through its defined boundaries and varied terrain. Many people live in this nation, which

is also home to the biggest enterprises. Pakistan is urbanizing at the quickest rate in south Asia, at a rate of 3% each year (Jabeen et al., 2017). The population of Faisalabad city is higher than 3,6 million and the area of the city was approximately 1,330 km² in 2023 (Copernicus Land Monitoring Service, 2020). Faisalabad referred to as the Manchester of Pakistan due to its largest textile industrial zone, is one of the cities in Pakistan that ranks third in terms of population and second in the eastern province of Punjab. Faisalabad's urbanization is driven by several factors, including natural growth, international migration, and local movement from rural to urban areas. Developments to lifestyle education and other service facilities have a direct impact on natural resources, such as the land, water, and vegetation. Increased growth and industrialization in Faisalabad are the main causes of land loss without any planning, policy, or monitoring system, as urban land directly contributes to the loss of agricultural and barren land (Safder, 2019).

3.2. Urban Soil Health and Pollution

3.2.1. Urban soil quality

However, investigations of entire landscapes have demonstrated that the biological, physical, and chemical reactions of soils to urban land use are diverse and complicated, leading to the identifications of highly fertile or relatively undisturbed soil in urban regions (Pouyat et al., 2007). Both the natural composition of the soil and modification brought about by human usage and management have an impact on its quality (de Paul Obade, 2019). In metropolitan areas, soils typically seen as extremely disturbed, diverse, and lacking in systematic patterns. Hence, most of the research has been on soils that have been created by humans along streets and places that have been severely affected (Jim, 1998). This has led to the perception that urban soils are extremely disturbed and unproductive (Craul, 1992). Urban soil heavy metal deposition and contamination, which are significantly influenced by the urban soil environment, are the features of the fast growth of urbanization and the expansion of industrial sectors in and around urban areas. Urban garbage, waste disposal, industrial effluents, car emissions, building waste, and extensive pesticides use are the usual ways that soil heavy metals are introduced into the urban environments (Sun et al., 2019). As a result different soil heavy metals have seriously contaminated almost five million sites worldwide (Liu et al., 2018).

3.2.2. Soil Pollution and Ecological consequences of human activity

Urban soils have been polluted by a variety of sources, such as pollutants from vehicle and industrial emissions that are deposited in the atmosphere, waste disposal and landfill sewage, industrial waste water, and fertilizer and pesticide applications. These sources change the physical, chemical, and biological characteristics of the soil and cause ecological change (Tang et al., 2024). Forests are frequently replaced by human-mediated ecosystems used for farming, urbanization, or industrialization because of anthropogenic changes in terrestrial environment (El Khalil et al., 2013). Human activity has varying effects on these land uses in terms of duration and intensity (Manzo et al., 2019). Urbanization has two-way effects on soil characteristics. Land-use changes and environmental disruption are just two of the many complex modifications that come with urbanization. Significant alterations in the formation and activities of organism communities are brought about by these changes, which also have a greater impact on the chemical and physical characteristics of soil (Memoli et al., 2019). While several studies have established that urban soils contain significant levels of organic matter and nutrients (Schindelbeck et al., 2008), others have found that these soils have limited nutrient support for plant growth (Herrmann et al., 2017) which is occasionally linked to high levels of heavy metal contamination.

Exposure of heavy metal of soil is currently one of the main important environmental problems. Heavy metals are considered potentially hazardous compounds generated by anthropogenic activity that pose a risk to human health and the environment, according to several scientific environmental studies. Global risk to human and ecological health is increasing due to the increasing levels of heavy metal contamination in environmental components toxic and harmful substances contaminating soil cause some soil functions to be lost or degraded (Weissmannová & Pavlovský, 2017). Heavy metals enter the environment through a variety of sources, including sewage sludges, commercial fertilizers, waste disposal and treatment, air deposition from industrial areas, and other processes resulting from the breakdown of different materials (He et al., 2005). Although metals are naturally occurring elements that are present in all parts of the earth's crust, human activity is primarily responsible for environmental contamination, human exposure, disruption of metal geochemical processes, and buildup of metals above background concentration. Three categories can be used to classify soil contamination; (1) contamination from industrial processes and solid waste that primarily affect surface soils and disturb their profiles; (2) contamination from urban and agricultural activities; and (3) contamination that primarily affects both surface and subsurface soils (Gao et al., 2013; Wang et al., 2015). Urban soils in cities worldwide show higher concentrations of metals like Cd, Cu, Pb, Zn, and Hg (H. Chen et al., 2015; Xiao et al., 2017). These metals can enter the

soil through fossil fuel burning, industry and traffic pollutants, and municipal trash. Lead and copper are primarily sourced from traffic and combustion. Other sources include incinerators and material deterioration. Soil absorbs these metals through fertilizer, sewage sludge, irrigation water, and air deposition (Sager et al., 2015). The heavy metals protocol in Europe mandates reductions in annual emissions of Cd, Pb, and Hg to prevent significant harm to ecosystems. The protocol on heavy metals, which was adopted in 1998 and went into effect in 2003, requires Parties to lower their emissions of cadmium (Cd), lead (Pb), and mercury (Hg) to levels below those of 1990. It also sets stricter limits for key industrial sources and requires the use of Best Available Techniques (BAT) (Nations & Pollution, 2015). This is crucial as the distribution and magnitude of these elements pose significant threats to European ecosystems, as reported by the coordination center for effects in 2000 and 2010 (Posch et al., 2003).

Since Vienna is the most populated city in Austria and one of the continents cultural hubs, study of heavy metal pollution in this region is extremely important from a sustainability perspective. The effects of urbanization on Vienna's urban ecology were investigated using element concentrations of soils. Simon et al. (2013) found a moderate quantity of Co, Pb, and Zn contamination using PI. Because the concentration of these metals is higher than their background concentration, their findings suggest that traffic emissions may be the primary source of these metals in Vienna.

Faisalabad, Pakistan's second largest industrial city, shares all the environmental problems that other cities in Pakistan and the world face. The urban environment of Faisalabad has long been contaminated by several contaminants, most notably heavy metals. Certainly, the possibility of heavy metal contamination of urban soil is causing Faisalabad residents to become more anxious and concerned. To determine the current level of heavy metal contamination, an extensive soil survey was conducted in the urban parks of Faisalabad, Pakistan. Faisalabad heavy metal pollution was caused by industrial, agricultural and ban activities (Parveen., 2012).

Pollution indices are crucial for assessing soil contamination with heavy metals. First soil pollution indices introduced by Muller (1969) and Hakanson (1980). These indices provide a comprehensive geochemical assessment of soil environment (Mazurek et al., 2017). Soil pollution indices allow the estimation of environmental risk and soil degradation degree and help to determine if heavy metal accumulation is due to natural processes or anthropogenic activities. The comprehensive nature of soil quality assessment through indices is demonstrated by their ability to accurately predict soil degradation (Peter & Adeniyi, 2011). Pollution indices are important for monitoring soil quality and ensuring future sustainability, especially in agro-ecosystems (Ripin et al., 2014). Soil pollution indices are calculated by

assessing the geochemical background , which distinguishes natural heavy metals concentration from abnormal ones (Reimann & Garrett, 2005). Hawkes & Webb, (1962) is defined geochemical background as the normal abundance of an element in barren earth material. Matschullat et al. (2000) describe geochemical background as characterized by spatio-temporal changes in heavy metal content, reflecting the natural composition of heavy metals.

3.3. Air pollution in urban areas

3.3.1. Air pollution causes, measurement issues, and health/ecological implications

The release of materials into the atmosphere that are hazardous to people and other living organisms is known as pollution. Hazardous solids, liquids, or gases produce more than normal concentration and degrade the quality of our environment known as pollutants. The ecosystem is negatively impacted by human activity because it contaminates the soil where plants grow, the water we drink, and the air we breathe. The Industrial revolution led to the generation of enormous amounts of airborne pollutants that are detrimental to global human health. Despite this, it was a major success in terms of technological advancement, societal development, and the provision of numerous services (Manisalidis et al., 2020).

Global environmental contamination is questionably seen as a complex international public health concern. In the modern period, urbanization and industrialization are undoubtedly approaching previously unthinkable and distressing levels on a global scale. Since anthropogenic air pollution causes roughly 9 million deaths annually, it is one of the largest threats to public health worldwide (WHO, 2019). The issue is more severe in developing countries (Mannucci & Franchini, 2017) because of population growth, unplanned urbanization, and the growth of industrialization. Poor air quality results from this, particularly in Pakistan with social gaps and an absence of knowledge about environmentally appropriate management. Numerous factors influence the dispersion of pollutants, but the two most important factors are wind and atmospheric stability (Kelishadi & Poursafa, 2010). Large scale human activities including using cars, power plants, combustion engines, and industrial machines are known to release most environmental contaminants. Automobiles are thought to be responsible for over 80% of today's pollution, making these activities the primary cause of air pollution due to their extensive scale (Möller et al., 1994). Field cultivation methods, petrol stations, fuel tank heaters, and cleaning practices are some other human activities that are also having a smaller impact on our

environment (Burt, 2003), in addition to several natural sources including soil and volcanic eruptions and forest fires.

The six main air pollutants that are reported by the World Health Organization (WHO) are lead, sulphur oxides, nitrogen oxides, carbon monoxides, ground-level ozone, and particulate matter pollution. All elements of the environment, including soil, ground water, and air can suffer greatly from air pollution. It also presents a significant risk to living things (Manisalidis et al., 2020). The environment in which we live is being harmed by air pollution in addition to human health.

Compared to the other air pollutants (Pascal et al., 2013), $PM_{2.5}$ and ground-level O_3 may have the greatest consequences on human health in cities, where 74% of the EU population resides (Gregor et al., 2018). These pollutants are linked to respiratory and cardiovascular disorder as well as death in the EU countries air pollution ($PM_{2.5}$) was responsible for 374.000 and O_3 for 14.600 non-accidental premature deaths in 2016 (European Environment Agency, 2018). Vienna is one of the central European most populous cities it is defined by industrial activity and automobile traffic, which puts a lot of pollution strain on the biota (Krommer et al., 2007). There have been reports of increased levels of trace elements, Ozone (O_3), Nitrogen oxide (NO_x) and Sulphur oxides (SO_X) in Vienna (Simon et al., 2011). PM_{10} concentration data from the European Environment Agency (EEA) were analyzed to assess air quality across EU Member States. The dataset represents the 90.4th percentile of daily mean PM_{10} concentrations, indicating compliance with the EU's regulatory standard, which allows for 35 exceedances annually of the daily limit value of 50 µg/m³ as defined in Directive 2008/50/EC. The map (Fig. 2) developed illustrates the distribution of PM_{10} pollution in Europe, highlighting areas where concentrations exceed EU air quality standards (European Environement Agency, 2025).

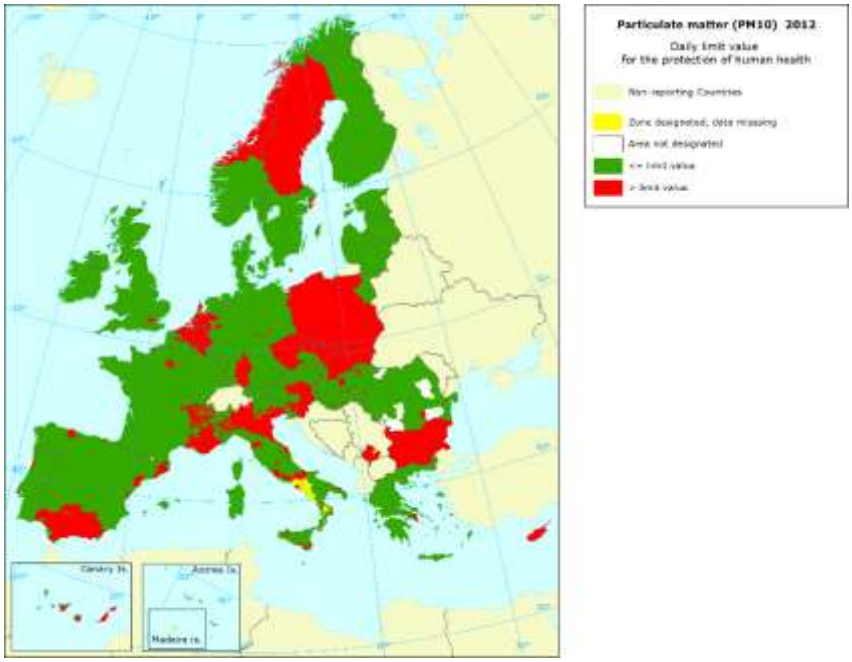

Figure 2. Concentration of PM_{10} based on European air quality data for 2023 (European Environement Agency, https://www.eea.europa.eu/en/analysis/publications/air-quality-status-report-2025/particulate-matter)

The issue of air pollution is getting worse in both developed and developing countries, including China, India, and Pakistan. The centers are particularly exposed to the negative effects of air pollution. The developed nations have already seen a significant loss of life and property (Yasir Niaz, Zhou Jiti, 2015). Pakistan's $PM_{2.5}$ exposure is among the highest in the world, with an annual average concentration of 66 $\mu g/m^{-3}$, exceeding the WHO guideline values. Air pollution causes around 135.000 premature deaths in Pakistan each year, ranking it as the country with the 5th highest number of pollution related deaths globally (Bilal et al., 2021). Faisalabad, one of Pakistan's largest cities, is known for its industrial activities and dense traffic, leading to major air pollution problems. Recent studies have shown that industry, vehicular emissions, including tire-derived particles, brick klins are important sources of particulate matter in Faisalabad (Hamid et al., 2023).

3.3.2. Plant leaves as Bioindicators of air pollution and APTI

The quality of the environment and its changes over time are evaluated using bioindicators, which might be biological processes, species or communities. Although anthropogenic stressors (such as drought or late spring

frost) or anthropogenic disturbances (such as pollution or changes in land use) significantly affect the ecosystem. The 1960's were the main decade for the broad development and use of bioindicators. The number of bioindicators has grown throughout time to help us investigate both terrestrial and marine ecosystems using all the major taxonomic groups (Burger, 2006). Bioindicators are living organisms, such as plants, planktons, animals, and microorganisms, that can monitor environmental health. As a result, bioindicators are an effective way to assess the detrimental environmental indictors are identifiable measures (e.g. chemical or genes) of environmental processes (Peakall, 1994). They are a useful tool not only for monitoring and evaluating environmental conditions, but also for developing our understanding of molecular toxicity mechanisms in various animal and plant species in the ecosystem (Nighat et al., 2000). As a result, plants can be utilized to determine whether specific physiological responses are appropriate biomarkers of urban pollution. Some plant indicators are specific to only one pollutant or combination of pollutants while others respond to a variety of pollutants and stressors (Petersen et al., 2009).

Plant species differ in their sensitivity to pollution stress. Matyssek et al. (1991) found that tolerance or resistance is achieved by ongoing biochemical, physiological, and morphological changes, allowing for survival even in extremely polluted environments. Adaptations boost plants tolerance to urban stressors such as drought, high temperatures, radiation, and pathogens.

The biochemical characteristics of plants, such as total chlorophyll, ascorbic acid, pH of the leaf extract, and relative water content can be used to screen plants near a pollution source for their sensitivity and tolerance levels for various pollutants (Kuddus et al., 2011). The air pollution tolerance index (APTI) is a single formula used to calculate these values. According to physiological and biochemical parameters that have been used to assess the tolerance of level of any plant species, APTI is a better means because studies of a single factor may not yield significant results or provide a clear picture of changes caused by pollutants (Leghari et al., 2011). One approach used to identify and categorize plants into groups that are sensitive and tolerant is the APTI. Under field conditions where the air is contaminated with various pollutants, the methodology provides a more dependable way to screen for sensitive and tolerant plant species. Several researchers have suggested that using the APTI to choose species that can with stand air pollution near polluting industries, it can be used for monitoring during the growing season (Chouhan et al., 2012). Air pollution tolerance was higher in plants with a high index value, and vice versa. Different species of plants were divided into sensitive, intermediate, slightly tolerant, and tolerant categories based on their indices (Singh et al., 1991).

