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Assessing the Impact of Urban Development on Soil Health and Nutrient Cycling Across Urban Areas

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ABSTRACT

Urbanization, a hallmark of the 21st century, has significantly altered land use and environmental systems worldwide. This study aimed to bridge a critical research gap by investigating the effects of urbanization on soil properties, using Astana, Kazakhstan, as a case study to reflect broader urban soil trends. The objective was to assess soil texture, humus content, pH, and soluble salts across various land use categories, including residential, commercial, industrial, and forested areas, which served as control/reference sites. Soil samples were analyzed for nitrate nitrogen, available phosphorus, potassium, sulfur, humus, pH, and soluble salts such as calcium, magnesium, chloride, sulfate, and bicarbonate. Comparative analyses revealed notable variations in bulk density across land use categories. Residential areas exhibited lower bulk densities (topsoil: 1.24–1.32 g/cm³; subsoil: 1.41– 1.54 g/cm³), indicating lesser compaction. Conversely, commercial zones showed increased bulk densities (topsoil: 1.41–1.55 g/cm³; subsoil: 1.52–1.65 g/cm³), reflective of foot traffic and impermeable surfaces. Industrial zones recorded the highest bulk densities (topsoil: 1.55–1.62 g/cm³; subsoil: 1.63–1.76 g/cm³), largely attributed to heavy machinery and construction activities. Agricultural lands demonstrated moderate bulk densities (topsoil: 1.30–1.42 g/cm³; subsoil: 1.52–1.66 g/cm³), influenced by tillage practices, while forested areas had the lowest bulk densities (topsoil: 1.20–1.30 g/cm³; subsoil: 1.34–1.45 g/cm³), indicating minimal disturbance and higher organic content. Nutrient assessments indicated that nitrate nitrogen and phosphorus levels were generally moderate, with agricultural areas exhibited significantly higher phosphorus concentrations due to fertilizer application. Additionally, heavy metal concentrations, particularly lead and chromium, were found to be elevated in industrial zones, highlighting potential contamination risks. The study concluded that urban soils display diverse nutrient levels and physical properties, with forested areas providing a baseline for comparison. These findings emphasize the need for comprehensive soil evaluations in urban planning to address the specific conditions of different land use types. Implementing tailored management practices can enhance soil health and foster sustainable urban development on a larger scale.

Keywords: urbanization, impervious surfaces, soil health, pollution, geographic information system.

INTRODUCTION

Urbanization, a defining trend of the 21st century, is profoundly reshaping global land use patterns at an unprecedented rate. Projections indicate that by 2050, approximately 70% of the global population will reside in urban areas, reflecting an ongoing and dramatic shift from rural to urban living [1, 2]. This transformation is not merely a demographic shift, but also a profound change in how land is utilized and managed. While urban land currently occupies only 0.5% of the Earth's surface [3], its expansion is accelerating at a remarkable pace, with estimates suggesting an increase of up to 1.2 million km² by 2030 [4]. This burgeoning urban sprawl is accompanied by significant ecological and environmental challenges, particularly concerning soil health and ecosystem functionality. Addressing these challenges requires a deep understanding of how urban expansion impacts soil systems, as well as the development of effective, sustainable management strategies. One of the most immediate and visible consequences of urbanization is the proliferation of impervious surfaces, such as roads, buildings, and pavements. These surfaces significantly disrupt natural soil processes by preventing water infiltration, thereby increasing surface runoff and exacerbating soil erosion [5]. This disruption not only impedes groundwater recharge, but also contributes to elevated flood risks, which can lead to infrastructure damage and ecological disturbances. Additionally, the urban heat island effect, which results from the extensive coverage of impervious surfaces, further complicates soil health by altering soil temperature and moisture levels [6]. This effect can lead to increased soil temperatures, reduced moisture retention, and heightened evaporation rates, all of which can adversely impact soil structure and health. The reduction of green spaces, which are vital for soil organic matter accumulation and overall soil health, adds another layer of complexity. The diminishing of these areas compromises soil fertility, decreases nutrient availability, and reduces microbial activity, leading to a cascade of negative effects on urban soil systems [7].

Urban soils are often subjected to constant disturbances, such as construction activities, heavy traffic, and other types of anthropogenic pressure, which lead to soil compaction and reduced aeration. These conditions hinder root growth, water movement, and overall soil functionality [8]. The degradation of soil properties has extensive consequences for ecosystem services, including reduced soil productivity and diminished capacity for water filtration and retention. Moreover, urban soils are increasingly burdened by pollution. Traditional soil assessment methods, designed primarily for rural or agricultural settings, often fall short in addressing the multifaceted impacts of urban pollutants [9]. Contaminants, such as heavy metals, hydrocarbons, and microplastics, are prevalent in urban environments and can significantly alter soil properties, complicating the efforts to assess and manage soil health accurately [10]. The presence of these pollutants necessitates advanced analytical techniques and approaches to fully understand their impact on soil systems as well as develop effective remediation strategies.

Previous research on soil management has predominantly focused on rural areas and agricultural practices, largely overlooking the unique challenges posed by urban environments [11–13]. Conventional assessment techniques, which often emphasize soil fertility and contamination levels, frequently fail to capture the complexity of urban soils and their diverse pollutant profiles [14]. Additionally, many studies have not fully employed spatial analysis tools, which are crucial for understanding the distribution and variation of soil properties across urban landscapes. This gap in research highlights the need for innovative approaches to urban soil assessment and management. By leveraging advanced technologies and methodologies, researchers can gain a more comprehensive understanding of urban soil dynamics and develop more effective strategies for addressing the challenges associated with urbanization.

This study sought to bridge this critical research gap by conducting a thorough analysis of urban soil composition and developing zoning maps to promote environmental sustainability in rapidly urbanizing contexts. By integrating advanced geographic information system (GIS) technology with detailed soil assessments, this research aimed to enhance the understanding of urban soil dynamics as well as provide practical insights for urban planning and management. The study findings are expected to contribute significantly to the advancement of knowledge on urban soil health and offer a model for similar studies in other burgeoning urban areas worldwide. This research underscores the importance of incorporating comprehensive soil assessments into urban development strategies to mitigate adverse environmental impacts and foster sustainable growth. As urban areas continue to expand, applying these insights can guide effective urban soil management practices and contribute to achieving broader sustainability goals in rapidly urbanizing regions.

MATERIALS AND METHODS

Study area

Astana, the capital of Kazakhstan, is situated in the northern part of the country, nestled on the banks of the Ishim River. As a burgeoning metropolis, Astana boasts a population of 1.4 million residents, representing 6% of Kazakhstan's total population (19.9 million). This rapid growth, earning it the status of a "millionaire city" in June 2017, has significantly transformed the city's landscape and placed it among the fastest-growing megacities in the Eurasian region.

Administratively divided into five districts – Almaty, Baikonur, Yesil, Saryarka, and Nura – Astana encompasses a diverse geographical area of 797.3 km^2. The city's natural soil environment, characterized by dark chestnut soils, meadow-chestnut soils, and salt marshes, is facing increasing pressure from urbanization. Intensive construction and industrial activities have led to significant technogenic changes in the soil profile across a large portion of the city. Consequently, vast areas of disturbed soils, often lacking a defined structure and referred to as "urban soils," have emerged, replacing the natural soil order. This anthropogenic influence has resulted in an intermittent and fragmented distribution of soil types within the urban environment. Pockets of relatively undisturbed soils, retaining the typical natural soil layer profile, are primarily found in preserved forest patches and wooded areas within the city limits. To gain a comprehensive understanding of the impact of urbanization on Astana's soils, this study focused on analyzing the mechanical and agrochemical properties of soil samples collected from across the city. A total of 60 sampling points were strategically distributed across the five administrative districts, as depicted in Figure 1 (Please insert the actual figure here). This stratified sampling approach, aided by ESRI ArcGIS 10.5 software, ensures a representative assessment of soil characteristics across different land use zones and levels of urban development intensity (Figure 1).