3.3.3. Bioaccumulation and Soil-Plant Interactions

The European Green Deal's goals of climate neutrality, biodiversity restoration, sustainable agriculture systems, and a resilient ecosystem depends on having high-quality soil. Since heavy metal builds up in the soil's top layer before moving up the topic chain, heavy metal contamination of soils is one of the primary causes of declining soil quality and biodiversity loss, which is also linked to plant contamination. Metals mobility is determined by their chemical composition in soil, as well as the soil's physical and chemical properties (Li et al., 2022). Analysis of the bioavailability and ecotoxicity of metals in soil using biological techniques based on bioassays or bioindicators are useful tools for determining the risk posed by the metals (Harmsen, 2007). The potential ability of a substance to enter biological receptors is known as bioavailability (Fritsch et al., 2011).

Plants are typically chosen for measuring metal bioavailability over conventional chemical tests because they provide a more direct assessment of metal bioaccumulation without requiring computation of extraction concentration to have an effect. However, the type of plant, the characteristics of soil, and the quantity of exchangeable metals in the soil all affect how heavy metals plants bioaccumulate (Harmsen, 2007).

The bioaccumulation factor (BAF) is a measure that effectively describes the connection between soil metal content and plant metal content (Kumar et al., 2022). A plant's capacity to absorb a metal from the soil and the degree of translocation to the above-ground portions are indicated by the bioaccumulation factor (BAF) value (Gruszecka-Kosowska et al., 2020). Plants serve as a link between the elemental composition of the soil and the food chain by providing significant amounts of dietary minerals for both humans and animals. Plants nutrient absorption is therefore crucial for growth and development of plants, as well as for its key function in element cycling (Cuypers et al., 2013). Furthermore, contamination with potentially harmful materials like metals and metalloids makes many parts of the world unsuitable for crop cultivation. Non-essential elements that endanger the fitness of the plant and the food chain enter through the absorption and transport mechanisms that are essential for essential elements (Peralta-Videa et al., 2009). In the present study, BAF varied among areas indicating an effect of urbanization on metal uptake.

4. MATERIAL AND METHODS

4.1. Studied areas

Vienna, Austria and Faisalabad, Pakistan are the study comparative regions because of their different meteorological conditions, environmental regulations and urban development patterns. Vienna is an example of a well-planned European city with advanced waste management systems, strong environmental rules and well-established green infrastructure. On the other hand, Faisalabad is a prime example of a quickly urbanizing industrial city in a developing country, where environmental control efforts are frequently overtaken by urban expansion. The study intends to illustrate how various urbanization models affect soil and air quality specifically through elements build up in soil and plants, by contrasting these two regions. These contrast factors affect the health of urban ecosystems in various worldwide environments.

The sampling locations were in and around Vienna, Austria (Fig. 3). Austria's most important administrative and cultural hub is Vienna where two million people live with an approximate population density of 4,000 people per square kilometer. Vienna has a transitional climate and the annually precipitation ranges between 1000–2000 mm of and an average temperature of 10–20°C. Traffic emissions, produced by numerous roads and highways with significant traffic volumes, are the primary cause of pollution. To investigate the impact of urbanization on soil and plant leaves, a gradient of urbanization was used with three different areas; rural, suburban and urban was chosen along the gradient. Urban, suburban, and rural areas were categorized as exhibiting high, moderate, and low levels of urbanization, respectively, according to criteria including industrial activity, traffic intensity, and building. The urban area was located close to the city center in Stadtpark (48°20'N, 16°38'E). The suburban area was in Kurpark wich was located in the Oberlaa district (48°14'N, 16°40'E), Lainzer Tiergarten, located in the Lainz district (48°16'N, 16°25'E) which was a rural area (Fig. 3). Sampling sites were selected to represent distinct levels of urbanization and pollution. Stadtpark served as the urban site due to high traffic volume, Kurpark as the suburban site with moderate traffic, and Lainzer Tiergarten as the rural site characterized by minimal traffic. Geographic Information System

(GIS) analysis was used to assess distances from major roads and industrial zones to support site classification.

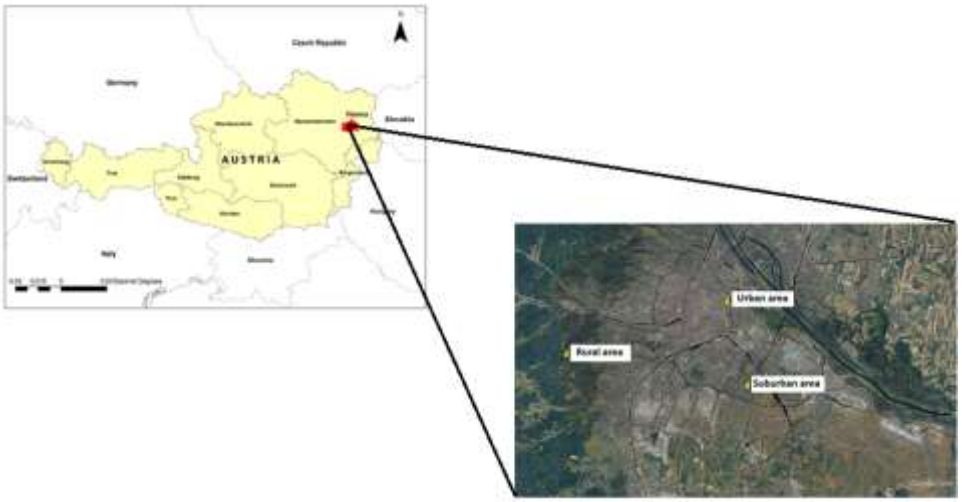

Figure 3. Map of Austria highlighting Vienna and sampling areas in Vienna along the urbanization gradient. (Created by author with QGIS and Google Earth Pro 7.3)

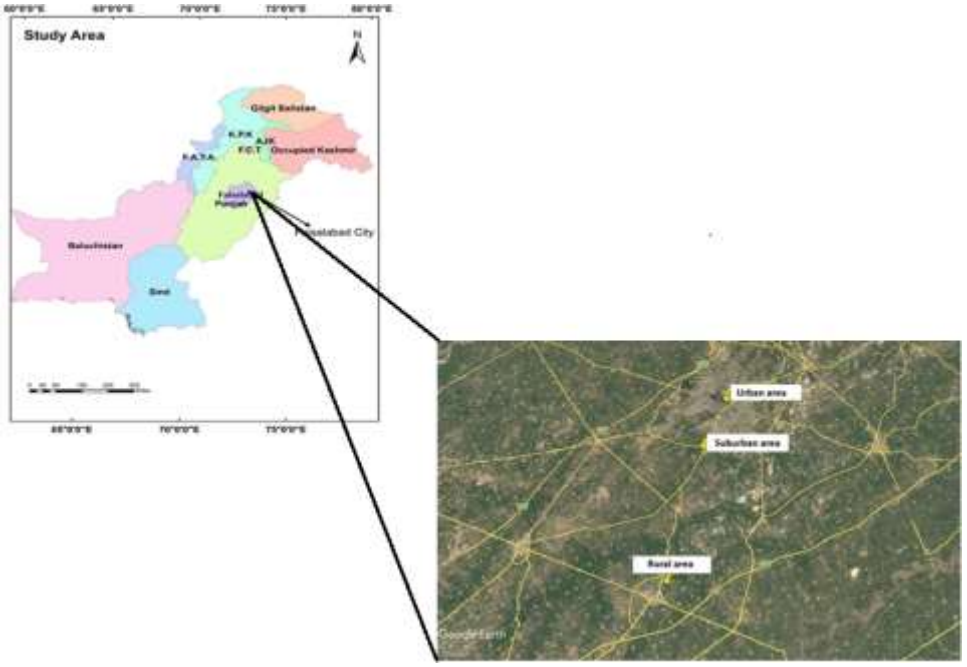

Figure 4. Map of Pakistan and Sampling areas in Faisalabad along an urbanization gradient (Created by author with QGIS and Google Earth Pro 7.3)

In case of Pakistan the sampling locations were located within and around the Pakistani city of Faisalabad. Because of its industrial center, the third-largest city in Pakistan (Fig. 4). With more than 5 million residents, In the Punjab region, Faisalabad is a heavily populated city and a significant industrial hub. It is renowned for having strong textile and hosiery industries as well. In addition to other companies, there are about 180 brick kilns, 140 textile dyeing plants, 120 foundries, and 80 engineering units in Faisalabad. Faisalabad has hot, humid summers and chilly, dry winters, with an annual rainfall of 526 mm. It falls into the semi-arid category. The primary source of pollution in cities is vehicle emissions, which are produced by many automobiles, motorcycles, and heavy-duty trucks. Along the urbanization gradient, samples were collected in rural, suburban, and urban areas. The urban area was Jinnah Garden in the city center (31° 25'N, 73° 5'E); the suburban area was Waris Pura (31° 40'N, 73° 08'E) and the rural area was Samundari Chak (31° 03'N, 72° 57'E) (Fig. 4). Jinnah Garden is situated in the heart of the city, an area marked by a dense population and constant vehicle movement. Waris Pura stands as a suburban area, characterized by its relatively moderate population and traffic levels. In contrast, Samundari Chak was chosen for its rural attributes: low population density, minimal vehicular movement, and a notable absence of industrial operations nearby.

4.2. Studied species

Acer platanoides (Norway maple), *Quercus robur* (oak), and *Fraxinus excelsior* (ash) were chosen for Vienna due to their widespread distribution in urban, suburban, and rural areas (Fig. 5). These species are perfect for examining urbanization gradients since they are either native to central Europe or have been widely adopted there. They are appropriate for comparing ecological studies due to their physiological characteristics, wide distribution, and ease of sampling.

Figure 5. (A) *Acer platanoides* (Norway maple), (B) *Quercus robur* (Oak) and (C) *Fraxinus excelsior* (Ash) (Captured by author)

Azadirachta indica (Neem) (Fig. 6) was selected for Pakistan because it is one of the most widely planted and naturally occurring tree species in metropolitan areas. Its long-term semi-arid environments and extensive distributions across several land-use zones make it a representative species for environmental monitoring in that region. Tree species chosen for this study were selected based on their ecological significance, widespread distribution, and ability to adapt to the usual ecosystems of cities in each area.

Figure 6. Individual of *Azadirachta indica* (Neem) in Faisalabad city (Captured by author)

4.3. Samples collection and pre-treatment

To represent urban, suburban, and rural locations, a total of 45 samples was collected, with 15 soil and plant leaf samples taken from each area in Vienna, Austria. The 15 samples per area were obtained from different locations within the area to capture spatial variability and reduce the influence of local heterogeneity. Soil and plant samples from Vienna were gathered in August 2021, during the late summer season, when vegetation is fully developed, and soil conditions reflect the peak of the growing season. Using a little hand spade, all samples were collected between 0 and 20 cm below the surface. Samples are kept in the refrigerator at -21°C in plastic bags. *Acer platanoides* (Norway maple), *Quercus robur* (oak) and *Fraxinus excelsior* (ash) leaves were collected from each sampling site, five tree individuals were chosen, and one tree's 30 leaves were sampled. Thus, along urbanization gradient, summary 150 leaf samples were collected from urban, suburban, and rural areas. The samples are labelled and kept in paper bags in the refrigerator at -21°C.

In Pakistan, 15 soil samples were collected, with 5 soil and plant leaf samples taken from each area. The 5 samples per area were obtained from different locations within the area. Using a little hand spade, all samples were gathered between 0 and 20 cm below the surface. samples were collected in December 2022, corresponding to the winter season, which represents the typical dry period in the study region. After collecting samples were stored at

room temperature in a polybag. In the case of the Neem tree (*Azadirachta indica*), a total of 15 leaf samples were collected along the urbanization gradient. From each of the five individually selected trees 30 leaves were taken at each sampling area. Samples were kept at room temperature in paper bags.

4.4. Physio-chemical soil parameters analysis

A soil solution made by mixing 5.0 g ± 0.03 soil samples with 30 ml of distilled water was used to measure the pH and electrical conductivity of soil samples from Vienna and Pakistan. A pH and electrical conductivity meter were used to measure the variables (Hach HQd Field Case No. 58258-00). Wet content was determined by measuring the samples in beakers after drying for 24 hours at 105°C and reweighing them (Simon et al., 2013, 2016, 2016; Valkó et al., 2013).

For the Arany-type plasticity index determination in a mortar 40 g air-dried soil was put and it was mixed with deionized water until homogeneous paste was formed. After the deionized water was added drop-wise till the upper limit of plasticity (Valkó et al., 2013). Arany-type plasticity index was calculated by the following equation:

$$PA = 100 * V/M,$$

where "V" is the amount of deionized water used, while "M" is the weight of the soil. The measured soil water capacity can be assigned to the following soil texture categories: $PA < 25$: coarse sand, $PA = 25–30$: sand, $PA = 31–37$: sandy loam, $PA = 38–42$: loam, $PA = 43–50$: clay loam, $PA = 51–60$: clay, and $PA > 60$: heavy clay soils.

For the determination of organic matter and calcium-carbonate content samples were dried at 550°C for 4 hours in a muffle furnace (Nabertherm L5/C6, Germany). To the organic matter content of soil was determined using the loss on ignition method, using the following equation:

$$LOI_{550} = ((DW_{105} - DW_{550})/DW_{105}) * 100 \quad (2)$$

where DW_{105} was the dry weight of samples at 105°C, LOI_{550} was the percentage of loss upon ignition at 550 °C, and DW_{550} was the sample weight at 550 °C (Heiri et al., 2001; Balogh et al., 2016).

The following formula was used to determine the calcium carbonate concentration after three duplicate samples (0.2 g) were incinerated in a muffle furnace for two hours at 950 °C.

$$LOI_{950} = ((DW_{550} - DW_{950})/DW_{105}) * 100 \quad (3)$$

where the dry weight of samples at 105°C was DW_{105}, the dry weight of samples at 950°C was DW_{950}, and the percentage of loss on ignition at 950°C was LOI_{950} (Heiri et al., 2001; Balogh et al., 2016).

4.5. Deposited Dust Amount Analysis

The leaf area was calculated by scanning the leaves in black and white to determine the amount of dust on the Vienna leaf samples. Image software was then used to analyze the images (Simon et al., 2014, 2016, 2021). Following the measurement of the leaf surface, the leaves were placed in 500 ml plastic containers. The leaves were then given 250 ml of deionized water. After it samples were shaken for ten minutes. A 150µm sieve was used to filter this suspension. The leaves were then shaken once again in 150 ml of deionized water, using the same process as before. Filter paper was used to filter this 300 ml suspension using a vacuum filter machine (N811KN.18Lapoport). Using filter paper (Munktell 392, Ahlstrom) with a retention diameter of 5-8µm, the amount of coarse dust (PM_{10}) was determined. The gravimeter method was used to measure the amount of dust; the amount of dust that accumulated on the filter papers was determined by weighing them both before and after filtration (Simon et al., 2014, 2016, 2021).

4.6. Air Pollution Tolerance Index (APTI)

For the leaf sample from Vienna, the concentration of ascorbic acid (mg g^{-1}(A)), total chlorophyll (mg g^{-1}(T)), relative water content (R), and pH of leaf extract (P) of the tree leaves were used to calculate the APTI values. We applied the APTI equation proposed by Singh et al. (1991) using these parameters:

$$APTI= [A \times (T+P) + R] /10 \quad (4)$$

To determine the ascorbic acid level, the redox titration method was employed. 50 ml of water were combined with 2g of crushed leaf tissue in three to four parts. After that, we collected the extract and added 100 ml to volumetric flasks. Each sample was analyzed in three replicates to ensure accuracy and reproducibility of the results. First, the pH of the leaves in this extract was measured using a digital pH meter (Hach HQd Field Case No. 58258-00). After the pH was determined, 20 ml portions of the sample were titrated in triplicate using 0.0025 mol of iodine solution in 1ml of 0.5 % (m/m)

starch solution. The blue color lasted for 20 seconds. 5ml of 96% ethanol were used to extract the chlorophyll from about 20 mg of fresh leaf material.