Rationale for selecting Astana as a case study

Astana was chosen as a case study for its unique blend of rapid urbanization and the specific environmental challenges it presents, making it an ideal model for analyzing the impact of urbanization on soil. As the capital of Kazakhstan, Astana has witnessed unprecedented growth, becoming a key economic and political center. The city's population boom, particularly its elevation to a "millionaire city" status in 2017, marks it as one of the fastest-growing urban centers in the Eurasian region, which provides a valuable context for studying how rapid urban expansion affects soil environments. One of the primary factors that strengthens the rationale for selecting Astana is the diversity of industrial activities prevalent in the city, such as construction, manufacturing, and infrastructure development. These sectors, essential to Astana's transformation into a modern metropolis, place immense pressure on the soil through pollution, heavy metal deposition, and soil compaction. Construction activity, in particular, has reshaped vast areas of the city, causing severe disruptions to natural soil profiles. Industrial pollutants, along with construction debris and urban waste, have altered the soil composition, introducing technogenic elements that create what are referred to as "urban soils" – soils with disturbed structures and non-uniform characteristics that differ from natural soil layers. Moreover, Astana's natural soil types – dark chestnut

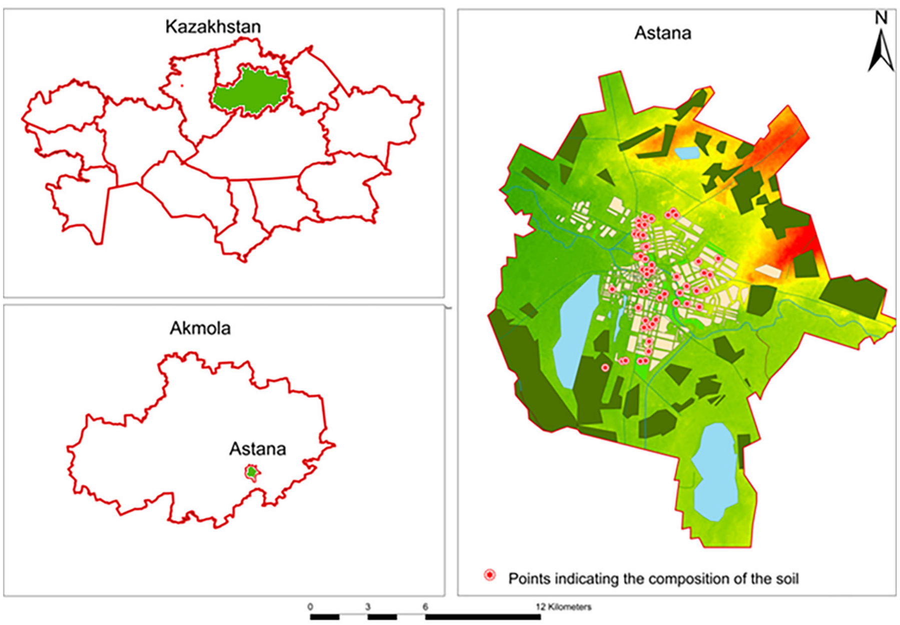

Figure 1. Sampled points for determining the mechanical and agrochemical composition of soil

soils, meadow-chestnut soils, and salt marshes – are representative of the steppe and semi-arid environments typical of northern Kazakhstan. These soils are particularly vulnerable to the effects of urbanization, as they have a relatively low resilience to compaction and contamination. The city's rapid development has led to the fragmentation of soil types, with relatively undisturbed soils being confined to isolated patches of forests and green spaces. This fragmentation disrupts the continuity of natural ecosystems and soil functions, complicating land management and conservation efforts. Astana's climate and geography also make it a noteworthy case study for assessing the urbanization effects on soils. The city experiences cold winters and hot summers, conditions that can exacerbate soil degradation, particularly in the areas where natural vegetation has been replaced by impervious surfaces such as roads and buildings. These factors combine to make Astana a highly dynamic urban landscape, with distinct zones of land use that provide a comprehensive picture of how varying degrees of urban intensity influence soil properties.

The selection of 60 sampling points across Astana's five administrative districts – Almaty, Baikonur, Yesil, Saryarka, and Nura – ensures a representative assessment of the city's diverse urban soil environments. This stratified sampling approach, supported by ESRI ArcGIS software, allows for an accurate analysis of both the mechanical and agrochemical properties of soils from different land use zones, ranging from heavily urbanized areas to relatively undisturbed green spaces. The findings from this study will not only provide insights into the specific case of Astana but can also be applied to other rapidly growing cities facing similar urbanization challenges, making this study highly generalizable. By investigating the specific characteristics of Astana's soils and the type of pressure they face, this research contributes valuable knowledge to the broader discourse on sustainable urban development and soil conservation in fast-growing cities across the globe.

Soil sampling design

To capture the inherent variability of urban soils, a stratified random sampling design was employed. The sampling framework was divided into five distinct land use categories: residential, commercial, industrial, and urban parks, with each category representing specific anthropogenic impacts on soil quality.

- Residential areas: Included the regions with varying housing densities and green spaces, providing a gradient of soil conditions influenced by different levels of urbanization and landscaping practices;
- Commercial zones: Focused on central business districts, office complexes, and shopping malls, where foot traffic and surface impermeability are expected to affect soil compaction and contamination levels;
- Industrial sites: Targeted locations likely to be impacted by potential soil contamination from manufacturing or construction activities, representing higher environmental risks;
- Urban parks: These designated green spaces served as controls or reference points, where soil might be less disturbed by human activities, providing baseline data for urban soil health comparison.

A total of 60 sampling points were strategically selected using stratified random sampling in each land use category, ensuring coverage of the entire urban area across all five districts. ESRI ArcGIS software facilitated the random selection of sampling points, enabling precise spatial representation (Figure 1). The distribution was validated to ensure that no significant gaps or clusters occurred in the spatial layout of the sampling locations.

In addition, at a subset of 20 sampling points, evenly distributed across the four land use categories, microclimate variables–including air temperature, humidity, and soil surface temperature–were measured using portable meteorological equipment. These data were collected simultaneously with soil sampling to assess the relationship between microclimatic conditions and soil properties.

Control parks

Park size and location

The urban parks, chosen as control sites were selected based on their size and strategic locations across Astana, ensuring a diverse representation of relatively undisturbed soil conditions. Central Park, covering approximately 12 hectares, is located in the Yesil district near the Ishim River, positioned between residential and commercial zones. Its central location, away from industrial activities, makes it a prime candidate for studying less disturbed soils. Another key site, Presidential

Park, spans 14 hectares in the Almaty district, situated at the city's outskirts, offering a larger area with fewer urban disturbances. In contrast, smaller parks in the Baikonur and Saryarka districts, ranging from 1 to 3 hectares, are closer to residential areas where they may experience more urban influences but still preserve green space within a highly developed environment.

Park management practices

Management practices across the parks vary, though all include regular irrigation, particularly during Astana's dry summer months. Central and Presidential Parks are irrigated twice a week, sometimes using recycled wastewater in addition to the municipal supply. Fertilization practices are also in place, with larger parks receiving controlled nitrogen-based fertilizers twice a year to maintain lawns and tree health, while smaller parks may see less frequent fertilization. Regular mowing and pruning of trees as well as ornamental plants are common in all parks, potentially impacting soil nutrient levels and compaction. However, efforts are made to manage these green spaces sustainably, particularly in the larger parks, which are maintained with a balance of natural and managed elements.

Sampling site selection

To ensure the sampling process captured relatively undisturbed soil conditions, specific areas within each park were selected based on low human interference. In Central Park, soil samples were taken from under dense tree canopies and near water features, where access is restricted, minimizing the risk of soil compaction or trampling. Similarly, in Presidential Park, samples were collected from the central forested section, away from lawns and public pathways. Sampling sites were located at least 30 meters from park boundaries, streets, or paved areas to avoid contamination from nearby traffic or infrastructure. In each park, particular attention was given to choosing the zones that were shielded from regular maintenance activities, focusing on the areas with the most natural vegetation and least foot traffic.

Potential confounding factors

Despite being designated as green spaces, urban parks are still subject to environmental influences that could impact soil health. Airborne pollution from nearby traffic or industrial activities is a potential concern, particularly in the parks located closer to high-density areas or roads. Urban runoff, especially after rainfall, may introduce pollutants into park soils, though larger parks like Presidential Park benefit from natural drainage systems that help reduce this effect. Even in low-traffic zones, maintenance activities, such as mowing or irrigation may still cause some degree of soil compaction. To mitigate these issues, samples were taken from the areas with minimal maintenance, such as underbrush and wooded areas, ensuring the sampling represented the least disturbed conditions within the urban environment.