Using spectrophotometric analysis, chlorophyll was extracted from approximately 20mg of fresh leaf tissue using 5mL of 96% ethanol. The extracts' absorbance was determined at wavelengths of 653, 666, and 750 nm with spectrophotometer (BOECO S-22 0 UV/VIS). The total chlorophyll content (T) was calculated as follows:

$$T\ (mg\ g^{-1}) = (17.12 \times E666 - 8.68 \times E653) \times V/m \times 1000 \quad (5)$$

where E666 and E653 are the absorbance at 666 nm and 653 nm minus the absorbance at 750 nm, respectively. V is the volume (ml) of the extract of the leaf and m is the fresh weight (g) of the leaf sample.

The fresh weight of individual leaves (FW) was measured to calculate the relative water content. The turgid weight (TW) of the leaves was then measured after they had been submerged in water for the entire night. To determine the dry weight (DW), the leaves were lastly dried in an oven set to 70 °C. The following formula was used to get the relative water content:

$$(R\%) = (FW - DW) / (TW - DW) \times 100 \quad (6)$$

The following tree species have been categorized using APTI values: 20–24 is tolerant; 15–19 is intermediate; APTI ≤ 14 is sensitive; and >24 is tolerant (Singh et al., 1991).

4.7. Elemental Analysis of Soil and Plant Leaves

For elemental analysis of soil and leaf samples from Vienna and Pakistan samples of soil were dried, and plastic tweezers were used to remove any stones, plant roots, or residues. A 2 mm plastic sieve was used to filter the samples. After that, electrical homogenizer (Retsch GM 200 Verder Company, Haan, Germany) was used to homogenize the soil and leaf samples. After it samples were dried at 105 ℃ overnight. For elemental analysis 0.5 ml of 30% (m/m) hydrogen peroxide and 4.5 ml of 65% (m/m) nitric acid were used to digest 0.1 g of soil. Digested samples were diluted with 10ml 1% (m/m) nitric acid. For the analysis 0.2g of plant tissue was digested using 5ml 65% (m/m) nitric acid and 1ml 30 % (m/m) hydrogen peroxide. Elements were analyzed by inductively coupled plasma optical emission spectrometer (ICP-OES) with IRIS Intrepid II XSP instrument. We used six-point calibration procedure with multi-element calibration solution (Merck ICP multi-element standard

solution IV).ICP-OES (ICP-OES Agilent 5110) was used to analyze the following elements: Al, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, P, Pb, S, Sr, and Zn (Simon et al., 2011, 2014, 2016, 2021). Use of CRM (soil: (SQC001-30G and leaves: 1547) resulted in recoveries that were within 10% of the elements' certified values.

4.8. Pollution Index

Regarding the Vienna soil samples urban soil pollution levels were evaluated using the PI, which is defined as the ratio of soil metal concentration to metal geochemical concentration (Faiz et al., 2009; Wei & Yang, 2010):

$$PI = C_n/B_n \quad (7)$$

where C_n is the measured concentration of the soil heavy metals and B_n is the background concentration of the metal in the local environment. The background concentrations (Bn) analyzed to calculate the pollution index (PI) were based on geochemical background values published in the literature rather than local background soils. This method was taken because identifying truly uncontaminated reference soils in long-established urban environments such as Vienna is difficult. The background level is a measure that is used to distinguish between the concentration of the natural substance and the concentration with an anthropogenic effect in a specific environmental sample (Matschullat et al., 2000). The threshold concentration of Cd, Cr, Cu, Ni, Pb, and Zn was used based on earlier reported data by Pfleiderer et al. (2012). Low level of pollution is indicated by PI≤1, moderate contamination by PI≤2, high pollution by PI≤5, and extremely high pollution by PI≤5 (Wei & Yang, 2010).

4.9. Bioaccumulation Factor Analysis (BAF)

To calculate the Bioaccumulation Factor (BAF) for the soil and leaf sample from Pakistan, the following formula was used:

$$BAF = C_{plant} / C_{soil} \quad (8)$$

where C_{plant} represents the metal concentration in leaves and C_{soil} represents the metal concentration in soil. For every sampling area (rural, suburban, and urban) along the urbanization gradient, the calculation was done (Ivanciuc et al., 2006; Van Gestel et al., 2011).

4.10. Meteorological Data Collection

The European Environment Agency's (EEA) air quality database, which is based on fixed monitoring stations operating within and surrounding the research area, provided data on the concentration of air pollutants (CO, NO_2, $PM_{2.5}$ and PM_{10}). Based on their official EEA classification and physical location in relation to the sampling sites, monitoring stations were chosen to reflect urban, suburban, and rural stations. The urban sampling point was namely Wien (SPO.09.AKC.55397.5.1), the suburban sampling point was namely Schwechat Sportplatz, Mühlgasse (SPO.03.2701.4756.5.1) and the rural was namely Mödling Bachgasse (SPO.03.1401.4889.5.1). The background air pollution levels in each zone were described using the annual mean concentration that corresponded to the sample period. Instead of representing site-specific exposure at specific sample locations, these data were used to help the interpretation of general pollution patterns (EEA, 2024).

4.11. Statistical Analysis

Calculations were performed using the IBM SPSS Statistics 21 and Canoco for Windows 4.5 statistical software packages. IBM SPSS Statistics 21 was used for the Shapiro–Wilk normality test, Levene's homogeneity test and canonical discriminant analysis (CDA). To the main principal analysis Canoco for Windows 4.5 statistical software package was used.

Levene's test was used to study homogeneity of variance (De Sá, 2007). and in all cases the normal distribution was tested with a Shapiro–Wilk test. All variables were evaluated for distributional aspects and standardized using ln (x+1) transformation before to multivariate statistical analysis (PCA and CDA).

To identify the main parameters which have significant effects canonical discriminant analysis (CDA) based on the main physical and chemical parameters of soil and elemental concentration and parameters of APTI for leaves along the urbanization gradient in Vienna. CDA is a statistical method that helps distinguish between predefined groups by finding the variables that separate them while also simplifying the data by reducing its dimensionality (Rencher, 1992). PCA was used to study the separation of studied areas along the urbanization gradient based on the elemental concentration of soil and leaf samples from Pakistan. The PCA is also commonly used multivariate statistical method to reduce the dimensionality

of a dataset. In this case the first principal component explained the largest number of variances and we used it as a preprocessing step for other analyses, such as variance analysis (Rencher, 1992).

For differences in elemental concentrations and fundamental physical and chemical properties of soils and elemental concentrations and biological parameters of leaves two-way variance analysis (ANOVA) was used to test differences along the urbanization gradient among the areas and species in Vienna. One factor was the areas and the other was the tree species. The elemental concentration of soil and leaves of Neem were compared by one-way ANOVA in the case of Pakistan samples In all samples cases a pairwise comparison was conducted using Tukey's test (De Sá, 2007).

Pearson correlation was used to examine the relationship between the elemental concentration and parameters of APTI in leaves and annual concentration of air contaminants. The European Environment Agency website provided the CO, NO_2, $PM_{2.5}$, and PM_{10} data (https://www.eea.europa.eu).

5. RESULTS

5.1. Soil Pollution of Heavy Metals in Vienna, Austria

5.1.1. Basic physical and chemical parameters of soil

Canonical discriminant analysis (CDA) was used to study the differences among rural, suburban and urban areas based on the main physical and chemical parameters of soil in Vienna. Physical and chemical properties of the soil were found to be same across areas, with the first discriminant function (CDA1) accounting for 64.6% of the variance. The second function (CDA2) contributed 35.4% (Fig. 7). However, all parameters showed notable variations, except for calcium-carbonate content. Suburban areas had higher pH levels and electrical conductivity compared to rural areas. Urban areas had the lowest levels of organic matter and moisture content. (Table. 1).

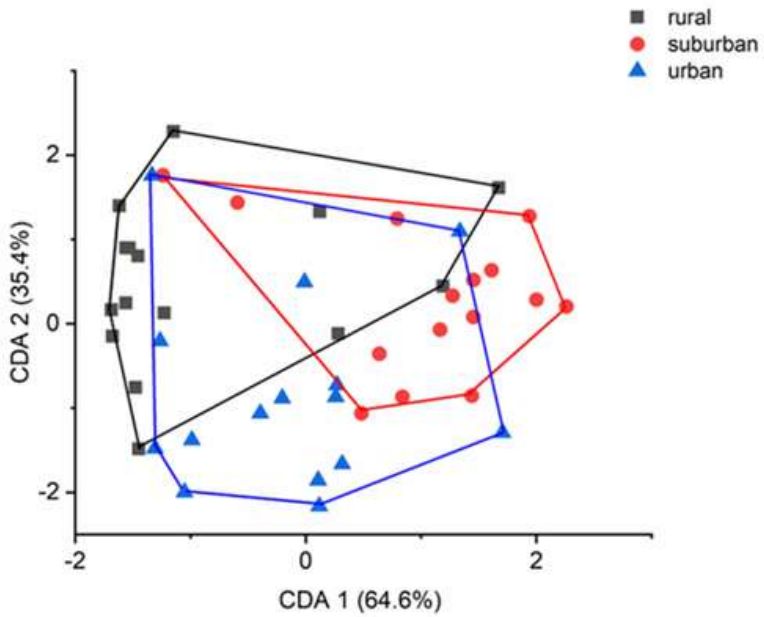

Figure 7. CDA scatter plot based on the basic physical and chemical parameters of soil from different areas along an urbanization gradient in Vienna

Table 1. Basic physical and chemical parameters of soil along the urbanization gradient. Notations: different superscripts indicate significant differences at $p < 0.05$.

Parameters	**Studied areas**		
	rural	suburban	urban
pH	7.1 ± 0.1^{a}	7.8 ± 0.1^{b}	7.5 ± 0.1^{ab}
Electrical conductivity, µS cm^{-2}	372 ± 91^{a}	931 ± 73^{b}	516 ± 67^{b}
Water Content, %	35 ± 3^{ab}	28 ± 4^{a}	22 ± 3^{b}
Organic matter, %	12.7 ± 0.8^{ab}	12.3 ± 0.5^{a}	10.0 ± 2.6^{b}
Calcium carbonate, %	6.7 ± 2.3	7.8 ± 1.3	6.0 ± 1.5
Arany-type plasticity index	36 ± 4	43 ± 4	41 ± 3
Soil texture	Sandy loam	Clay loam	Loam

5.1.2. Elemental Concentrations of Soil

CDA found total separation based on major and minor elements in the studied areas. Major elements had little overlap between suburban and urban areas, while minor element concentrations also showed overlap between suburban and rural areas (Fig. 8 and 9). The first Discriminant Functions (CDA1) contributed to 56.7% of the total variance, while the second one (CDA2) contributed 43.3% of the total variance for macro elements. In the case of microelements CDA1 contributed to 81.3% of the total variance, while the CDA2 contributed 18.7% of the total variance Furthermore, canonical correlation was 0.813 (macro elements) and 0.906 (micro elements) for CDA1; and 0.773 (macro elements) and 0.717 (micro elements) for CDA2.

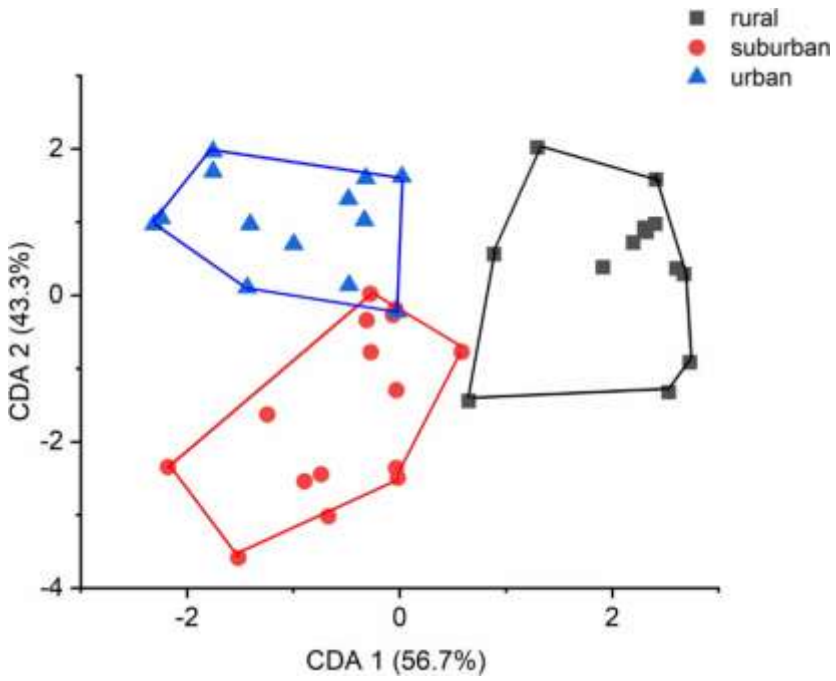

Figure 8. CDA scatterplot based on the major element concentration of soil from different areas along an urbanization gradient in Vienna.

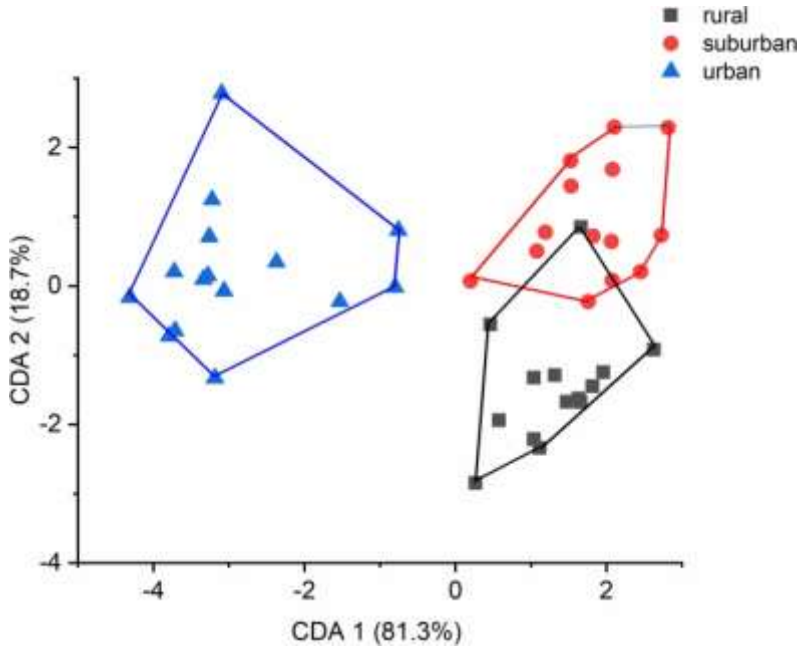

Figure 9. CDA scatterplot is based on the minor element concentration of soil from different areas along an urbanization gradient in Vienna.

Significant variations in metal concentrations were found by the study along the urbanization gradient, with higher concentrations in rural areas (Table. 2). Using the Tukey multiple comparison test, there were no significant differences in metal concentrations for Co, Fe, Ni, and P between suburban and rural areas. However, for Cu, Pb, Sr, and Zn, the metal concentrations were higher in urban and suburban areas. Interestingly, Al, Co, Fe, and Li concentrations were significantly lower in urban areas compared to suburban and rural areas (Appendix Table1).

Table 2. The concentration of major and minor elements (mean ± SD, mg kg^{-1}) in the soil samples along the urbanization gradient. Notations: different legends indicate the significant differences at $p < 0.05$.

	Studied areas		
Elements	**rural**	**suburban**	**urban**
Al	10128 ± 850[a]	9787 ± 465[a]	7096 ± 264[b]
B	23 ± 3	21 ± 2	28 ± 4
Ba	98 ± 9	103 ± 4	107 ± 4
Ca	35379 ± 12468	54150 ± 4091	47005 ± 3927
Cd	1.6 ± 0.1	1.5 ± 0.1	1.4 ± 0.1
Co	7.7 ± 0.7[a]	7.4 ± 0.3[a]	5.5 ± 0.2[b]
Cr	19 ± 1	19 ± 1	15 ± 1
Cu	25 ± 3[a]	39 ± 3[b]	49 ± 2[c]
Fe	18285 ± 1464[ab]	16970 ± 713[a]	14098 ± 498[b]
K	1689 ± 158[a]	2422 ± 146[b]	1830 ± 81[ab]
Li	28 ± 2[a]	29 ± 1[a]	20 ± 1[b]
Mg	10827 ± 2805	12695 ± 1256	12121 ± 1146
Mn	623 ± 72	553 ± 22	464 ± 19
Na	210 ± 20	233 ± 17	252 ± 23
Ni	28 ± 2[a]	26 ± 1[a]	20 ± 1[b]
P	459 ± 66[a]	849 ± 50[a]	1500 ± 196[b]
Pb	25 ± 4[a]	36 ± 3[a]	79 ± 8[b]
S	395 ± 30	406 ± 12	422 ± 12
Sr	51 ± 8[a]	75 ± 3[b]	69 ± 4[ab]
Zn	78 ± 7[a]	88 ± 3[a]	130 ± 5[b]

5.1.3. Pollution Index

For Cd, the PI value is higher than 1 along the urbanization gradient in all the areas, indicating a moderate level of pollution (Fig. 10). In the case of

other elements (Cr, Cu, Ni, Pb, and Zn), low level of pollution was found (Fig. 11-15).

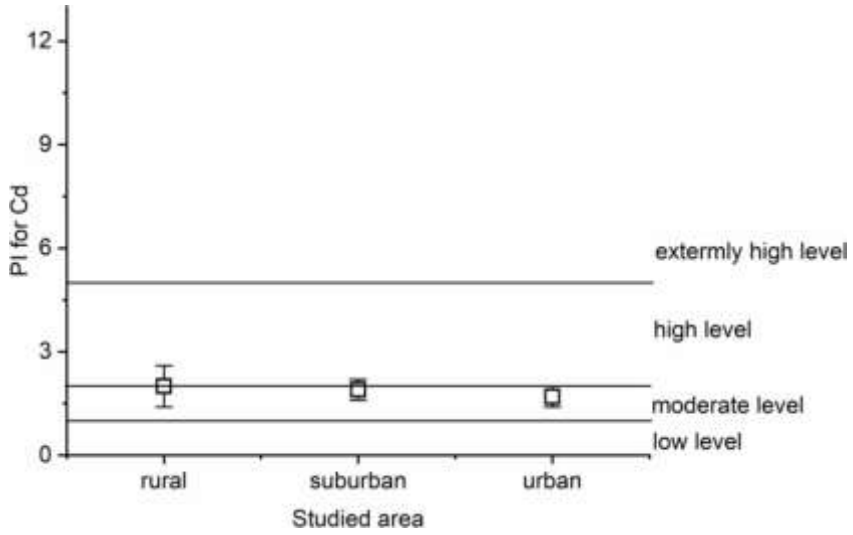

Figure 10. Value of pollution index (PI) which indicated a moderate level of pollution for Cd along the urbanization gradient (mean ± SE)

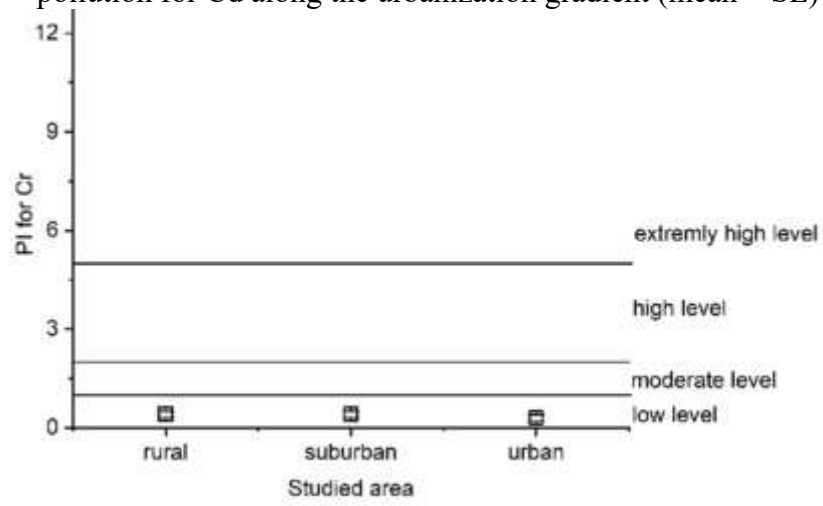

Figure 11. Cr pollution index (PI) along the urbanization gradient (mean ± SE), indicating low pollution level

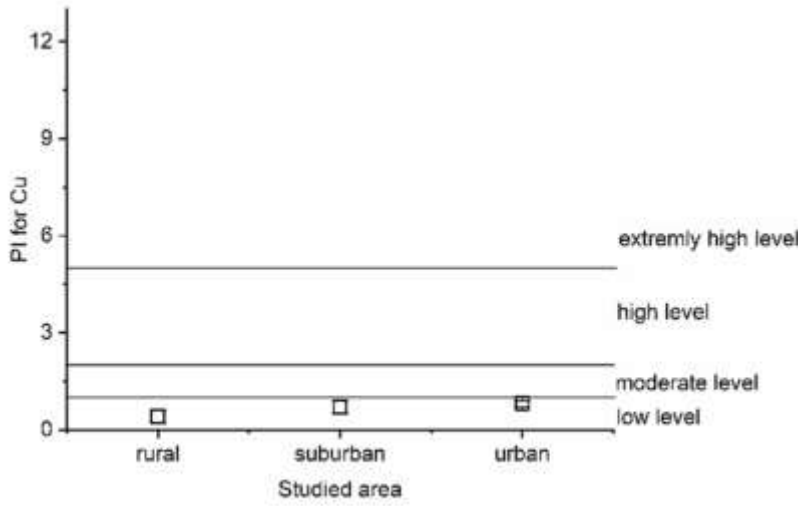

Figure 12. Cu pollution index (PI) along the urbanization gradient (mean ± SE), indicating low pollution level

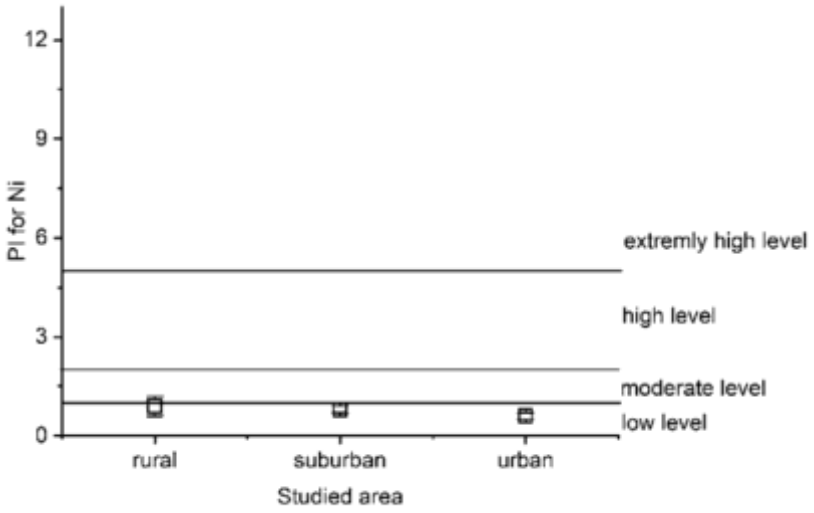

Figure 13. Ni pollution index (PI) along the urbanization gradient (mean ± SE), indicating low pollution level

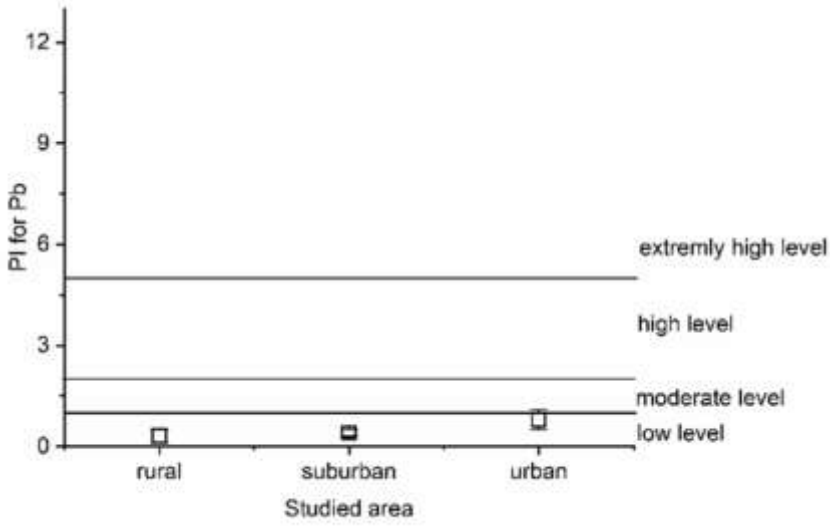

Figure 14. Pb pollution index (PI) along the urbanization gradient (mean ± SE), indicating low pollution level

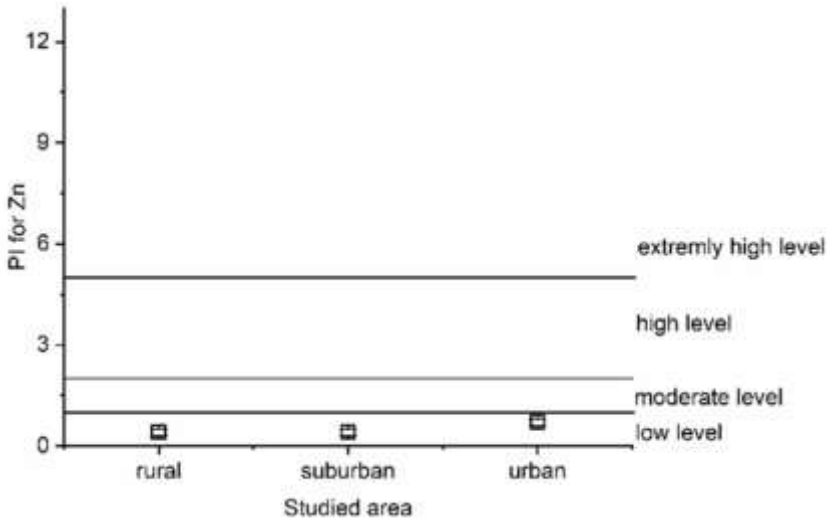

Figure 15. Zn pollution index (PI) along the urbanization gradient (mean ± SE), indicating low pollution level

5.2. Air pollution based on tree species in Vienna

5.2.1. Differences along an urbanization gradient

Based on all APTI parameters and the elemental concentration of *A. platanoides,* significant differences were found among urban, suburban, and rural areas using canonical discriminant analysis (CDA) (Fig. 16). APTI values showed no significant differences among urban, suburban, and rural areas for *A. platanoides,* but the APTI values of the species suggest that it is sensitive to air pollution (Fig. 17). The areas showed significant differences in PM_{10}, Al Cr, Fe, and Mn (Appendix Table 2). The suburban areas had the highest PM_{10} and Cr concentrations, while the urban areas had the highest Al and Fe concentrations. The highest Mn concentration was found in the rural area (Table. 3).

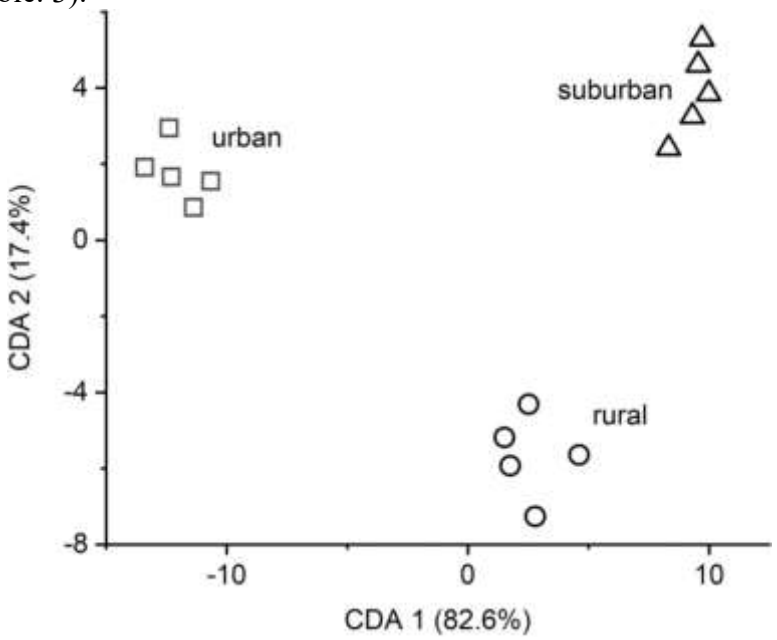

Figure 16. Discriminant score plots of *A. platanoides* based on APTI parameters and the elemental concentrations of tree leaves

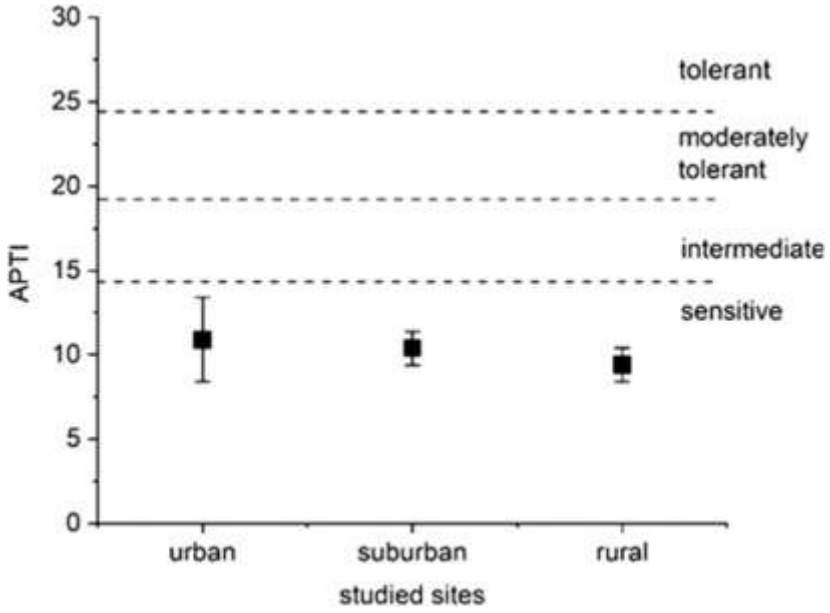

Figure 17. APTI values (mean ± SD) for *A. platanoides* along the urbanization gradient in Vienna

Table 3. Studied parameters of *A. platanoides* leaves along the urbanization gradient (mean ± standard error).