Soil sample collection and preparation

At each designated sampling location, soil cores were extracted using a stainless steel hand auger with a diameter of 5 cm, ensuring minimal contamination and accurate representation of the soil profile. The auger was sterilized with 70% ethanol between locations to prevent cross-contamination. Soil cores were extracted to a depth of 60 cm and subsequently divided into two distinct depth intervals:

- 0–30 cm (Topsoil layer): This layer was chosen to represent the most biologically active portion of the soil, which is directly influenced by surface activities, such as foot traffic, construction, and urban pollutants.
- 30–60 cm (Subsoil layer): This layer was sampled to capture information on natural soil processes, as well as potential contaminant migration from surface layers through leaching.

Each sample from both depth intervals was immediately placed into pre-labeled, airtight polyethylene bags (500 mL capacity) to maintain sample integrity, minimize the exposure to atmospheric oxygen, and prevent moisture loss. The bags were sealed tightly and transported in a cooled, insulated container (maintained at 4 °C) to the laboratory within 24 hours.

Laboratory analysis

Soil texture analysis

Soil texture was determined using the pipette method following GOST 12536-2014 standards. Briefly, 50 grams of air-dried soil was pre-treated with a 5% sodium hexametaphosphate solution and stirred for 4 hours. The suspension was transferred to a sedimentation cylinder, and the sand, silt, as well as clay fractions were separated based on their settling velocities. The mass of each fraction was measured, and their percentages were used to classify soil texture according to the USDA soil textural triangle.

Agrochemical and contaminant analysis

In the study, a comprehensive suite of soil parameters and contaminants was analyzed to assess soil quality and environmental impacts. Soil samples were collected from various locations, and key agrochemical indicators, such as nitrate nitrogen, available phosphorus, potassium, sulfur, and organic matter were evaluated to understand nutrient availability and soil health. Additionally, the pH, soluble salts, and bulk density of the soil were measured to assess its physical and chemical properties. Heavy metal concentrations were analyzed to identify potential contamination from industrial activities. The data presented in the Table 1 summarize the extraction and analytical methods used for these assessments, providing a detailed overview of the soil characteristics and potential environmental concerns.

Microclimate measurements

At the designated 20 locations, microclimate variables were measured in conjunction with soil sampling, between 11:00 AM and 2:00 PM to capture peak daytime conditions. Microclimate measurements were conducted at each sampling location to capture environmental conditions. Air temperature and relative humidity were recorded at a height of 1.5 meters above ground using a calibrated digital thermometer and hygrometer, respectively. Wind speed was measured at 2 meters above ground with a portable anemometer to assess atmospheric movement. Surface temperature was evaluated using an infrared thermometer, focusing on representative bare soil patches to gauge the thermal characteristics of the soil. These measurements provided a comprehensive understanding of the local microclimate conditions at each site (Table 2).

Table 1. Summary of the extraction and analytical methods

Parameter	Extraction method	Analytical technique	Standard/Method
Nitrate nitrogen ($N\text{-}NO_3$)	2 M KCl extraction	Flow injection analysis	GOST 26951-85
Available phosphorus (P_2O_5)	Olsen's reagent (0.5 M $NaHCO_3$)	Molybdenum blue colorimetric method	GOST 26205-91
Available potassium (K)	1 M ammonium acetate extraction	Flame photometry	GOST 26205-91
Available sulfur (S)	0.01 M calcium phosphate solution	Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)	GOST 26490-86
Soil organic matter (Humus)	Oxidation with potassium dichromate, titration with ferrous ammonium sulfate	Tyurin method	GOST 26213-2021
Soil pH	1:2 soil-to-water suspension	Calibrated pH meter	GOST 26483-85
Soluble Salts (Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2+}, HCO_3^-)	1:5 soil-to-water ratio	Titration, ion chromatography, spectrophotometry	PND F 16.1:2:2.2:2.3.74-2012; GOST 26424-
Bulk density	Calculated from core samples	Dry soil mass to volume ratio (core sampler)	N/A
Heavy metals (Pb, Cd, Cr, Ni, etc.)	Acid digestion	ICP-OES	EPA Method 3051A

Table 2. Microclimate measurements technical specifications

Parameter	Measurement height	Instrument	Method of measurement
Air temperature (°C)	1.5 meters above ground level	Calibrated digital thermometer	Direct measurement of air temperature
Relative humidity (%)	1.5 meters above ground level	Calibrated digital hygrometer	Direct measurement of air humidity
Wind speed (m/s)	2 meters above ground level	Portable anemometer	Direct measurement of wind speed
Surface temperature (°C)	Targeting bare soil patches	Infrared thermometer	Non-contact measurement of soil surface temperature

Bioremediation potential assessment

On the basis of the identified soil contaminants and prevailing environmental conditions, an experimental selection of plant species for bioremediation was conducted. The process involved assessing plant species for their contaminant uptake capacity, biomass production, drought tolerance, and cold hardiness. Specifically, contaminant uptake was evaluated using atomic absorption spectroscopy (AAS) or inductively coupled plasma mass spectrometry (ICP-MS) on plant tissues. Biomass production was measured by harvesting and weighing dry plant material after oven-drying at 70 °C. Drought tolerance was tested under controlled water deficit conditions with soil moisture monitored by tensiometers, while cold hardiness was assessed in an environmental chamber with temperatures ranging from -5 °C to -15 °C. The results determined the most effective species for bioremediation (Table 3).

Data analysis and visualization

This study employed a combined approach of descriptive statistics, geostatistical analysis, and machine learning to analyze the collected soil data and develop predictive models for key soil properties and functions.

Descriptive statistics and geostatistical analysis

Descriptive statistics, including mean, standard deviation, minimum, and maximum values, were calculated for all measured soil properties to summarize their central tendencies and variability. Inverse distance weighting (IDW) interpolation was performed using ArcGIS 10.5 software to generate continuous surface maps, visualizing the spatial distribution of soil characteristics. These maps provided insights into the spatial patterns of soil properties and their relationships with urban land use.

RESULTS

General soil characteristics

Soil texture

The elemental concentration results for soil samples across different locations reveal important insights into soil fertility and nutrient availability. The nitrate nitrogen ($N\text{-}NO_3$) concentrations range from 6.32 mg/kg to 9.2 mg/kg, with an average value of 8.15 mg/kg. This variation suggests differences in soil nutrient availability, which is crucial for plant growth as nitrate nitrogen is a key component of soil fertility. Higher concentrations at certain locations indicate better nutrient availability, potentially supporting more robust plant growth. Available phosphorus (P_2O_5) concentrations vary from 16.53 mg/kg to 26.27 mg/kg, with an average of 20.97 mg/kg. These levels are essential for plant energy transfer and root development.

The variation in phosphorus concentrations among the locations could impact soil fertility and plant performance differently. Locations with higher phosphorus levels are likely to support better plant growth and crop yields, given the critical role of phosphorus in photosynthesis and energy storage. The potassium (K) levels range from 331.58 mg/kg to 408.03 mg/kg, averaging 374.75 mg/kg. Potassium is vital for various plant processes, including water regulation and enzyme activation. The observed variation in potassium concentrations across the locations suggests differences in soil nutrient content that can influence plant health and productivity. The highest potassium concentrations at certain locations may provide a better environment for crop growth and resilience. Sulfur (S) concentrations, ranging from 2.632 mg/kg to 5.607 mg/kg with an average of 4.09 mg/kg, are also notable. Sulfur is important for protein synthesis and enzyme function; its levels can affect soil and plant health. The variation in sulfur concentrations indicates differences

Table 3. Bioremediation potential assessment technical specifications

Parameter	Experimental detail	Measurement technique	Values/Conditions
Contaminant uptake	Absorption of contaminants in plant tissues	AAS or ICP-MS	Contaminants: Pb, Cd, Cr, Ni, etc.
Biomass production	Total biomass of plants	Dry mass measurement	Drying temperature: 70 °C
Drought tolerance	Plant response to water deficit	Leaf water potential, relative water content	Soil moisture levels: 10–30 kPa
Cold hardiness	Plant survival in cold conditions	Survival rates, physiological performance	Temperature range: -5 °C to -15 °C

in soil quality and its potential to support plant growth (Table 4).

The analysis of humus content and soil pH across different locations provides valuable insights into soil health and suitability for plant growth. The humus content ranges from 2.845% to 3.2%, with an average value of 3.058%. Humus is crucial for enhancing soil fertility, structure, and water retention. The relatively consistent levels of humus across the locations suggest a generally good organic matter content, which is beneficial for supporting plant growth and improving soil health. Soil pH values range from 6.73 to 6.96, with an average pH of 6.85. This pH range is slightly acidic to neutral, which is optimal for most crops and plants. The variation in pH values indicates some differences in soil acidity, which can influence nutrient availability and microbial activity. The soils with a pH closer to neutral typically offer better conditions for nutrient uptake by plants, while slightly acidic soils are also suitable but may require occasional lime applications to maintain optimal pH levels. Generally, the data indicate that the soil conditions across the studied locations are generally favorable for plant growth, with consistent humus content and suitable pH levels. These characteristics suggest that the soils in these areas are well-suited for agriculture and other vegetation, supporting good soil structure and nutrient availability. However, slight variations in pH and humus content may still affect specific plant requirements and should be considered in land management and agricultural practices (Table 5).

Moreover, the study identified a range of pH values for urban soils, generally falling between neutral and slightly alkaline. The typical pH values observed were around 6.7 to 7.8. The majority of soils were found to be neutral, with pH values commonly ranging from 6.7 to 7.0. In certain areas, soils exhibited slightly alkaline conditions, with pH values reaching up to 7.8. These typical pH ranges suggest that urban soils are often well-suited for a variety of plant species, as neutral to slightly alkaline soils are generally favorable for plant growth. The presence of slightly alkaline conditions in some areas may be attributed to localized impacts, such as the use of soil amendments or environmental factors affecting soil chemistry. Understanding these typical pH values helps in assessing soil health and planning appropriate soil management strategies. For instance, maintaining soil pH within these typical ranges can support effective nutrient availability and overall plant health in urban green spaces. This approach ensures that soil management practices are aligned with the general soil conditions observed across urban environments (Figure 2).

Spatial variability of soluble salts

Analysis of 60 soil samples collected revealed significant spatial variability in the concentrations of soluble salts, reflecting the heterogeneous nature of urban soil development and potential influences from anthropogenic activities. Calcium (Ca^{2+}) concentrations ranged from 0.0032% to 0.0184%, with the highest value observed in the Almaty district. Similarly, magnesium (Mg^{2+}) concentrations varied from 0.0023% to 0.0130%, highlighting the spatial heterogeneity within the city's soils. Chloride (Cl^-) concentrations were highest in the Nura district (reaching 0.0292%), while the lowest values were found in the Baikonur district. Sulfate (SO_4^{2-}) concentrations exhibited the most pronounced spatial variation, ranging from 0.0137% in the Almaty district to 0.0716% in the Saryarka district. Bicarbonate (HCO_3-) concentrations also

Table 4. Elemental concentration in the soil samples of micro districts for plant growth

Elements	Saryarka	Baikonur	Almaty	Yesil	Nura	Average
$N\text{-}NO_3$	9.1	6.32	7.45	9.2	8.71	8.15
P_2O_5	22.97	16.53	26.27	22.38	16.72	20.97
K	393.76	353.84	331.58	386.54	408.03	374.75
S	4.803	5.607	3.116	2.632	4.34	4.09

Table 5. Content of humus and pH in the soil

Characteristic	Saryarka	Baikonur	Almaty	Yesil	Nura	Average
Humus (%)	3.2	2.845	3.045	3.15	3.052	3.058
pH	6.87	6.92	6.96	6.73	6.79	6.85

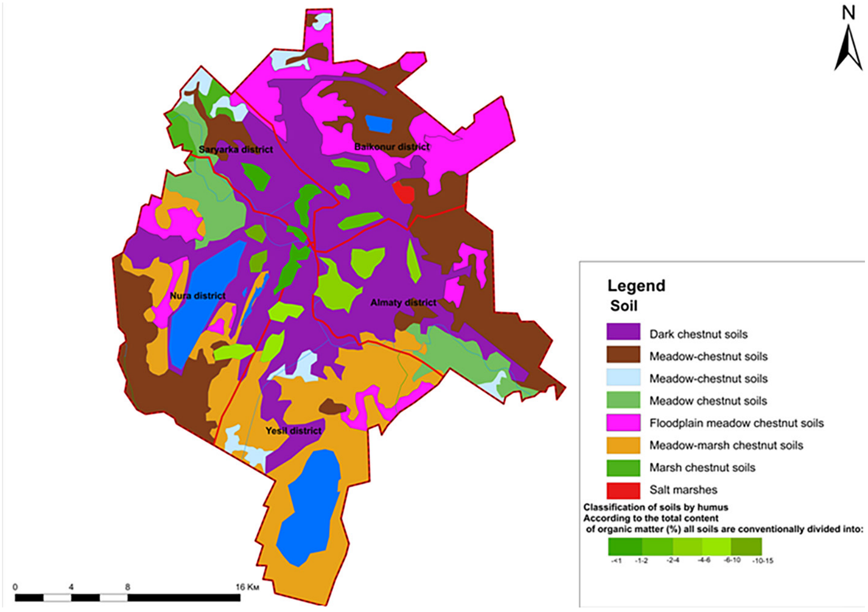

Figure 2. Agrochemical composition of soil

displayed spatial variability, with values ranging from 0.0031% to 0.0244% across different sampling locations. Further analysis of the aqueous extract composition revealed a predominance of sulfates among the anions, followed by chlorides (approximately 1.5 times lower) and bicarbonates (almost 3 times lower). This anion ratio suggests a chloride-sulfate type of salinization in urban soils, which is likely influenced by both natural factors and anthropogenic activities. Detailed district-wise average values for each soluble salt are presented in Table 6 and Figure 3.

Table 6. Salinity parameters (%)

Elements	Saryarka	Baikonur	Almaty	Yesil	Nura	Average
Ca^{2+}	0.011	0.01	0.009	0.015	0.01	0.011
Mg^{2+}	0.006	0.005	0.006	0.009	0.005	0.006
Cl^{-}	0.019	0.018	0.019	0.019	0.02	0.019
SO_4^{2-}	0.032	0.029	0.029	0.027	0.029	0.029
HCO^{3-}	0.012	0.011	0.013	0.012	0.011	0.011

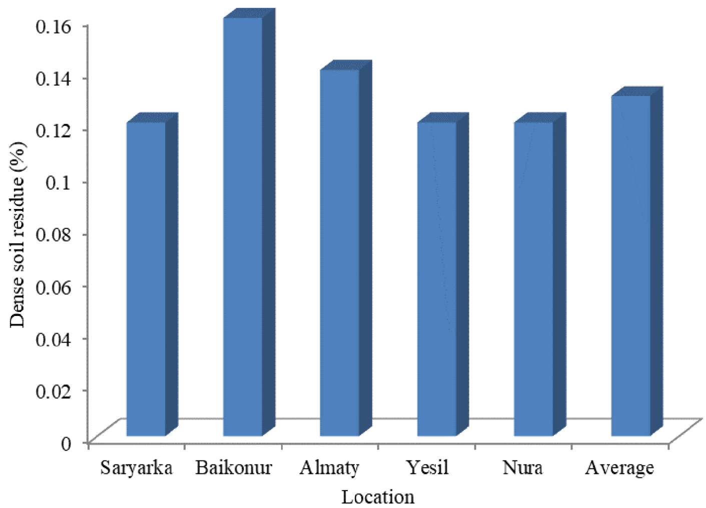

Figure 3. Indicator of dense soil residues

Dense soil residues

An essential indicator of soil salinity is the concentration of dense residues, which plays a pivotal role in assessing soil quality and its implications for agricultural and environmental practices. A thorough analysis of soil samples revealed variability in salinity levels across different urban areas. In a comprehensive study involving 60 soil samples, the concentration of dense residues ranged from 0.0923% to 0.2961%, with an average of 0.13%. These findings suggest that while the average dense residue content is well below the 0.3% threshold typically used to classify soil as saline, certain areas approach or slightly exceed 0.2%, indicating potential slight salinity. The distribution of these residues varies, with some locations exhibiting characteristics that could impact land use and soil management. Figure 3 illustrates the spatial distribution of dense residues and categorizes soil salinity levels, showing that most urban soils do not reach saline thresholds, but some localized areas may exhibit slight salinity. Understanding these salinity levels is crucial for urban planners and environmental managers. Although the majority of soils remain within non-saline ranges, the presence of slightly saline conditions in specific areas highlights the need for targeted management strategies. Addressing these localized salinity issues is essential to maintaining soil health and productivity, particularly in urban environments where land use and development pressures are significant (Figure 3).