	Urbanisation gradient		
Parameters	**urban**	**suburban**	**rural**
RWC, %	60.5 ± 14.6	68.2 ± 5.8	63.1 ± 5.5
pH	6.2 ± 0.1	6.2 ± 0.1	6.3 ± 0.1
AAC, mg g^{-1}	2.9 ± 1.0	2.7 ± 0.7	2.4 ± 1.5
TChl, mg g^{-1}	10.7 ± 1.7	8.1 ± 3.9	9.1 ± 3.9
APTI	10.9 ± 2.5	10.4 ± 1.0	9.4 ± 1.0
PM_{10}, µg cm^{-2}	0.6 ± 0.8	2.0 ± 1.4	0.01 ± 0.01
Al, mg kg^{-1}	58.7 ± 3.9	46.0 ± 4.7	32.7 ± 5.1
Ba, mg kg^{-1}	13.7 ± 4.1	12.5 ± 3.8	7.3 ± 1.8
Cr, mg kg^{-1}	0.4 ± 0.0	0.9 ± 0.5	0.3 ± 0.0
Cu, mg kg^{-1}	10.5 ± 1.8	8.2 ± 1.2	8.2 ± 1.8
Fe, mg kg^{-1}	132.8 ± 9.6	94.0 ± 9.9	70.1 ± 11.6
Mn, mg kg^{-1}	50.4 ± 14.2	54.5 ± 14.6	148.5 ± 91.8
Ni, mg kg^{-1}	0.5 ± 0.0	0.7 ± 0.4	1.1 ± 0.7
Sr, mg kg^{-1}	32.3 ± 6.7	37.9 ± 21.5	28.0 ± 12.0
Zn, mg kg^{-1}	19.6 ± 3.8	17.4 ± 2.4	23.1 ± 3.9

Using CDA based on all APTI parameters and elemental concentration of *F. excelsior*, we found significant differences among areas (Fig. 18). No significant difference was observed among areas based on the APTI value of *F. excelsior*; it is also a sensitive species (Fig. 19). We observed significant differences among the areas in the amounts of AAC, TChl, Ba, Cr, Cu, Fe, Sr, and Zn in *F. excelsior* leaves (Appendix Table 3). The highest AAC amount, and Cu, Fe, and Zn concentrations were found in the urban area. The highest Ba and Cr concentrations were found in the suburban area. The highest TChl amount, and Sr concentration was found in the rural area (Table. 4).

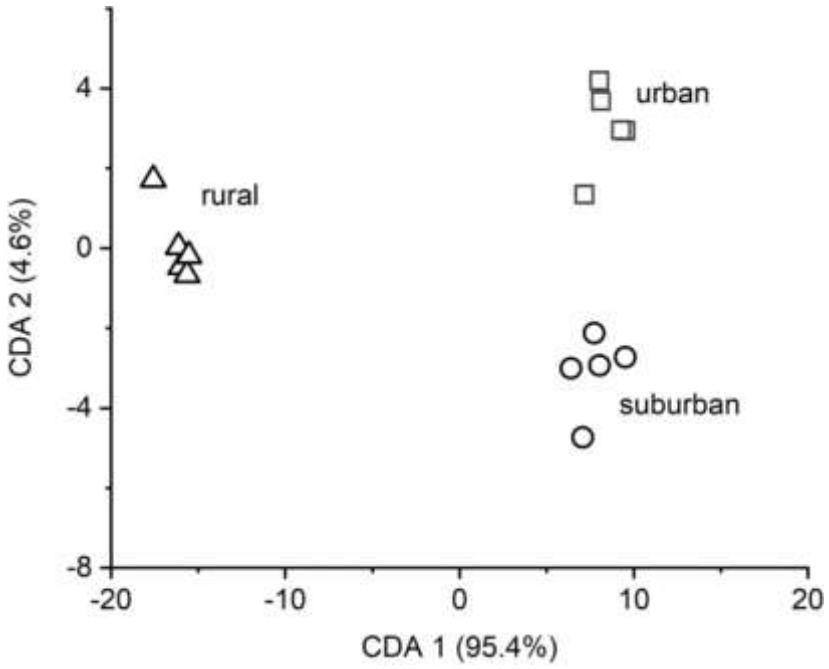

Figure 18. Discriminant score plots of *F. excelsior* based on APTI parameters and the elemental concentrations of tree leaves

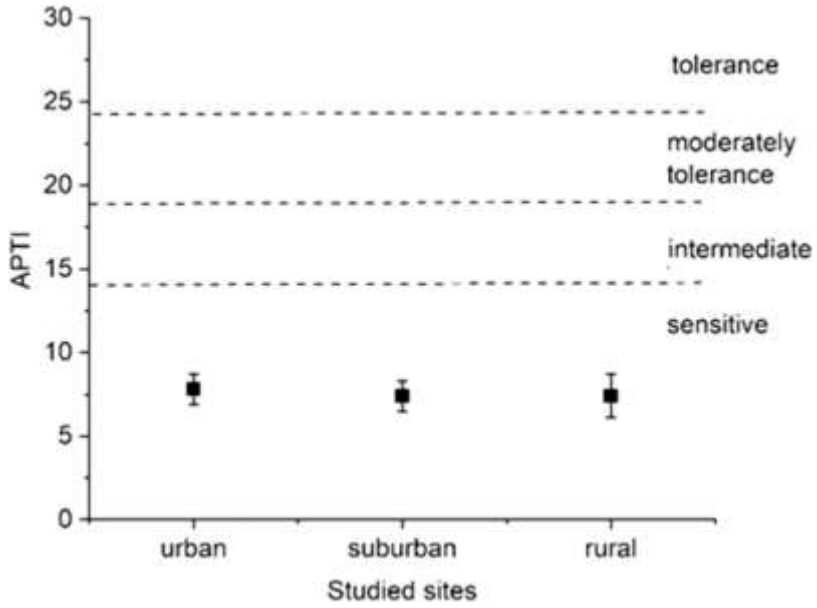

Figure 19. APTI values (mean ± SD) for *F. excelsior* along the urbanization gradient in Vienna

Table 4. Studied parameters of *F. excelsior* leaves along the urbanization gradient (mean ± standard error).

	Urbanisation gradient		
Parameters	**urban**	**suburban**	**rural**
RWC, %	63.5 ± 7.7	63.8 ± 7.1	65.7 ± 12.2
pH	6.0 ± 0.0	5.9 ± 0.1	6.0 ± 0.1
AAC, mg g^{-1}	1.2 ± 0.1	0.9 ± 0.1	0.7 ± 0.1
TChl, mg g^{-1}	5.5 ± 0.9	5.0 ± 0.7	6.9 ± 1.2
APTI	7.8 ± 0.9	7.4 ± 0.9	7.4 ± 1.3
PM10, µg cm^{-2}	1.2 ± 1.2	0.4 ± 0.5	0.2 ± 0.4
Al, mg kg^{-1}	34.7 ± 4.7	32.0 ± 5.5	27.4 ± 2.8
Ba, mg kg^{-1}	15.9 ± 4.5	25.4 ± 3.9	16.0 ± 3.4
Cr, mg kg^{-1}	0.3 ± 0.0	0.7 ± 0.4	0.2 ± 0.0
Cu, mg kg^{-1}	16.1 ± 5.1	10.1 ± 4.6	10.4 ± 1.4
Fe, mg kg^{-1}	86.2 ± 9.4	68.1 ± 9.8	70.1 ± 13.4
Mn, mg kg^{-1}	42.2 ± 10.5	24.6 ± 13.7	27.9 ± 9.8
Ni, mg kg^{-1}	1.0 ± 0.2	1.5 ± 0.4	3.7 ± 4.1
Sr, mg kg^{-1}	49.1 ± 8.3	62.9 ± 17.7	82.5 ± 23.3
Zn, mg kg^{-1}	19.4 ± 4.1	9.8 ± 1.3	12.2 ± 1.9

Based on all APTI parameters and the elemental concentration of *Q. robur,* significant differences were found among areas using CDA (Fig. 20). *Q. robur* is a sensitive species. Significant differences were not found among areas based on APTI (Fig. 21). We did, however, find significant differences among the areas in the amounts of TChl, Al, Cr, Fe, Mn, Ni and Sr in *Q. robur* leaves (Appendix Table 4). The highest TChl amount, and Al, Cr, and Fe concentrations were found in the urban area. The highest Sr concentration was found in the suburban area. The highest Mn and Ni concentrations were found in the rural area (Table. 5).

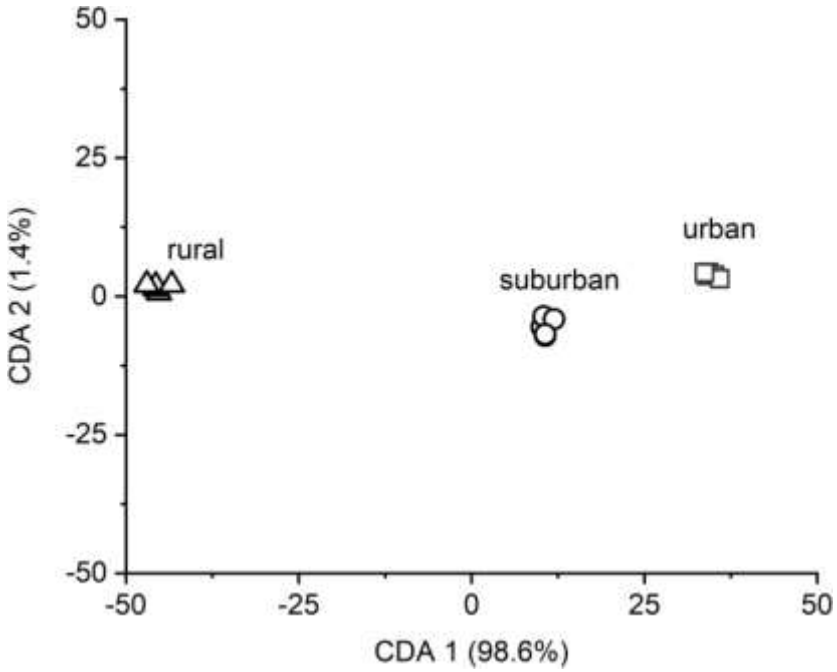

Figure 20. Discriminant score plots of *Q. robur* based on APTI parameters and the elemental concentrations of tree leaves

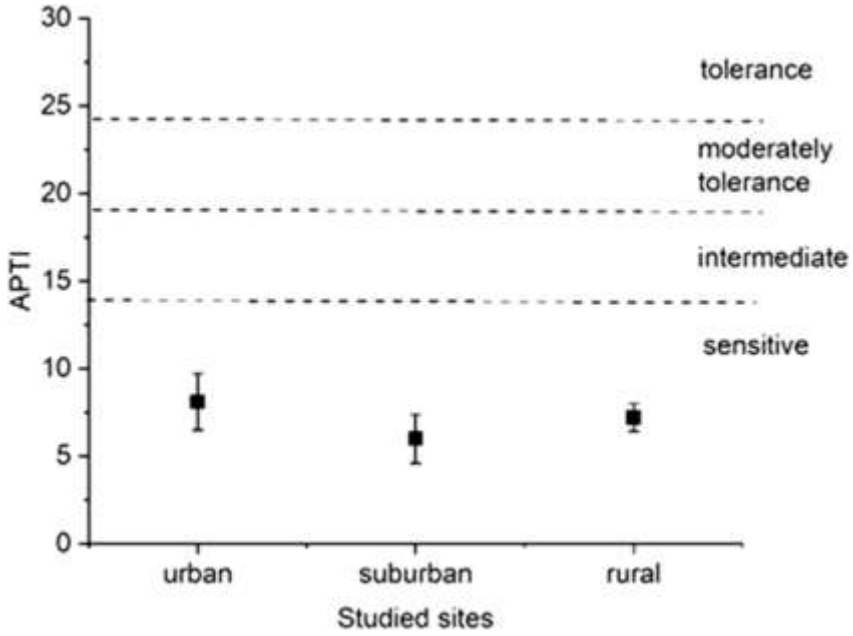

Figure 21. APTI values (mean ± SD) for *Q. robur* along the urbanization gradient in Vienna

Table 5. Studied parameters of *Q. robur* leaves along the urbanization gradient (mean ± standard error).

	Urbanisation gradient		
Parameters	**urban**	**suburban**	**rural**
RWC, %	38.0 ± 5.5	31.2 ± 15.0	38.0 ± 5.4
pH	6.3 ± 0.2	6.2 ± 0.1	6.3 ± 0.1
AAC, mg g^{-1}	3.3 ± 0.8	2.9 ± 0.6	2.8 ± 0.7
TChl, mg g^{-1}	6.7 ± 1.1	3.6 ± 0.8	6.1 ± 1.4
APTI	8.1 ± 1.6	6.0 ± 1.4	7.2 ± 0.8
PM10, µg cm^{-2}	0.6 ± 0.8	0.2 ± 0.4	0.6 ± 0.8
Al, mg kg^{-1}	43.6 ± 4.7	31.0 ± 6.9	33.8 ± 6.7
Ba, mg kg^{-1}	20.7 ± 10.8	18.5 ± 3.0	14.8 ± 6.1
Cr, mg kg^{-1}	0.4 ± 0.1	0.2 ± 0.0	0.2 ± 0.0
Cu, mg kg^{-1}	8.5 ± 1.2	7.8 ± 0.9	8.9 ± 1.4
Fe, mg kg^{-1}	123.3 ± 14.8	55.6 ± 13.2	74.6 ± 15.5
Mn, mg kg^{-1}	20.2 ± 7.3	28.3 ± 10.8	97.8 ± 62.5
Ni, mg kg^{-1}	0.4 ± 0.1	1.0 ± 0.2	2.1 ± 0.6
Sr, mg kg^{-1}	13.0 ± 8.3	24.3 ± 7.0	14.2 ± 3.3
Zn, mg kg^{-1}	15.3 ± 1.3	17.9 ± 2.9	14.7 ± 3.9

5.2.2. Differences among the species

We found significant differences among species based on all APTI parameters and elemental concentrations using CDA within all areas studied (Fig. 22-24). We also found significant differences among the species in the urban area in the amounts of RWC, pH, AAC, TChl, APTI, Al, Cr, Cu, Fe, Mn, Ni, and Sr (Appendix Table 5). The highest TChl and APTI amounts and Al, Fe, and Mn concentrations were found in *Acer* leaves from the urban area. The highest RWC amount, and Cu, Ni, and Sr concentrations were found in the leaves of *Fraxinus* from the urban area. The highest pH and AAC amounts and Cr concentration were found in the *Quercus* leaves from the urban area.

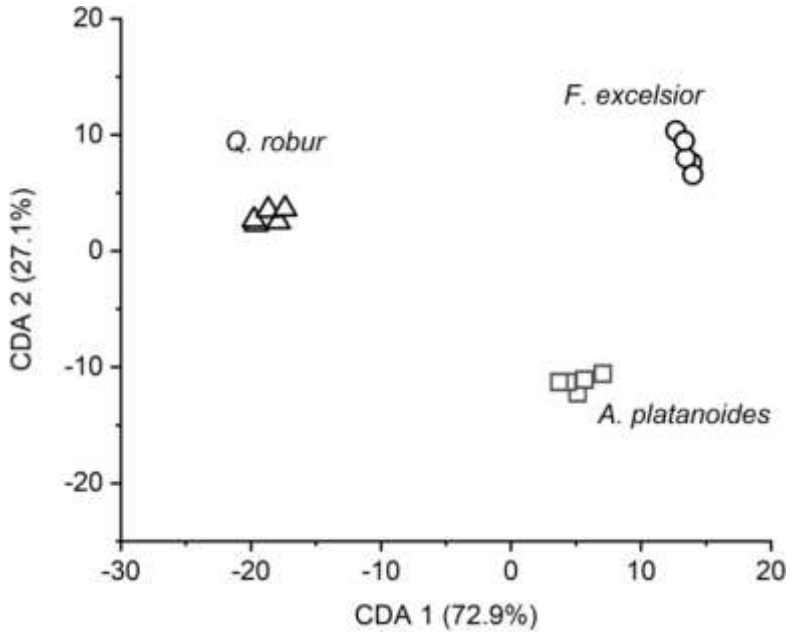

Figure 22. Discriminant score plots for the urban area based on APTI parameters and the elemental concentrations of the leaves of tree species

Significant differences were found among the species in the amounts of RWC, pH, ACC, TChl, APTI, PM_{10}, Al, B, Ba, Cr, Fe, Mn, Ni, Sr, and Zn in the Kurpark suburban area (Appendix Table 6). The highest RWC, pH, TChl, APTI, PM_{10} amounts, and Al, B, Cr, Fe, and Mn concentrations were found in *Acer* leaves from the suburban area. The highest Ba, Ni, and Sr concentrations were found in *Fraxinus* leaves from the suburban area. Additionally, the highest pH and AAC amounts, and the highest Zn concentration were found in *Quercus* leaves from the suburban area.