Bulk density

The bulk density values across various land use categories show distinct differences, reflecting the varying degrees of human impact and soil management practices (Table 7). In residential areas, topsoil bulk density ranges from 1.24 to 1.32 g/cm³, and subsoil bulk density ranges from 1.41 to 1.54 g/cm³. These relatively lower bulk densities, particularly in the topsoil, suggest less soil compaction, likely due to the presence of gardens, lawns, and other permeable surfaces. The moderate compaction in the subsoil could be attributed to construction activities or foot traffic, which might compress deeper soil layers. Commercial zones exhibit higher bulk densities, with topsoil values ranging from 1.41 to 1.55 g/cm³ and subsoil densities from 1.52 to 1.65 g/cm³. These higher values indicate significant soil compaction, often a result of impervious surfaces, such as concrete and asphalt that dominate commercial areas. Foot traffic, vehicle movement, and limited vegetation likely contribute to the higher compaction levels. The higher bulk density in both topsoil and subsoil can negatively affect water infiltration, root growth, and overall soil health in these zones. In industrial areas, bulk density values are the highest, with topsoil densities ranging from 1.55 to 1.62 g/cm³ and subsoil densities from 1.63 to 1.76 g/cm³. The elevated bulk densities reflect heavy machinery use, construction activities, and minimal vegetation cover, leading to significant soil compaction. The highly compacted soils in industrial areas can hinder plant growth, reduce soil aeration, and limit water retention, which may exacerbate surface runoff and erosion. Such conditions require targeted soil management strategies, including soil remediation and vegetation cover to reduce compaction. Agricultural and forested areas demonstrate lower bulk densities compared to commercial and industrial zones. Agricultural land, with topsoil densities ranging from 1.30 to 1.42 g/cm³ and subsoil densities from 1.52 to 1.66 g/cm³, reflects moderate compaction due to tillage and farming practices. Forested areas, serving as a control, have the lowest bulk densities, with topsoil values between 1.20 and 1.30 g/cm³ and subsoil values between 1.34 and 1.45 g/cm³. These results highlight the minimal disturbance in forest soils and the beneficial effects of organic matter accumulation, which helps maintain soil structure and porosity, supporting healthy ecosystems. The variations across land use types underscore the need for tailored soil management practices to maintain soil health in urban and industrial environments.

Table 7. Bulk density results

Land use category	Topsoil bulk density (g/cm³)	Subsoil bulk density (g/cm³)
Residential	1.24–1.32	1.41–1.54
Commercial	1.41–1.55	1.52–1.65
Industrial	1.55–1.62	1.63–1.76
Agricultural	1.30–1.42	1.52–1.66
Forest	1.20–1.30	1.34–1.45

Soil chemical properties

Elemental concentrations

The nitrate nitrogen ($N-NO_3$) concentrations in the soil range from 13.1 to 17.2 mg/kg, with an average value of 15.3 mg/kg. These levels are considered moderate, which is important for promoting plant growth and maintaining soil fertility. Nitrate is a key nutrient for plants, particularly in urban and agricultural areas, as it is readily available for uptake. However, excessive nitrogen can lead to environmental issues, such as leaching into groundwater, emphasizing the need for careful nutrient management to balance crop productivity and environmental health. Available phosphorus (P_2O_5) concentrations vary between 12.2 and 19.4 mg/kg, with an average of 14.7 mg/kg. This variability suggests differing levels of nutrient enrichment across land use categories, potentially influenced by fertilizer applications or natural soil fertility. Higher phosphorus levels are beneficial for plant growth, but excessive amounts can lead to eutrophication in water bodies due to runoff. Phosphorus availability is also critical for root development and energy transfer within plants, making it an essential element for productive soils in both urban and agricultural settings. Potassium (K) and sulfur (S) levels show consistency, with potassium ranging from 87.5 to 95.2 mg/kg and sulfur between 20.0 and 25.0 mg/kg. Potassium is crucial for plant metabolism, aiding in water regulation and enzyme activation, while sulfur supports protein synthesis and overall plant health. The relatively stable potassium values reflect its importance in maintaining soil structure and fertility. The role of sulfur in protein and enzyme formation highlights its necessity, with its concentration potentially influenced by soil management practices, including the use of fertilizers and organic matter amendments. The moderate variations in these elemental concentrations underscore the importance of balanced nutrient management for sustaining soil productivity and environmental health (Table 8).

Humus content and pH

The humus content across different districts varies significantly, ranging from 21.2 to 44.5 g/kg, with an average of 32.8 g/kg. Humus, which is the organic component of soil formed by the decomposition of plant and animal material, plays a crucial role in soil fertility. Higher humus levels indicate richer organic matter, which enhances soil structure, water retention, and nutrient availability. This variability may be influenced by factors such as land use, vegetation cover, and organic input in the districts. Soils with higher humus content generally support better plant growth due to improved nutrient cycling. The soil pH values across the districts range from 5.4 to 7.6, with an average of 6.2, indicating conditions from slightly acidic to neutral. Soil pH is a key factor affecting nutrient availability, microbial activity, and overall soil health. Slightly acidic soils (pH 5.4–6.0) may limit the availability of certain nutrients like phosphorus, but can enhance the uptake of micronutrients, such as iron and manganese. On the other hand, near-neutral pH levels (6.0– 7.6) are ideal for most plant species, allowing for optimal nutrient availability and microbial activity, which promotes healthy plant growth and soil function. The observed variations in both humus content and pH reflect the influence of different environmental conditions, land management practices, and anthropogenic factors in the districts. The areas with higher humus content and balanced pH levels are likely to exhibit greater soil fertility and agricultural potential. Meanwhile, the regions with lower humus or extreme pH values may require soil amendments or management practices to improve soil quality and productivity, emphasizing the importance of monitoring and adjusting these parameters for sustainable land use (Table 9).

Table 8. Summary of the elemental concentrations

Parameter	Value range	Average value	Observations
Nitrate nitrogen ($N-NO_3$)	13.1–17.2 mg/kg	15.3 mg/kg	Nitrate levels are generally moderate, influencing plant growth and soil fertility
Available phosphorus (P_2O_5)	12.2–19.4 mg/kg	14.7 mg/kg	Phosphorus levels vary; higher concentrations may indicate nutrient enrichment
Potassium (K)	87.5–95.2 mg/kg	91.2 mg/kg	Potassium is fairly consistent, essential for plant metabolism and soil health
Sulfur (S)	20.0–25.0 mg/kg	22.5 mg/kg	Sulfur levels support protein synthesis; variability may reflect soil management practices

Table 9. Humus content and pH values across different districts

Parameter	Value range	Average value	Observations
Humus content (g/kg)	21.2–44.5 g/kg	32.8 g/kg	Humus content varies; higher levels indicate richer organic matter and potentially better soil fertility
Soil pH	5.4–7.6	6.2	pH levels vary from slightly acidic to neutral; affects nutrient availability and microbial activity

Soluble salts

The concentration of calcium (Ca^{2+}) in the soils ranges from 2.2 to 6.8 mg/L, with an average of 4.2 mg/L, reflecting moderate levels across different districts. Calcium is a vital component in maintaining soil structure, helping to improve soil aggregation and reducing compaction. Its presence also promotes root growth and is crucial for plant cell wall development. The moderate calcium concentrations suggest that the soils are generally supportive of good plant health, though some areas may require supplementation for the crops that have higher calcium demands. Magnesium (Mg^{2+}) concentrations, which range from 1.5 to 4.6 mg/L, average at 3.4 mg/L, indicate typical levels for plant nutrition. Magnesium is essential for chlorophyll production and plays a key role in photosynthesis. The observed range suggests that the soils can generally meet plant nutritional requirements, although the lower end of the range may require additional magnesium input, particularly for high-demand crops. Maintaining proper magnesium levels is critical for ensuring optimal plant growth and metabolic functioning. The concentrations of chloride (Cl^-) show significant variability, ranging from 11.2 to 52.2 mg/L, with an average of 31.3 mg/L. Elevated chloride levels could be attributed to sources such as de-icing salts or industrial activities. High chloride concentrations can be detrimental to plant health, as excessive chloride can lead to toxicity, especially in sensitive species. Sulfate (SO_4^{2-}) levels, ranging from 5.4 to 20.2 mg/L with an average of 12.4 mg/L, are moderate and influence soil as well as and nutrient availability. Bicarbonate (HCO_3^-) levels, averaging 11.4 mg/L, are typical and influence both soil pH and calcium availability, playing a role in buffering soil acidity and ensuring nutrient stability (Table 10).

Heavy metal concentrations

The concentrations of heavy metals in the soils vary across different land use areas, with notable differences between topsoil and subsoil. The lead (Pb) concentrations in the topsoil range from 11.1 to 52.3 mg/kg, with an average of 32.2 mg/kg, while subsoil levels range from 8.2 to 45.4 mg/kg, averaging 25.2 mg/kg. These levels are concerning, as lead can have harmful effects on both human health and the environment, especially in the areas with higher concentrations. The slightly lower levels in the subsoil suggest that lead contamination is primarily surface-based, likely from anthropogenic activities, such as vehicle emissions and industrial waste. Cadmium (Cd) concentrations are comparatively lower, ranging from 0.5 to 2.3 mg/kg in the topsoil and 0.4 to 2.2 mg/kg in the subsoil, with average values of 1.5 mg/kg and 1.2 mg/kg, respectively. Despite the lower concentrations, cadmium is a highly toxic metal, and even small amounts can pose serious risks to plant and human health. The consistent distribution between topsoil and subsoil indicates potential leaching or uniform contamination sources, possibly related to fertilizers or industrial pollution. Chromium (Cr) and nickel (Ni)

Table 10. The average concentrations of soluble salts

Soluble salt	Concentration range	Average concentration	Observations
Calcium (Ca^{2+})	2.2–6.8 mg/L	4.2 mg/L	Calcium levels are generally moderate; affects soil structure and plant health
Magnesium (Mg^{2+})	1.5–4.6 mg/L	3.4 mg/L	Magnesium concentrations are within typical ranges; essential for plant nutrition
Chloride (Cl^-)	11.2–52.2 mg/L	31.3 mg/L	Chloride levels vary; elevated concentrations may indicate sources such as de-icing salts.
Sulfate (SO_4^{2-})	5.4–20.2 mg/L	12.4 mg/L	Sulfate levels are moderate; impacts soil pH and nutrient availability
Bicarbonate (HCO_3^-)	5.2–16.9 mg/L	11.4 mg/L	Bicarbonate concentrations are typical; affects soil pH and calcium availability

concentrations show significant variability. Chromium ranges from 19.9 to 100.1 mg/kg in the topsoil (average: 61.4 mg/kg) and 15.1 to 90.0 mg/kg in the subsoil (average: 53.5 mg/kg). Nickel ranges from 15.2 to 75.4 mg/kg in the topsoil and 9.6 to 71.3 mg/kg in the subsoil, with average concentrations of 45.5 mg/kg and 43.4 mg/kg, respectively. Both metals are essential in trace amounts, but become harmful at elevated levels. The data suggests that these metals, especially chromium, may originate from industrial activities, such as metal processing or wastewater discharge. Their presence in both topsoil and subsoil indicates possible long-term contamination and potential mobility through the soil profile (Table 11).

Microclimate and soil properties

The microclimate data from different land use categories reveal distinct variations in air temperature, relative humidity, and wind speed, which are likely influenced by human activities and land use patterns. Urban parks exhibit the coolest average air temperature at 18 °C, with minimum and maximum temperatures of 10 °C and 25 °C, respectively. This cooling effect is likely due to the presence of vegetation and green spaces, which help moderate temperatures through shading and evapotranspiration. Additionally, urban parks have the highest relative humidity at 60%, reflecting the moisture retention capacity of green areas. In contrast, commercial and industrial zones demonstrate the highest average and maximum air temperatures, with industrial areas reaching an average of 21 °C and a maximum of 30 °C. These zones are characterized by extensive hard surfaces, such as concrete and asphalt, which absorb and radiate heat, contributing to the urban heat island effect. Industrial areas, in particular, exhibit the highest wind speed (3.5 m/s), which could be attributed to open layouts and fewer windbreaks like trees or buildings. However, the lower relative humidity (45% in industrial areas and 50% in commercial zones) suggests that these areas experience drier conditions, likely due to limited vegetation. Surface temperature data further emphasize the impact of land use on microclimate conditions. Industrial areas have the highest average surface temperature at 28 °C, followed by commercial zones at 26 °C and residential areas at 24 °C. Urban parks, with an average surface temperature of 22 °C, maintain cooler surface conditions, reinforcing the role of green spaces in mitigating urban heat. The variations in microclimate and soil properties across these land use categories underline the importance of urban planning that incorporates green infrastructure to improve thermal comfort and reduce the adverse effects of heat in densely built environments (Table 12).

Bioremediation potential assessment

The assessment of bioremediation potential reveals critical insights into the factors influencing the effectiveness of soil in remediating contaminants. The methodology focused on evaluating soil samples based on organic matter content and the

Table 11. Heavy metal concentrations

Heavy metal	Concentration range (Topsoil)	Concentration range (Subsoil)	Average concentration (Topsoil)	Average concentration (Subsoil)
Lead (Pb)	11.1–52.3 mg/kg	8.2–45.4 mg/kg	32.2 mg/kg	25.2 mg/kg
Cadmium (Cd)	0.5–2.3 mg/kg	0.4–2.2 mg/kg	1.5 mg/kg	1.2 mg/kg
Chromium (Cr)	19.9–100.1 mg/kg	15.1–90.0 mg/kg	61.4 mg/kg	53.5 mg/kg
Nickel (Ni)	15.2–75.4 mg/kg	9.6–71.3 mg/kg	45.5 mg/kg	43.4 mg/kg

Table 12. Microclimate and soil properties

Land use category	Average air temperature (°C)	Minimum air temperature (°C)	Maximum air temperature (°C)	Average relative humidity (%)	Average wind speed (m/s)	Average surface temperature (°C)
Urban parks	18	10	25	60	2.5	22
Commercial zones	20	12	28	50	3	26
Residential areas	19	11	27	55	2.8	24
Industrial areas	21	13	30	45	3.5	28

presence of pollutants. Results indicated that the soils with higher organic matter content were more suitable for bioremediation, highlighting the essential role that organic materials play in enhancing soil health and its ability to support microbial life. Organic matter content serves as a key indicator of bioremediation potential. The soils with 6% to 9% organic matter were identified as suitable for effective bioremediation, exhibiting enhanced capacity to break down contaminants. In contrast, the soils with lower organic matter levels (1% to 3%) demonstrated reduced potential for remediation. This relationship underscores the importance of maintaining and improving organic matter in soils to promote effective bioremediation processes. Microbial activity further emphasizes the connection between organic matter and bioremediation effectiveness. High microbial populations (between 10^6 to 10^7 CFU/g) were observed in the soils with more than 5% organic matter, facilitating greater contaminant degradation. The assessment measured contaminant reduction, showing that the soils with higher organic matter achieved reductions of 81% to 92%, while those with lower organic matter only managed 24% to 33%. Despite the promising findings, challenges remain, particularly in the soils with low organic matter and high contaminant levels, which can hinder bioremediation success. Addressing these challenges is crucial for optimizing bioremediation strategies and improving soil health (Table 13).

Statistical analysis

The statistical analysis of soil properties reveals significant differences across various land use categories, highlighting the impact of urbanization and land management practices. For bulk density, an ANOVA test indicated a significant difference between residential and industrial areas, with residential soils averaging 1.2 g/cm³ compared to 1.6 g/cm³ in industrial zones. This higher density in industrial areas suggests increased soil compaction, which can adversely affect water infiltration, root growth, and overall soil health. Further analysis of heavy metal concentrations using t-tests showed marked differences between industrial and non-industrial areas. Specifically, lead concentrations were found to be significantly higher in industrial areas, averaging 302 mg/kg, compared to 155 mg/kg in non-industrial areas. This disparity indicates the potential for contamination related to industrial activities, raising concerns about soil and environmental quality, as elevated heavy metal levels can have detrimental effects on plant and animal health. Nutrient levels also exhibited significant variations, as revealed by an ANOVA test comparing agricultural and non-agricultural lands. Phosphorus levels were notably higher in agricultural areas, averaging 54 mg/kg, while non-agricultural areas averaged only 23 mg/kg. This increase is likely attributable to the application of fertilizers in agricultural practices, which enhances soil fertility, but also necessitates careful management to prevent nutrient runoff and potential environmental issues. Overall, these findings underscore the importance of tailored land management strategies to address the specific conditions and challenges posed by different land use types (Table 14).