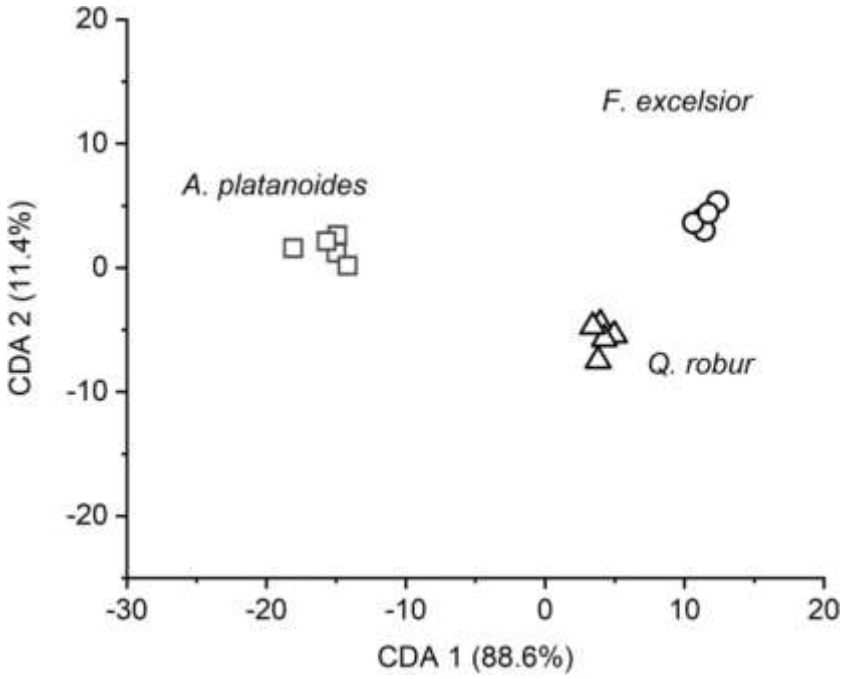

Figure 23. Discriminant score plots for the suburban area based on APTI parameters and the elemental concentrations of the leaves of tree species

We found significant differences among the species in the rural area in the amounts of RWC, pH, ACC, APTI, B, Ba, Cr, Mn, Sr and Zn (Appendix Table 7). The highest pH and APTI values and B, Cr, Mn, and Zn concentrations were found in *Acer* leaves from the rural area. The highest RWC amount, and Ba and Sr concentrations were found in *Fraxinus* leaves from the rural area. Additionally, the highest pH and AAC amounts were found in *Quercus* leaves from the rural area.

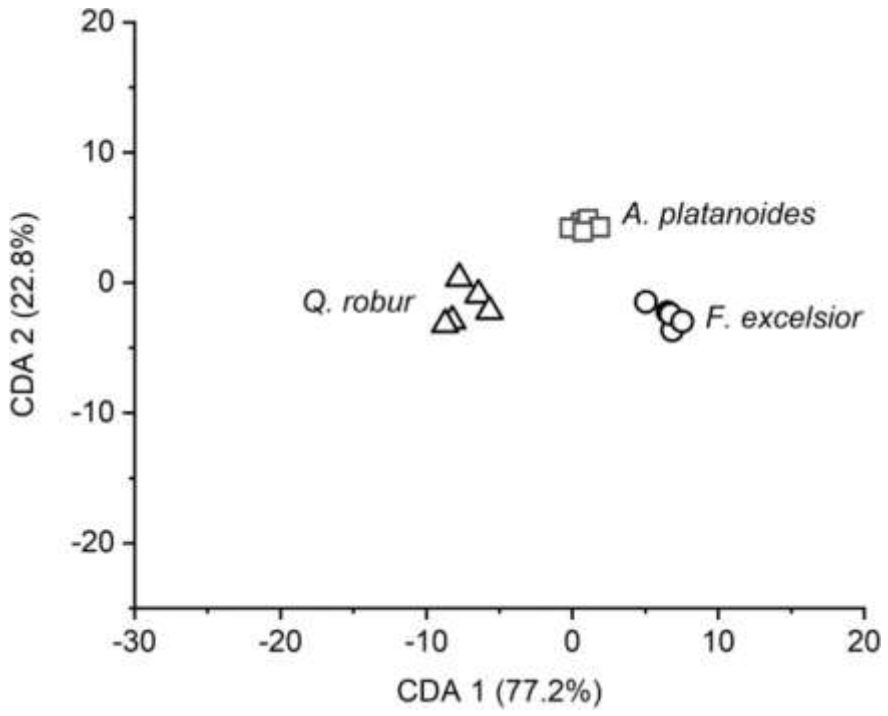

Figure 24. Discriminant score plots for the rural area based on APTI parameters and the elemental concentrations of the leaves of tree species

5.2.3. Correlation between studied parameters and air pollutants

For all studied species, we found a positive correlation between all studied parameters and annual NO_2 and $PM_{2.5}$ averages. For *Q. robur*, we also found a significant positive correlation between Cr concentration and annual NO_2 and $PM_{2.5}$ averages. For *A. pseudoplatanus* and *F. excelsior*, we found a positive correlation between Cu concentration and annual NO_2 and $PM_{2.5}$ averages (Appendix Table8).

5. 3. Pollution Analysis by soil and plant leaves in Faisalabad

5.3.1. Physio-Chemical Properties of Soil in Faisalabad

The principal component analysis method (PCA) was used to study the physio-chemical parameters of soil samples from different locations (Fig. 25). The percentage of variance was 96.203 for the first principal component, 3.752% was for the second principal component. The eigenvalue was 3371.88 in the case of first and 131.510 was for the second principal component. The results showed no significant changes except for pH and electrical conductivity. The soil pH ranged from 6.37 to 7.63, with the highest in rural and urban soil, and the lowest in suburban soil (Fig. 26, Table 6). Electrical conductivity was highest in suburban soil, while the lowest in rural areas (Fig. 27, Table 6). Soil moisture levels were not significant, with the lowest in urban soil and the highest in rural soil (Table 6). Organic matter levels were highest in urban areas, and calcium carbonate levels were lowest in rural soil and highest in suburban soil (Table 6). Overall, the soil's physio-chemical parameters remained consistent across sampling sites.

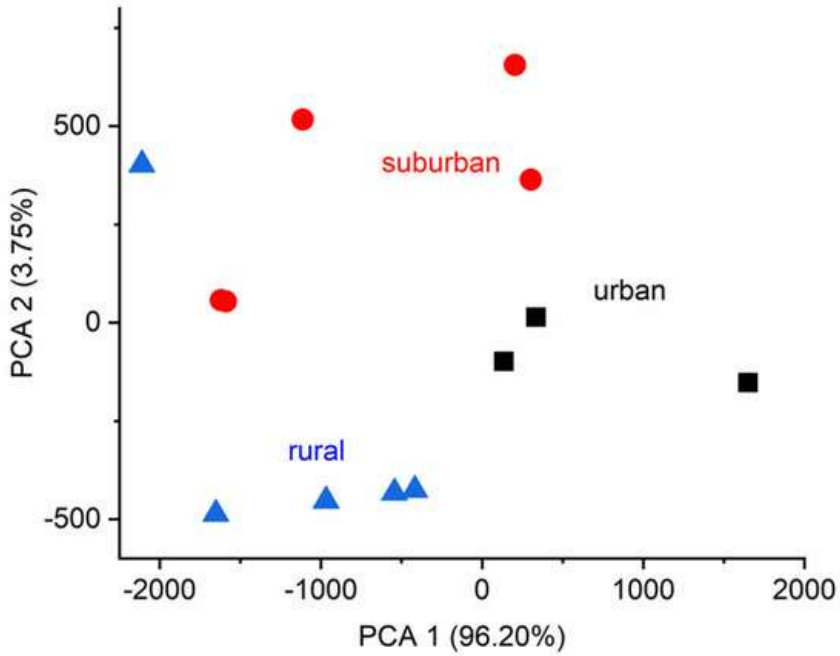

Figure 25. Scatter plot based on principal component analysis (PCA) of physio-chemical properties of soil in Faisalabad, in Pakistan.

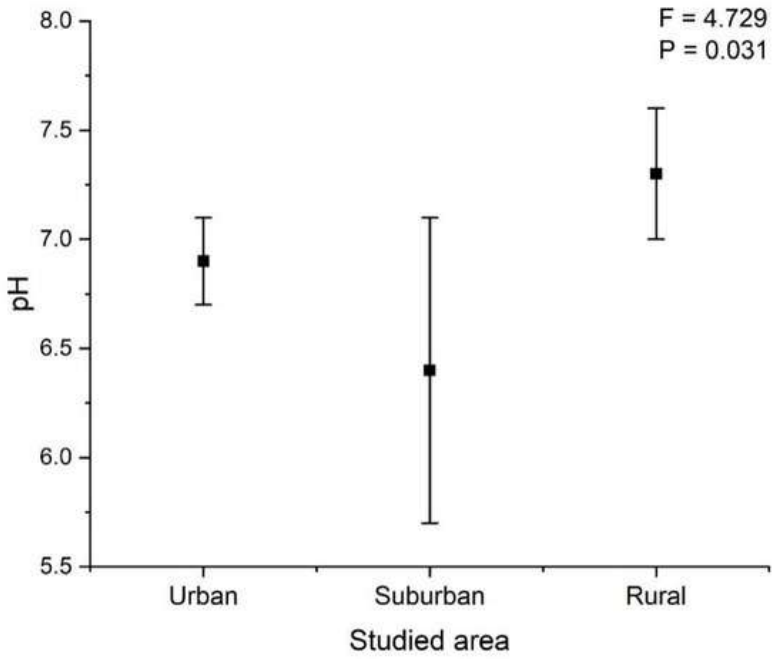

Figure 26. Results of pH (mean ± SD) along an urbanization gradient from different areas in Faisalabad.

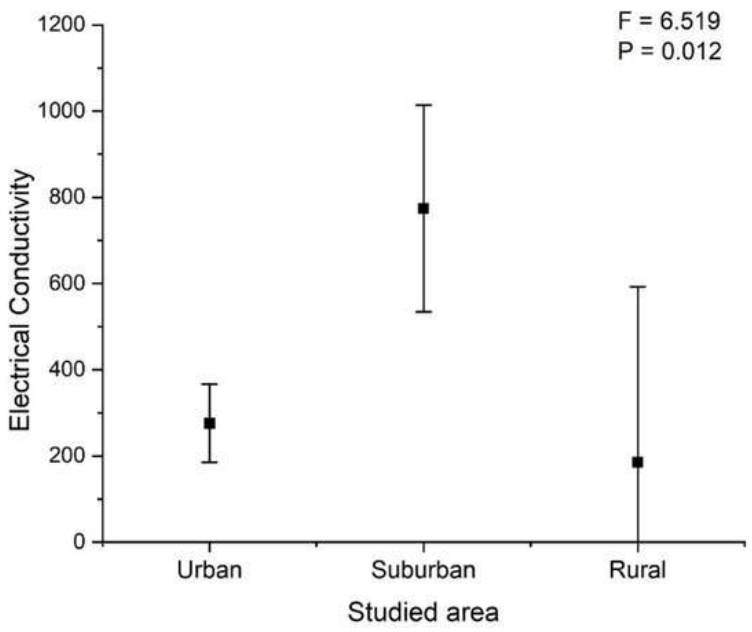

Figure 27. Results of EC (mean ± SD) along an urbanization gradient from different areas in Faisalabad.

Table 6. Physio-chemical properties of soil (mean ± SD, mg kg^{-1}) along the urbanization gradient in Faisalabad.

Parameters	Studied areas			Results of ANOVA	
	Urban	Suburban	Rural	F	P
pH	6.9 ± 0.2	6.4 ± 0.7	7.3 ± 0.3	4.729	0.031
Electrical conductivity, µS cm^2	276 ± 90.6	774 ± 239.7	186 ± 406.5	6.519	0.012
Moisture content, %	3.99 ± 1.89	4.22 ± 2.25	14.04 ± 21.59	1.047	0.381
Organic matter, %	5.8 ± 1.4	4.49 ± 0.49	4.6 ± 0.8	2.955	0.90
Calcium carbonate, %	2.9 ± 0.4	3.40 ± 1.63	2.1 ± 0.6	1.920	0.189

5.3.2. Elemental concentration in Soil

In the case of soil, we found significant differences in all elements, and for each element, the highest concentrations were often detected in urban soil samples, having a propensity to expand in line with the urbanization gradient (Table 7). This means that minor concentration remains in the rural area, except manganese, which is in suburban area (Table 7).

Table 7. Soil concentration of elements (mean ± SD, mg kg^{-1}) along an urbanization gradient from different areas in Faisalabad.

Elements	Studied area			Results of ANOVA	
	Urban	Suburban	Rural	F	p
Ba	99.6 ± 3.9	73.7 ± 5.7	65.3 ± 4.3	72.340	<0.001
Co	5.3 ± 0.4	3.9 ± 0.5	3.8 ± 0.3	21.717	<0.001
Cr	15.4 ± 1.5	12.5 ± 0.6	11.1 ± 0.8	20.974	<0.001
Cu	19.9 ± 2.3	14.3 ± 1.4	9.6 ± 1.0	47.248	<0.001
Fe	13558.3 ± 1863.6	10926.6 ± 958.7	10521.9 ± 713.8	8.321	0.005
Mn	616.3 ± 173.8	355.0 ± 27.3	369.3 ± 39.3	9.978	0.003
Ni	21.4 ± 2.6	16.9 ± 1.6	16.8 ± 1.3	9.463	0.003
Pb	26.0 ± 4.0	13.9 ± 0.6	9.0 ± 0.8	69.785	<0.001
Sr	22.5 ± 4.2	21.2 ± 2.2	13.4 ± 1.5	14.556	0.001
Zn	111.0 ± 15.8	100.6 ± 29.6	52.5 ± 4.8	12.798	0.001

5.3.3. Elemental Concentration in *A. indica* Leaves

The PCA results show a separation of sites based on tree leaf elemental concentration (Fig. 28). The percentage of variance was 86.530 for the first principal component, 12.399 % was for the second principal component. The eigenvalue was 38252.6 in the case of first and 5455.5 was for the second principal component. Plants showed significant differences in all metals except for Cd and Cu. Urban areas had higher pollution levels for Ba, Pb, Co, Ni, Cr, and Cd, while urban and suburban areas had low pollution intensity for Zn, Fe, Mn, and Sr, and rural area had high pollution levels for Fe and Cu (Table. 8).

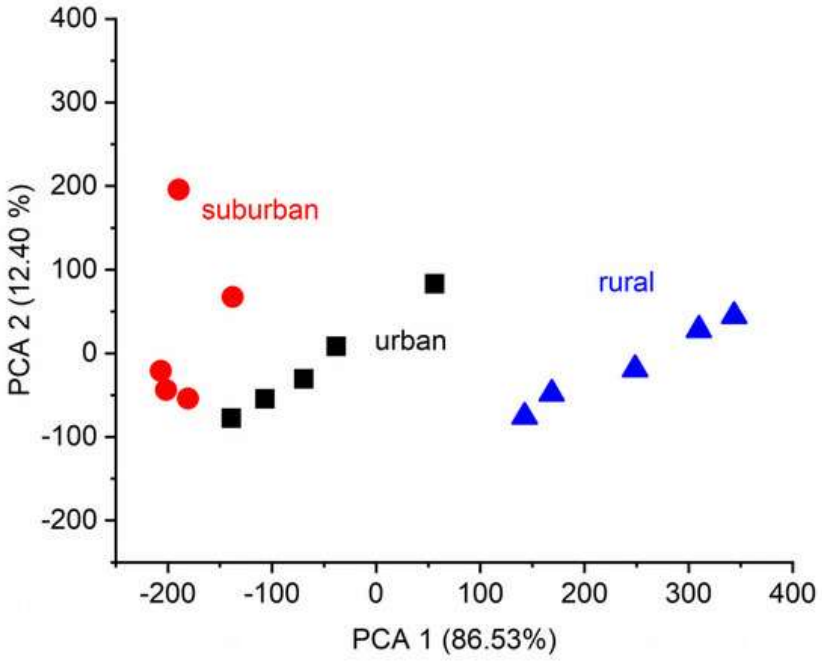

Figure 28. Scatter plot based on principal component analysis (PCA) of elemental concentration of *A. indica* leaves.