DISCUSSION

Nitrate nitrogen ($N\text{-}NO_3$) concentrations, averaging 8.15 mg/kg, indicate generally moderate

Table 13. Bioremediation potential assessment

Assessment aspect	Details	Typical findings	Results
Methodology	Evaluation of soil samples for bioremediation capacity	Organic matter content and contaminants	Soil samples with higher organic matter content were found more suitable for bioremediation
Organic matter content	Measures the potential for bioremediation	High: 6–9% (suitable); Low: 1–3%	Areas with 6–9% organic matter showed enhanced bioremediation potential
Microbial activity	Indicator of bioremediation effectiveness	High: 106 to 107 CFU/g; Low: 104 CFU/g	High microbial activity was observed in soils with > 5% organic matter
Contaminant degradation	Measurement of contaminant reduction	High: 81–92% reduction; Low: 24–33%	Soils with higher organic matter showed 81–92% reduction in contaminants, while low organic matter soils showed only 24–33%
Potential benefits	Improvement in soil health and reduction of contamination	Increased fertility and reduced pollution	Enhanced soil fertility and reduced pollutant levels in high organic matter soils
Challenges	Factors affecting bioremediation success	Low organic matter, high contaminant levels	Challenges included less effective bioremediation in low organic matter soils and high contamination areas

Table 14. Summary of the statistical analysis results

Soil property	Statistical test	Significant differences	Typical values	Implications
Bulk density (g/cm^3)	ANOVA	Residential vs. industrial areas	Residential: 1.2; Industrial: 1.6	Higher density in industrial areas indicates compaction
Heavy metal concentrations	t-tests	Industrial vs. non-industrial areas	Pb: Industrial: 302 mg/kg; Non-Industrial: 155 mg/kg	Higher metal concentrations in industrial areas
Nutrient levels	ANOVA	Agricultural vs. non-agricultural	P_2O_5: Agricultural: 54 mg/kg; Non-Agricultural: 23 mg/kg	Higher phosphorus in agricultural areas due to fertilizers

levels for plant growth. Similar average nitrate levels (7.8 mg/kg) were reported by Bai et al. [15] in urban soils of Shizuishan, suggesting comparable nitrogen availability in both cities. However, the observed spatial variation in the case study highlights the need for site-specific management strategies to address potential nutrient deficiencies in certain areas. Available phosphorus (P_2O_5) concentrations, averaging 20.97 mg/kg, are generally sufficient for plant growth. These findings are consistent with those of Qin et al. [16], who reported that the soils in urban areas exhibited significantly higher total phosphorus content compared to the soils in suburban and rural regions ($p < 0.001$). However, the higher phosphorus levels in some parts of the case study, likely attributed to agricultural runoff, warrant attention to mitigate potential risks of phosphorus leaching and water pollution.

Potassium (K) levels, averaging 374.75 mg/kg, are relatively high, indicating sufficient availability for plant growth. This finding aligns with the observations by Li et al. [17], who reported similar potassium levels in urban soils of Weifang City, East China. The consistent potassium levels across different parts of the case study suggest less spatial variability compared to phosphorus and nitrogen. Humus content, averaging 3.058%, indicates generally good organic matter levels. This finding is comparable to the average humus content reported by Du et al. [18], in urban green spaces of Guangzhou City, suggesting similar levels of organic matter accumulation. The relatively consistent humus content across different parts of the case study highlights the role of vegetation in maintaining soil organic matter. Soil pH values, ranging from 6.73 to 6.96, are slightly acidic to neutral, generally favorable for plant growth. These pH ranges are consistent with those reported by Chai et al. [19], in urban soils of Lanzhou, China, indicating similar potential impacts. The slightly acidic to neutral pH facilitates nutrient availability for plants and supports healthy microbial activity.

The study identified spatial variability in soluble salt concentrations, indicating potential salinity issues in some areas. The chloride-sulfate type of salinization observed in the case study is consistent with the findings by Zhao et al. (2019) who reported similar salinity patterns in urban soils of Xi'an, attributed to both natural and anthropogenic factors. The elevated chloride levels in parts of the case study, likely due to de-icing salts, highlight the need for alternative winter maintenance practices to minimize salt accumulation in urban soils.

Dense residue concentrations, averaging 0.13%, are generally below the saline threshold (0.3%). However, certain areas approaching 0.2% warrant attention. This finding aligns with the observations by Peng et al. [20], who reported similar dense residue levels in the urban soils of Beijing, emphasizing the need for monitoring and managing potential salinity risks.

The study revealed variations in bulk density across different land use categories. The lower bulk densities in residential areas compared to commercial and industrial areas are consistent with the findings by Zhou et al. [21], who reported similar patterns in Shanghai. This difference is attributed to varying levels of compaction due to human activities. The higher bulk densities in commercial and industrial areas, resulting from increased traffic and construction, can negatively impact soil aeration and water infiltration, hindering plant growth.

The study identified elevated heavy metal concentrations in industrial areas, exceeding environmental quality standards. This finding is consistent with the observations by Su et al. [22], who reported similar heavy metal accumulation patterns in industrial areas of South China. The higher concentrations of lead, cadmium, chromium, and nickel in industrial areas pose potential risks to human and ecological health, highlighting the need for remediation measures and stricter industrial regulations.

The microclimate analysis revealed variations in temperature and humidity across different land use categories. The lower surface temperatures in urban parks compared to commercial zones are consistent with the urban heat island effect, as reported by Oke [23]. The correlations between microclimate variables and soil properties, such as the effect of surface temperature on soil moisture, highlight the influence of microclimatic variations on soil conditions.

The bioremediation potential assessment indicated that the areas with higher organic matter content are more suitable for bioremediation. This finding is consistent with the well-established role of organic matter in supporting microbial activity, which is crucial for bioremediation processes [24]. The study highlights the potential of bioremediation for soil remediation, particularly in the areas with higher organic matter content. However, challenges such as low organic matter levels and high contaminant concentrations in certain areas need to be addressed. This study provides a comprehensive assessment of soil characteristics, highlighting their spatial variability and influencing factors. The findings emphasize the detrimental impacts of urbanization on soil quality, particularly in terms of compaction, heavy metal contamination, and nutrient depletion. The study underscores the importance of sustainable urban planning and management practices, such as promoting green infrastructure, minimizing soil sealing, and implementing bioremediation strategies, to mitigate the negative impacts of urbanization and preserve soil health in urban areas.

The variability in soil characteristics observed across Astana's urban landscape underscores the importance of integrating detailed soil assessments into urban planning processes. By regularly evaluating soil properties before and after construction or development activities, city planners can ensure that soil health is maintained and that interventions are tailored to the specific needs of each land use type. For instance, in the areas undergoing rapid urbanization, regular soil health monitoring could help identify the early signs of degradation, prompting timely remediation efforts. Moreover, adopting best practices in sustainable land management–such as promoting green infrastructure, reducing impermeable surfaces, and utilizing soil amendments–can help preserve soil functionality and enhance ecosystem services, even in densely populated urban areas. The insights gained from this research are not only relevant to Astana but also offer a framework for other rapidly growing cities worldwide. Urbanization is a global phenomenon, and the challenges faced by Astana–such as soil compaction, nutrient imbalances, and contamination–are common to many other cities. By tailoring management strategies to the specific conditions of each urban environment, cities can better support plant health, improve soil functionality, and ensure sustainable urban growth. This approach has the potential to enhance urban resilience, improve air quality, and promote biodiversity in rapidly expanding metropolitan areas.