Table 8. Concentration of elements (mean ± SD, mg kg−1) along the urbanization in *A. indica* leaves.

Elements	Studied area			Results of ANOVA	
	Urban	Suburban	Rural	F	P
Ba	21.5 ± 1.3	11.5 ± 0.8	7.7 ± 0.7	271.098	<0.001
Cd	0.09 ± 0.01	0.07 ± 0. 02	0.07 ± 0.02	2.032	0.174
Co	0.55 ± 0.04	0.25± 0.03	0.43 ± 0.03	100.100	<0.001
Cr	1.75 ± 0.16	0.38 ± 0.02	0.76 ± 0.18	130.133	<0.001
Cu	5.85 ± 0.73	5.46 ± 0.44	6.08 ± 0.91	0.944	0.416
Fe	645.7 ± 88.5	537.3 ± 42.1	938.3 ± 96.9	34.121	<0.001
Mn	76.2 ± 20.2	37.98 ± 2.17	38.9 ± 4.19	16.419	<0.001
Ni	4.76± 0.54	3.83 ± 0.4	3.24 ± 0.3	16.159	<0.001
Pb	5.39 ± 0.64	3.74 ± 0.47	2.76 ± 0.42	32.923	<0.001
Sr	264.1 ± 40.7	339.7 ± 98.7	191.0 ± 26.93	6.826	0.010
Zn	41.11 ± 6.67	41. 3 ± 16.5	28.32 ± 2.85	2.550	0.119

5.3.4. Bio-Accumulation Factor (BAF)

The statistical analysis indicated that the bio-accumulation factor varies greatly between areas except for strontium. This suggests that the urbanization gradient has an effect on the uptake of metals by plants, but as with plants, no obvious pattern was identified. For Co, Cu, Fe, Pb, and Zn, the rural area had the highest BAF, with this being the area where most elements had their highest bio-accumulation factor. This showed that for these metals, the level of urbanization reduces their BAF; this may occur because urbanization alters soil characteristics in ways that make elements less soluble, and therefore, more difficult for plants to absorb. For Ni and Sr, the highest BAF values were found in suburban areas and for Ba, Cr, and Mn in urban areas (Table 9).

Table 9. The results (mean ± SD, mg kg^{-1}) of BAF along the urbanization gradient from different areas in Faisalabad.

Elements	Studied area			Results of ANOVA	
	Urban	Suburban	Rural	F	P
Ba	0.22 ± 0.02	0.16 ± 0.01	0.12 ± 0.00	82.828	<0.001
Co	0.10 ± 0.00	0.07 ± 0.00	0.11 ± 0.00	681.266	<0.001
Cr	0.11 ± 0.00	0.03 ± 0.00	0.07 ± 0.01	184.187	<0.001
Cu	0.29 ± 0.01	0.38 ± 0.01	0.63 ± 0.03	349.040	<0.001
Fe	0.05 ± 0.00	0.05 ± 0.00	0.09 ± 0.00	562.426	<0.001
Mn	0.12 ± 0.00	0.11 ± 0.00	0.11 ± 0.00	47.486	<0.001
Ni	0.22 ± 0.01	0.23 ± 0.01	0.19 ± 0.00	38.957	<0.001
Pb	0.21 ± 0.01	0.27 ± 0.02	0.31 ± 0.02	30.802	<0.001
Sr	11.82 ± 0.46	15.96 ± 4.12	14.22 ± 0.61	3.697	<0.001
Zn	0.37 ± 0.01	0.40 ± 0.04	0.54 ± 0.01	61.876	<0.001

6. DISCUSSION

6.1. Soil pollution of heavy metals in Vienna, Austria

6.1.1. Basic physical and chemical parameters of Soil

We studied the physical and chemical characteristics of soil along an urbanization gradient in Vienna, Austria. According to the correlation between physiochemical characteristics and soil elemental concentration, urban and suburban areas had greater Ca and Mg concentrations due to alkaline pH values (Ogbodo, 2012). Lower Austria, Salzburg, Tyrol, and Vorarlberg all have moderate regional forest soil acidification, according to Blum et al. (2005). It was not supported by our study's high P, S, Ca, and Mg concentrations or pH value. We found that the urban region's soil had higher concentrations of Mn, Al, Fe, and K, indicating that the soil in Vienna varied from one area to another. A key component of soil quality, soil organic matter plays a crucial role in water retention, pesticide and pollutant distribution, nutrient cycling, and carbon sequestration (Mehmood et al., 2021). In contrast to previous research, we discovered that Vienna has a comparatively high organic matter concentration (11.7 ± 1.3%). In Lower Austria, organic matter concentration was typically less than 2% in topsoil zone, while in Salzburg, it was lower which was 8% (Blum et al., 2005). Such factors, as geological and climatic factors, plant cover, soil use, and the age of soil layers have effect on the amount of organic matter in the soil (Schmidt et al., 2011). Strongly acidic regions were found in Styria and Tyrol, according to Kralik (1999) the organic matter, particularly the humus content, was very low in agricultural used soil, with a higher rate in the west of Austria than the east (Chen et al., 2019). Kobler et al. (2010) reported that soil type has a significant impact on the degree of movement of minor elements (Pb and Cd). The Arany-type plasticity index indicates that the soil texture in Vienna is loam. Compared to acid and sandy loam soil types, (Barsova et al., 2019) showed that neutral loam soil had a greater metal concentration. The movement and retention of heavy metals are affected by the texture and structure of the soil. While rough, poorly structured soils allow metals to move more easily with water flow, fine particles and good pore networks create more surface area and binding sites where metals can be adsorbed and maintained in place (Mohammad et al., 2025). According to studies Yu et al. (2023), sandy soils with larger particles and fewer adsorption sites tend to allow greater metal leaching and mobility toward groundwater, while soils rich in clay and fine particles have a higher sorption capacity and can retain more heavy metals like Pb, Cu, Zn, and Cd due to larger surface area and stronger electrostatic binding.

6.1.2. Elemental Concentrations and Pollution Index of Soil

To determine the amount of pollution, we examined metal PI (pollution index) values. Along with the urbanization gradient, we discovered incredibly high levels of Cd pollution in each studied area. Additionally, we discovered that urban areas had high levels of Cu and Pb pollution, but both urban and rural areas had moderate levels of Co, Ni, and Zn contamination. Similar to our findings Rodríguez-Eugenio et al. (2018) also demonstrated that the content of heavy metals in soils varies depending on the various land uses and other human activities. High concentrations of Cd, Pb, Zn, and Cu have frequently been recorded in urban soils (Madrid et al., 2002). The amount of Cd, Pb, Cu, and Zn that accumulated in urban soils increased linearly with urban age, or the number of years after establishment, and was greatly influenced by land uses. Cu pollution is primarily found in the areas near industrial copper ore processing facilities and in regions with intense animal husbandry in Austria (Gentile et al., 2009). The presence of Cd and Cu are commonly found in agricultural areas as a result of long-term usage of phosphate fertilizers, pesticides, sewage sludge, and animal manures (Wan et al., 2024). Pb and Cu levels are usually higher in urban and roadside environments due to vehicle exhaust residues, urban dust deposits, and traffic emissions (tyre and brake wear). In highly populated areas, industry emissions further contribute to these levels (Mkhonza et al., 2026). According to our findings, the pollution levels in urban, suburban, and rural areas differ significantly. The valley of the Inn River is the most polluted area in Tyrol due to high transit traffic. Lead levels are higher in the soils of Tyrol at 9.2% of the sites and in Salzburg at 3.6% of the sites (Kralik, 1999). Compared to the suburban and rural areas, the urban area had incredibly high concentrations of Cd. This increased concentration in the sample regions might be brought on by being closer to the city center and the area around Austria's busiest route. However, the levels of soil contamination were likewise high in the rural and suburban areas. The type of soil and soil variations brought on by human activity could be the source of this difference. In Austria, the primary causes of the buildup of heavy metals in urban soils are determined to be industrial emissions and traffic. The Cd contents were higher than the recommended value in 5% of the monitoring sites in forests and 6% of the sites in grasslands areas based earlier study (Gentile et al., 2009). Industrial plants in the southeast of Vienna, which are not in the primary wind direction, are the nearest sources of pollution (Zehetner et al., 2009). The Northern Calcareous Alps may have a naturally high cadmium concentration, and long-range pollution and subsequent deposition on exposed slopes are partially responsible for high cadmium contents (Kralik, 1999). Compared to our results with Zehetner et al. (2009),

who investigated the distribution of heavy metals over a highway that links the cities of Vienna, Austria, and Brno, Czech Republic, we discovered higher quantities of Cd and Ni in the topsoil. Roadside soil pollution is extremely diverse, and traffic-borne heavy metals are more mobile than geogenic ones, travelling farther from the source (Zehetner et al., 2009). Weiss et al. (1994) found a high correlation in soil concentrations among pollutants, suggesting identical or adjacent sources for soil pollution in Linz, Upper Austria. Pfleiderer et al. (2012) also found anthropogenic contamination, with higher Cd and Pb concentrations in traffic and industrial areas compared to Vienna parks, indicating a higher level of pollution.

6.2. Air pollution based on tree species in Vienna

6.2.1. Differences along an urbanization gradient

There were significant differences among tree species in terms of pH, ascorbic acid, chlorophyll concentration, and relative moisture content. Based on APTI results, we discovered that all three species are sensitive to air pollution. APTI values for *A. platanoides, F. excelsior,* and *Q. robur* did not significantly differ between areas along the urbanization gradient. In cities across Europe, the United States, and Australia, *A. platanoides* is the most common species, and its global spread is increasing. In the past, *A. platanoides* trees were selected more for their pleasing appearance and urban adaptability than for biomonitoring (McKinney, 2006). *A. platanoides* can withstand a variety of anthropogenic stresses, it seems to be the ideal choice for city parks (Krzyżaniak et al., 2015). Furthermore, because of its exceptional resistance to harsh climatic conditions, *F. excelsior* is a great option for urban landscaping. This species maintains an acceptable amount of biochemical markers even in experimental plots with high and extremely high pollution levels (Petrova et al., 2022). Simon et al. (2014) also demonstrated that *Q. robur's* large stomata size and high stomata density made them valuable biological markers. Additionally, *Q. robur* demonstrated a strong association with the results of scanning electron microscopy. Prusty et al. (2005) and Arend et al. (2011) explained how variations in leaf shapes and epidermal traits affect the quantity of dust that is deposited. In our results, species response along the urbanization gradient was evaluated using the Air Pollution Tolerance Index (APTI). However, specie-specific physiological characteristics, seasonal variation, leaf age and other biotic and abiotic stress factors all have an important on APTI values in addition to environmental air pollution levels. As a result, rather than providing an absolute indicator of air pollution intensity, APTI should be considered a relative measure of tolerance and sensitivity (Kuddus et al., 2011b).

6.2.2. Differences among the species

Acer laurinum species have moderate mineral element requirements and can tolerate high pollution concentrations, making them very adaptable to changing site circumstances, Baker (1993) suggests that the plant's abundance in urban areas could be due to this. Norway maple (*Acer platanoides*) is tolerant or medium sensitive to contaminants, making it ideal for urban air quality improvement (Supuka, 1994). Previous research indicates that *Acer platanoides* is either resistant or sensitive to SO_2 and NO_2 (Taylor et al., 1975). Norway maple (*Acer platanoides*) is commonly utilized in urban landscaping due to its adaptability to diverse ecological situations.

Quercus robur (English oak) can be found in temperate deciduous mixed woods and co-occur at numerous locations. They also have several traits in common oaks have played a significant part in European human culture since the beginning. Because of their size and shade, oaks are especially valued as wayside or park trees (Eaton et al., 2016). The ecological benefits of *Q. robur* promotes ecosystem balance and biodiversity, while its economic worth supports a range of areas, including tourism and limber industry. Among evergreen species, *Q. robur* is thought to be a relatively significant contributor of climate change and a highly drought-tolerant species. Many oak species, including *Q. robur,* have "climatypes" that enables them to adjust to a variety of environmental circumstances(Krutovsky et al., 2025). According to the analysis of Simon et al. (2014), the size and distribution of stomata were the primary determinants of the accumulation of air pollutants in leaves, and *Q. robur's* huge stomata size and high stomata density made them effective biological indicators.

The deciduous tree *Fraxinus excelsior* (Ash) can grow to a height of more than 40 meters in the best circumstances. *F. excelsior* can grow in rich soil that grows up in the splits of mountain limestone, but it needs the soil to be rich in humus and nutrients. F. excelsior has been found to be an important heavy metal biomonitor (Aksoy & Demirezen, 2006). Also, its strong resistance to environmental stressors makes it an excellent choice for urban landscaping. Even in experimental plots that were extremely polluted, this species retained a reasonable level of biological indicators. Additionally, there appears to be a significant reserve of adaptability potential that has not yet been utilized (S. Petrova et al., 2022).

The statistical analysis revealed that the species differed significantly in terms of relative moisture content, pH, ascorbic acid, and chlorophyll concentration. We also discovered that the pH and chlorophyll content varied significantly between areas. We found a much lower relative moisture content

in *Q. robur* and a significantly lower ascorbic acid concentration in *F. excelsior. A. platanoides* have the largest amount of chlorophyll. The amounts of Al, B, Ba, Cr, Fe, Mg, Mn, Na, Ni, P, S, and Zn in leaves varied significantly between species. Our findings were in accordance with the results presented by (Simon et al., 2021); APTI values showed that *P. accerifolia* had an intermediate tolerance and *A. saccharinum* a moderate tolerance. We found that the ascorbic acid content, pH, and total chlorophyll content of leaves varied significantly between species. We demonstrated that concentration of Al, Ba, Ca, Fe, Mg, Ni, S, Sr, and Zn in leaves varied significantly between species. Alotaibi et al. (2020) reported that *P. accerifolia* leaf area in contaminated areas significantly decreased. The ability of the leaves to absorb air pollutants may be the cause of the variations in the reduction of leaf areas across these species at various sites (Haynes et al., 2019). Rai & Panda (2014) found that *Ficus bengalensis* was tolerant in industrial sites and *Mangifera indica* was tolerant in non-industrial sites, suggesting that plants' tolerance to air pollution may vary by site. Ogunkunle et al. (2015) proposed that a green belt may be developed utilizing APTI values by integrating plant tolerance and performance indices for tree species selection. Jyothi & Jaya (2010) state that tolerant tree species can function as sinks for air pollution, whereas sensitive tree species can operate as indicators for its decrease. Furthermore, plants with higher APTI values can be utilized to reduce air pollution, whereas plants with lower APTI values can be used to assess air pollution, as determined by (Gholami et al., 2016).

6.3. Pollution Analysis by soil and plant leaves in Faisalabad

6.3.1. Physio-Chemical Properties of Soil

The focus of our research was on the physio-chemical properties of the soil in Faisalabad, Pakistan, across an urbanization gradient. Regarding the soil parameters, it has been found that the water content reduces as one becomes urban sites; this may be because urban soils are highly compacted due to development or transportation, a process that does not occur as strongly in rural areas (Clinton & Owens, 2023). According to the classification given by Biernbaum (2012), a low organic matter content is around 1%, an average content is around 2–4%, and a high OM content is greater than 5%. It was discovered that urbanization leads to an increase in organic matter, with urban soil having a high content and suburban and rural soil having an average content. The high organic matter content in urban soil may be related to the role that soils play in the carbon cycle; in urban areas, there are higher carbon emissions, so soils tend to accumulate more carbon, increasing the organic carbon content (Clinton & Owens, 2023). According to a study conducted in

Ghana, the large number of organic debris brought on by littering in metropolitan areas like (Asabere et al., 2018) is another explanation. There was no correlation found between the amount of calcium carbonate in soil and urbanization. The Food and Agriculture Organization of the United Nations states that the soils in Faisalabad have optimum pH levels since the pH range of 6.0 to 7.5 promotes nutrient availability and is safe for most plants.

6.3.2. Elemental concentration in Soil and Plant leaves

The *Azadirachta indica* (Neem) tree is a hard, quickly growing evergreen with a straight truck, long, spreading branches and rough bark. It is considered to cleanse the blood and is helpful to elders in managing high blood sugar levels (Udeinya et al., 2008). In Pakistan, neem leaves are dried and stored in cabinets to keep insects from destroying clothes and burned the leaves to prevent mosquitoes. Numerous experts have studied therapeutic plants, including neem tree, Researchers investigated into the levels of many heavy metals (Co, Cd, Pb, Ni, Cr) in plants leaves near polluted and unpolluted areas in the nearby areas of the Agra region of India. According to, the presence of these metal ions in plant leaves indicates that these leaves are useful bioindicators and can be employed in studies to monitor air pollution in industrial locations. Another study found that the leaves of neem tree are indictors of pollution from both human activities and vehicle traffic (Abdullateef et al., 2014).

The element concentrations in soil and plant leaves (*Azadirachta indica*) were also tested. There are numerous studies in Pakistan that compare and examine the levels of heavy metals in soil and vegetables since eating vegetables contaminated with these metals is harmful to human health. Even though the leaves of trees like the Neem tree are used for medicinal purposes and sometimes even as vegetables in recipes, not much research has compared the concentrations in soil with those in plant leaves (Kumar & Kumar, 2022). Lead, cadmium, chromium, nickel, arsenic, and mercury levels in two main ingredients (*Azadirachta indica*) of the polyherbal product Ampucare were assessed by Naithani et al. (2010). In a significant coal-burning area, it was discovered that *Azadirachta indica* leaves acquire five heavy metals, including As, Fe, Cu, Zn, and Cd (Patel et al., 2015). In contrast to the concentrations of Cd observed in the Neem trees used in this study, which vary from 0.07 to 0.09 mg kg^{-1}. The results showed that the concentration of Cd in the leaves of different vegetable varieties in Faisalabad ranged from 0.035 to 0.073 mg kg^{-1}. In contrast to the values identified for Neem trees, which range from 28 to 41 mg kg^{-1} for Zn and 5.46 to 6.08 mg kg^{-1} for Cu, the report discovered levels of Zn in Faisalabad between 0.46 and 1.89 mg kg^{-1} and Cu between 0.252 and

0.923 mg kg^{-1}. We also demonstrated that the Neem tree may be an excellent bio-accumulator of Zn and Cu. Waseem et al. (2014) showed that the soil concentrations of Zn in Pakistan range from 0.1 to 1193 mg kg^{-1} and for Cu, from 6 to 412 mg kg^{-1}.

In Faisalabad, the two main sources of Fe dispersion are automobiles and industry. Vehicles have been discovered to release Fe by a variety of processes, including brake abrasion and exhaust emissions, particularly from diesel engines (Wang et al., 2003). Zając et al. (2015) predicted a concentration of 16–267 mg kg^{-1} Fe metal in used oil. A respectable iron business that manufactures heavy iron agricultural equipment and distributes it to other parts of Pakistan is the second source of iron in Faisalabad. Filipiak-Szok et al. (2015) demonstrated these industrial operations are a high-level source of Fe dispersion. Cadmium is the most dangerous heavy metal for humans, animals, and plants. The main cause of cadmium pollution in plants and soil is anthropogenic activity. Because cadmium compounds are more soluble than other heavy metals, they are more likely to build up in plant parts that can be eaten. The Cd values in soil samples from Pakistan's Islamabad highway range from 5.8 to 6.1 mg kg^{-1}, with an average of 5.95 mg kg^{-1} (Faiz et al., 2009). This is essential because it was previously mentioned that the concentration of cadmium in tree leaves increased along with the urbanization gradient, but that the concentration in soil was below the level that can be detected. Based on this, we can conclude that neem trees are a good bioindicator and bio-accumulator of cadmium and can be used to make soil much less contaminated.

It is probable that the pigments used in textile production contain Mn and are contaminating the soils in the Faisalabad region because textile production is the main industry in the area and pigments are one of the anthropogenic sources of Mn. The description of the sampling sites has made reference to this. Another industry that can be responsible for soil Mn contamination is the manufacturing of chemical fertilizers. The use of these fertilizers to local crops may possibly be the cause of the elevated manganese levels in the soil because Mn is found in fertilizers as $MnSO_4$ (Ayaz et al., 2023). The presence of industries and traffic is responsible for the increased Mn concentrations in the city's soils, which range from 354 to 746 mg kg^{-1} in Faisalabad. Fe concentrations were also measured and found to be high (ranging from 6716 to 9119 mg kg^{-1}), although they were lower than the current levels (Umer et al., 2022).

In relation to the soil analysis, as was already mentioned, the data indicates that the degree of urbanization is associated with a rise in metal concentrations in soils, a finding that has been noted in a number of studies. Rezapour et al. (2022) found that all metals were significantly higher in the soil from urban maize cultivation than in the soil from rural maize cultivation.

According to one study, the content of zinc in Beijing soils rose from natural to urban settings (Wang et al., 2017). The accumulation of heavy metals was found to be larger in the city center than in the outskirts of Beijing, according to another study conducted there as well. However, this study discovered a substantial association between population density and metal accumulation (Xie et al., 2019).

6.3.3. Bio-Accumulation Factor (BAF)

Numerous studies have shown that, for the BAF, there is an inverse relationship between pH and metal uptake for a large range of metals. In addition to the fact that the highest BAF for most metals is found in the rural region, which has the highest pH, this is because lower pH values improve metal solubility, which facilitates metal absorption by plants (Adamczyk-Szabela & Wolf, 2022). He et al. (2020) showed that calcium carbonate was probably the element that had the biggest impact on metal uptake. Because metals can form compounds like hydrated hydroxides and carbonate minerals in soils rich in calcium carbonate, plants absorb less metal when the calcium carbonate content is higher. Furthermore, for plants to absorb metals from the soil, they must be soluble in water (Yan et al., 2020). This means that water is required to transport the metal from the soil to the root and shoot systems, which may account for why the BAF for most metals is typically highest in rural areas because the soil there has the highest moisture content and the lowest calcium carbonate content. A. indica leaves had lower BAF values (>1) of metals like Fe, Cu, Zn, and Cd than in a previous study that used this species as a bioindicator for soil contamination of the heavy metals in the nation's coal-burning regions (Patel et al., 2015). This contrasts with our findings, which only indicate a BAF greater than 1 for strontium.

7. CONCLUSION

Element concentrations in soil samples were analyzed to evaluate the impact of urbanization on the ecological health of Vienna's urban ecosystems. The pollution index indicated moderate pollution levels for cadmium (Cd) and low levels for chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) across the urbanization gradient. The study identified traffic emissions as the primary contributor to metal pollution, evidenced by heightened concentrations of these metals compared to their background levels. Results confirmed that both elemental soil analysis and pollution index values are effective indicators for assessing pollution levels in urban environments. We also evaluated the role of tree species in urban green area planning regarding their pollution tolerance and bioindication of air quality using APTI, PM_{10}, and heavy metal contents. APTI was found to be effective for identifying pollution-tolerant species beneficial for urban planning. *A. platanoides, F. excelsior,* and *Q. robur* were identified as sensitive indicators of air pollution. Significant variations were noted in the leaves' relative moisture, pH, ascorbic acid, and chlorophyll content, with notable differences along the urbanization gradient. Specifically, tree species showed variations in Al, B, Ba, Cr, Fe, Mg, Na, Ni, P, S, and Zn concentrations in their leaves. Our study confirmed that tree leaves serve as reliable bioindicators of urban air pollution, with higher concentrations of pollutants detected in urban areas compared to rural areas. similarly, the environmental impact of urbanization in Faisalabad, Pakistan, focusing on metal concentrations in soils and Neem tree leaves (*A. indica*). Urban soil samples had the highest metal concentrations, confirming urbanization negatively affects soil quality. Significant variations in leaf metal concentrations were noted, with the Neem tree identified as a potential bio-accumulator for cadmium and strontium. The analysis revealed that high soil metal concentrations do not necessarily correlate with increased plant absorption due to other soil factors. It was concluded that industrial pollutants and increased traffic are major contributors to metal contamination in this industrial city, making elemental analysis of plants and soil a reliable pollution assessment method. Because the two cities are viewed as complementary case studies, cross-site comparisons are evaluated qualitatively, taking into account variations in applied indicators and species.

8. NEW SCIENTIFIC RESULTS

- The study revealed that the pollution index results indicated that the Cd had moderate pollution level ($1 \leq PI \leq 2$), whereas Cr, Cu, Ni, Pb, and Zn remained within the low pollution level throughout the urbanization gradient.
- The traffic emissions may be the major source of the metal pollution in Vienna.
- The elemental analysis of soil and the values of PI are adequate indicators to assess the level of pollution.
- APTI is useful for selecting pollution-tolerant species, which can be used for urban green infrastructure planning.
- Based on APTI values of *A. platanoide*, *F. excelsior* and *Q. robur* were sensitive indicator species of air pollution.
- *Azadirachta indica* (Neem), indicating strong tolerance to air pollution. This species is recommended as an accumulator species, as tolerant plants can survive under polluted conditions and help to reduce it.
- Tree leaves are reliable bioindicators of urban air pollution.
- The presence of high metal concentrations in soil does not always result in increased plant absorption due to the impact of other soil factors.
- The primary cause of the metals in Faisalabad are probably industrial pollutants and the traffic emissions.
- Conducting elemental analysis of plant leaves and soil provides a reliable method for evaluating environmental pollution.

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10. APPENDIX

Appendix Table 1. Results of ANOVA for soil samples in Vienna

Parameters	F	p
pH	7.626	0.001
Electrical conductivity, μS cm^{-2}	13.105	<0.001
Moisture content, %	4.188	0.022
Organic matter, %	4.088	0.024
Calcium carbonate, %	0.324	0.725
Arany-type plasticity index	2.911	0.131
Al	7.658	0.001
B	1.055	0.357
Ba	0.511	0.604
Ca	1.339	0.273
Cd	1.460	0.244
Co	6.244	0.004
Cr	3.843	0.029
Cu	21.337	<0.001
Fe	4.441	0.018
K	8.058	0.001
Li	15.121	<0.001
Mg	0.238	0.789
Mn	2.927	0.065
Na	1.034	0.364
Ni	7.989	0.001
P	17.178	<0.001
Pb	26.370	<0.001
S	0.435	0.650
Sr	5.070	0.011
Zn	28.191	<0.001

Appendix Table 2. Result of ANOVA for *A. platanoides*

Parameters	F	P
PM_{10}	4.786	0.030
Al	31.950	<0.001
Cr	4.757	0.030
Fe	4.181	0.042
Mn	4.181	0.042

Appendix Table 3. Result of ANOVA for *F. excelsior*

Parameters	F	P
AAC	25.043	<0.001
TChl	4.286	0.039
Ba	7.629	0.007
Cr	4.922	0.027
Cu	2.817	0.099
Fe	3.240	0.075
Sr	3.662	0.057
Zn	13.915	0.001

Appendix Table 4. Result of ANOVA for *Q. robur*

Parameters	F	P
TChl	9.101	0.004
Al	4.542	0.034
Cr	12.462	0.001
Fe	23.159	<0.001
Mn	5.353	0.022
Ni	20.651	<0.001
Sr	3.580	0.060

Appendix Table 5. Result of ANOVA of urban area among the tree species

Parameters	F	P
RWC	7.999	0.007
pH	5.833	0.017
ACC	8.134	0.006
TChl	17.666	<0.001
APTI	3.384	0.068
Al	30.118	<0.001
Cr	6.222	0.014
Cu	6.182	0.014
Fe	18.207	0.000
Mn	8.006	0.006
Ni	19.289	0.001
Sr	21.348	<0.001

Appendix Table 6. Result of ANOVA of suburban area among the tree species

Parameters	F	P
RWC	15.883	<0.001
pH	17.182	<0.001
ACC	17.044	<0.001
TChl	3.956	0.048
APTI	17.089	<0.001
PM_{10}	4.856	0.028
Al	8.510	0.005
B	3.687	0.056
Ba	13.002	0.001
Cr	3.010	0.087
Fe	12.535	0.001
Mn	6.135	0.015
Ni	4.146	0.048
Sr	5.585	0.019
Zn	15.377	0.015

Appendix Table 7. Result of ANOVA of rural area among the tree species

Parameters	F	P
RWC	13.471	0.001
pH	11.872	0.001
ACC	5.370	0.022
APTI	5.399	0.012
B	10.813	0.002
Ba	5.399	0.024
Cr	4.800	0.029
Mn	3.542	0.062
Sr	22.492	<0.001
Zn	11.527	0.002

Appendix 8. Pearson correlation based on the studied leaf parameters and air pollutant data. Notations: Bold letter indicates the significant differences, $p<0.05$.

	A. pseudoplatanus				*F. excelsior*				*Q. robur*			
	PM_{10}	CO	NO_2	$PM_{2.5}$	PM_{10}	CO	NO_2	$PM_{2.5}$	PM_{10}	CO	NO_2	$PM_{2.5}$
RWC	0.451	0.562	**<0.001**	**<0.001**	0.586	0.476	**<0.001**	**<0.001**	0.667	0.777	**<0.001**	**<0.001**
pH	0.667	0.556	**<0.001**	**<0.001**	0.667	0.777	**<0.001**	**<0.001**	0.667	0.777	**<0.001**	**<0.001**
AAC	0.407	0.296	**<0.001**	**<0.001**	0.260	0.149	**<0.001**	**<0.001**	0.121	0.010	**<0.001**	**<0.001**
TChl	0.249	0.360	**<0.001**	**<0.001**	0.830	0.719	**<0.001**	**<0.001**	0.550	0.661	**<0.001**	**<0.001**
Al	0.342	0.231	**<0.001**	**<0.001**	0.428	0.318	**<0.001**	**<0.001**	0.136	0.246	**<0.001**	**<0.001**
Ba	0.554	0.443	**<0.001**	**<0.001**	0.661	0.772	**<0.001**	**<0.001**	0.426	0.315	**<0.001**	**<0.001**
Cr	0.766	0.877	**<0.001**	**<0.001**	0.788	0.898	**<0.001**	**<0.001**	**<0.001**	0.111	**<0.001**	**<0.001**
Cu	**<0.001**	0.111	**<0.001**	**<0.001**	**0.025**	0.139	**<0.001**	**<0.001**	0.901	0.989	**<0.001**	**<0.001**
Fe	0.247	0.136	**<0.001**	**<0.001**	0.064	0.175	**<0.001**	**<0.001**	0.175	0.286	**<0.001**	**<0.001**
Mn	0.643	0.532	**<0.001**	**<0.001**	0.113	0.224	**<0.001**	**<0.001**	0.606	0.495	**<0.001**	**<0.001**
Ni	0.454	0.344	**<0.001**	**<0.001**	0.555	0.445	**<0.001**	**<0.001**	0.440	0.330	**<0.001**	**<0.001**
Sr	0.952	0.937	**<0.001**	**<0.001**	0.397	0.286	**<0.001**	**<0.001**	0.605	0.716	**<0.001**	**<0.001**
Zn	0.917	0.806	**<0.001**	**<0.001**	0.154	0.265	**<0.001**	**<0.001**	0.780	0.890	**<0.001**	**<0.001**