CONCLUSIONS

This study provided a comprehensive assessment of the effects of urbanization on soil health and nutrient dynamics across various land use types, including residential, commercial, industrial, and green spaces. The findings revealed significant spatial variability in the physical and chemical properties of soil, driven by differences in urban development intensity. Residential areas exhibited lower bulk densities and better soil conditions, while commercial zones showed elevated compaction due to foot traffic and impermeable surfaces. Industrial areas experienced the highest levels of soil compaction, reflecting the impacts of heavy machinery and construction activities. In contrast, forested areas, serving as control sites, demonstrated minimal disturbance, offering valuable baseline data for urban soil health comparison. Although urban soils generally supported plant growth, localized challenges—such as increased salinity, nutrient imbalances, and heavy metal contamination in industrial zones—were identified as potential threats to soil functionality and ecosystem services. These issues highlight the need for tailored soil management strategies. For example, mitigating soil compaction in commercial and industrial zones could involve the use of permeable pavements and deep tilling, while addressing heavy metal contamination may require phytoremediation and soil amendments. Moreover, managing salinity and nutrient imbalances in the affected areas can be achieved through improved drainage systems and localized fertilization practices. The spatial variability observed in soil characteristics underscores the importance of integrating detailed soil assessments into urban planning to guide sustainable development. By adapting management practices to specific land uses and addressing localized soil challenges, cities can enhance urban soil health, support plant growth, and promote ecosystem resilience. These insights not only inform urban soil management in Astana but also provide a valuable framework for rapidly growing cities worldwide to ensure sustainable urban growth while maintaining critical ecosystem services.

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REFERENCES

1. Ruas R. de B., Costa L.M.S., Bered F. 2022. Urbanization driving changes in plant species and communities – A global view, Glob. Ecol. Conserv. 38, e02243. https://doi.org/10.1016/j.gecco.2022.e02243
2. Gebre T., Gebremedhin B. 2019. The mutual benefits of promoting rural-urban interdependence through linked ecosystem services, Glob. Ecol. Conserv. 20, e00707. https://doi.org/10.1016/j.gecco.2019.e00707
3. Zhou Y., Smith S.J., Zhao K., Imhoff M., Thomson A., Bond-Lamberty B., Asrar G.R., Zhang X., He C., Elvidge C.D. 2015. A global map of urban extent from nightlights, Environ. Res. Lett. 10054011. https://doi.org/10.1088/1748-9326/10/5/054011
4. Seto K.C., Güneralp B., Hutyra L.R. 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools, Proc. Natl. Acad. Sci. U. S. A. https://doi.org/10.1073/pnas.1211658109
5. Tang J., Liu D., Shang C., Niu J. 2024. Impacts of land use change on surface infiltration capacity and urban flood risk in a representative karst mountain city over the last two decades, J. Clean. Prod. 454, 142196. https://doi.org/10.1016/j.jclepro.2024.142196
6. Mathew A., Khandelwal S., Kaul N. 2016. Spatial and temporal variations of urban heat island effect and the effect of percentage impervious surface area and elevation on land surface temperature: Study of Chandigarh city, India, Sustain. Cities Soc. https://doi.org/10.1016/j.scs.2016.06.018.
7. Zhang F., Zhong J., Zhao Y., Cai C., Liu W., Wang Q., Wang W., Wang H., Jiang X., Yuan R. 2024. Urbanization-induced soil organic carbon loss and microbial-enzymatic drivers: insights from aggregate size classes in Nanchang city, China, Front. Microbiol. https://doi.org/10.3389/fmicb.2024.1367725
8. Yang J.L., Zhang G.L. 2015. Formation, characteristics and eco-environmental implications of urban soils – A review, Soil Sci. Plant Nutr. https://doi.org/10.1080/00380768.2015.1035622
9. Zhang J., Peng W., Lin M., Liu C., Chen S., Wang X., Gui H. 2023. Environmental geochemical baseline determination and pollution assessment of heavy metals in farmland soil of typical coal-based cities: A case study of Suzhou City in Anhui Province, China, Heliyon. https://doi.org/10.1016/j.heliyon.2023.e14841
10. Sajjad M., Huang Q., Khan S., Khan M.A., Liu Y., Wang J., Lian F., Wang Q., Guo G. 2022. Microplastics in the soil environment: A critical review, Environ. Technol. Innov. 27, 102408. https://doi.org/10.1016/j.eti.2022.102408
11. Chuma G.B., Mondo J.M., Ndeko A.B., Bagula E.M., Lucungu P.B., Bora F.S., Karume K., Mushagalusa G.N., Schmitz S., Bielders C.L. 2022. Farmers' knowledge and practices of soil conservation techniques in smallholder farming systems of Northern Kabare, East of D.R. Congo, Environ. Challenges. 7, 100516. https://doi.org/10.1016/j.envc.2022.100516
12. Mwanake H., Mehdi-Schulz B., Schulz K., Kitaka N., Olang L.O., Lederer J., Herrnegger M. 2023. Agricultural practices and soil and water conservation in the transboundary region of Kenya and Uganda: Farmers' perspectives of current soil erosion, Agric. https://doi.org/10.3390/agriculture13071434
13. Braito M., Leonhardt H., Penker M., Schauppenlehner-Kloyber E., Thaler G., Flint C.G. 2020. The plurality of farmers' views on soil management calls for a policy mix, Land Use Policy. 99, 104876. https://doi.org/10.1016/j.landusepol.2020.104876
14. Padhye L.P., Srivastava P., Jasemizad T., Bolan S., Hou D., Shaheen S.M., Rinklebe J., O'Connor D., Lamb D., Wang H., Siddique K.H.M., Bolan N. 2023 Contaminant containment for sustainable remediation of persistent contaminants in soil and groundwater, J. Hazard. Mater. 455, 131575. https://doi.org/10.1016/j.jhazmat.2023.131575
15. Bai Y., Zhang Y., Liu X., Wang Y. 2023. The spatial distribution and source apportionment of heavy metals in soil of Shizuishan, China, Environ. Earth Sci. 82, 494. https://doi.org/10.1007/s12665-023-11192-8
16. Qin G., Wu J., Zheng X., Zhou R., Wei Z. 2019. Phosphorus forms and associated properties along an urban–rural gradient in Southern China, Water. 11, 2504. https://doi.org/10.3390/w11122504
17. Li Y., Xu Z., Ren H., Wang D., Wang J., Wu Z., Cai P. 2022. Spatial distribution and source apportionment of heavy metals in the topsoil of Weifang

City, East China, Front. Environ. Sci. https://doi.org/10.3389/fenvs.2022.893938

18. Du J., Yu M., Cong Y., Lv H., Yuan Z. 2022. Soil organic carbon storage in urban green space and its influencing factors: A case study of the 0–20 cm soil layer in Guangzhou City, Land. 11, 1484. https://doi.org/10.3390/land11091484
19. Chai L., Wang Y., Wang X., Ma L., Cheng Z., Su L. 2021. Pollution characteristics, spatial distributions, and source apportionment of heavy metals in cultivated soil in Lanzhou, China, Ecol. Indic. 125, 107507. https://doi.org/10.1016/j.ecolind.2021.107507
20. Peng C., Chen W., Liao X., Wang M., Ouyang Z., Jiao W., Bai Y. 2011. Polycyclic aromatic hydrocarbons in urban soils of Beijing: Status, sources, distribution and potential risk, Environ. Pollut. 159, 802–808. https://doi.org/10.1016/j.envpol.2010.11.003
21. Zhou J., Gao P., Wu C., Mu X. 2023. Analysis of land use change characteristics and its driving forces in the loess plateau: A case study in the Yan River Basin, Land. https://doi.org/10.3390/land12091653
22. Su C., Meng J., Zhou Y., Bi R., Chen Z., Diao J., Huang Z., Kan Z., Wang T. 2022. Heavy metals in soils from intense industrial areas in South China: Spatial distribution, source apportionment, and risk assessment, front. Environ. Sci. https://doi.org/10.3389/fenvs.2022.820536
23. Oke T.R. 1982. The energetic basis of the urban heat island, Q. J. R. Meteorol. Soc. https://doi.org/10.1002/qj.49710845502
24. Park J.H., Lamb D., Paneerselvam P., Choppala G., Bolan N., Chung J.-W. 2011. Role of organic amendments on enhanced bioremediation of heavy metal(loid) contaminated soils, J. Hazard. Mater. 185, 549–574. https://doi.org/10.1016/j.jhazmat.2010.09.082