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The Influence Of Anthropogenic Factors On The Agrochemical Properties And Fertility Levels Of Soils In Tashkent City And Region

Mukaddam Toshmukhamedova Bakhodir kizi
Tashkent, Uzbekistan
National University of Uzbekistan
Faculty of Biology and Ecology, Ecology Program

Abstract

The soils of the Tashkent region, primarily Serozems, constitute a critical natural resource for Uzbekistan's food security and ecological stability. However, this region simultaneously represents the nation's largest urban agglomeration and a historically intensive agricultural oasis, subjecting its soil cover to immense and conflicting anthropogenic pressures. This study provides a comprehensive assessment of the impacts of urbanization, intensive irrigated agriculture, and industrial activities on the key agrochemical properties and overall fertility of these soils. A stratified sampling methodology was employed, collecting topsoil samples (0-30 cm) from distinct land-use zones: urban (parks, residential), peri-urban (industrial proximity, small-scale farming), and rural (intensive agriculture). Samples were analyzed for core fertility indicators (humus, N, P, K), fundamental properties (pH, electrical conductivity - EC), and heavy metal contaminants (Pb, Zn, Cu, Cd). The results reveal two primary degradation trajectories. Rural agricultural soils exhibit significant fertility decline, characterized by humus depletion (averaging 1.1%) and pronounced secondary salinization (mean EC > 3.0 dS/m), driven by long-term monoculture and inefficient irrigation. Conversely, urban and peri-urban soils demonstrate severe technogenic contamination, with concentrations of Pb (up to 75.8 mg/kg) and Zn (up to 180.4 mg/kg) significantly exceeding background levels, primarily due to transport and industrial emissions. This research quantifies the divergent degradation pathways and underscores the urgent necessity for differentiated land management strategies to mitigate soil degradation, ensure food safety, and preserve the ecological functions of the soil cover in this vital region.

Keywords: Soil Fertility, Anthropogenic Impact, Agrochemical Properties, Serozems, Tashkent Region, Urban Soils, Salinization, Heavy Metal Contamination

1. Introduction

Soil, the unconsolidated mineral and organic layer of the Earth's crust, serves as the fundamental substrate for terrestrial life, underpinning global food production, regulating hydrological cycles, and acting as the planet's largest terrestrial carbon sink [1]. The sustainable management of this finite and non-renewable resource is, therefore, inextricably linked to human well-being and the achievement of global sustainable development goals, particularly those concerning zero hunger and ecosystem health [2]. However, across the globe, soil resources are facing unprecedented threats from a burgeoning human population, rapid urbanization, and the intensification of agricultural systems. Anthropogenic activities are accelerating soil degradation processes such as erosion, salinization, nutrient depletion, and chemical pollution at rates that far outpace natural soil formation, compromising long-term productivity and ecological resilience [3]. This global challenge is particularly acute in arid and semi-arid regions, where fragile ecosystems are highly susceptible to anthropogenic disturbance and climatic variability.

Central Asia, and specifically Uzbekistan, epitomizes this challenge. The region is characterized by an arid continental climate, where precipitation is scarce, and agricultural productivity is almost entirely dependent on extensive irrigation systems sourced from transboundary rivers [4]. This reliance has historically transformed vast desert landscapes into productive agricultural oases, but it has also created profound ecological vulnerabilities, most notably manifested in the Aral Sea desiccation crisis, a stark reminder of the consequences of large-scale, unsustainable anthropogenic intervention in water and land systems [5]. Within this context, the Tashkent region occupies a unique and critical position. It functions as the political, economic, and demographic heart of Uzbekistan, hosting the sprawling Tashkent metropolis, the largest city in Central Asia. Simultaneously, the surrounding Tashkent province, situated within the fertile Chirchiq-Ahangaran basin, is one of the nation's most important agricultural zones, historically responsible for a significant portion of its cotton, wheat, fruit, and vegetable production [6].

This juxtaposition of intense urbanization and intensive agriculture creates a complex nexus of competing pressures on a finite soil resource base. The soils of this region, predominantly classified as Serozems (gray desert soils) and their irrigated variants (Agro-irrigated soils), are naturally characterized by low organic matter content, high carbonate levels, and a neutral-to-alkaline reaction [7]. While potentially fertile when managed and irrigated correctly, they are exceptionally vulnerable to degradation. The expansion of the Tashkent agglomeration directly consumes vast tracts of valuable agricultural land through soil sealing—the irreversible covering of land with impervious surfaces like concrete and asphalt, which destroys all soil functions [8]. Concurrently, the remaining agricultural lands are subjected to decades of intensive farming, often characterized by cotton and wheat monocultures, heavy reliance on mineral fertilizers, and, most critically, continuous furrow irrigation. This long-term irrigation, often practiced with inadequate drainage infrastructure, inevitably leads to a gradual rise in groundwater tables, triggering secondary salinization and waterlogging, which are the principal threats to soil fertility in arid regions [9, 10].

Furthermore, the Tashkent region is a major industrial hub, with significant metallurgical, chemical, and manufacturing centers located in cities such as Almalyk, Chirchiq, and Bekabad [11]. These industrial activities release a spectrum of pollutants, including heavy metals (e.g., copper, zinc, lead, cadmium) and acidic compounds, into the atmosphere, which are subsequently deposited onto surrounding soils, posing a direct threat to soil health, crop safety, and human well-being [12]. The combined and synergistic impacts of these multiple stressors—urban sprawl, agricultural intensification, salinization, and industrial pollution—create a complex degradation mosaic that is poorly understood in a holistic sense. While numerous studies have investigated isolated aspects, such as the salinization of specific irrigated plots [13] or heavy metal pollution near a particular industrial site [11], there is a discernible gap in the literature regarding a comprehensive, synchronous assessment of the agrochemical status of soils across the full urban-rural-industrial gradient of the Tashkent region. Understanding how these divergent anthropogenic factors (agricultural vs. urban) shape soil properties is critical for diagnosing the current state of soil health and formulating effective, targeted management policies.

Therefore, this research aims to provide a systematic evaluation of the influence of dominant anthropogenic factors on the key agrochemical properties and fertility levels of soils in Tashkent city and the surrounding region. The primary objectives are: (1) to characterize and compare the current status of essential soil fertility parameters (humus, nitrogen, phosphorus, potassium), pH, and electrical conductivity (salinity) in soils under urban, peri-urban, and intensive rural-agricultural land use; (2) to quantify the extent of heavy metal (Pb, Zn, Cu, Cd) contamination in these distinct zones; and (3) to analyze these data to determine the specific degradation pathways associated with different anthropogenic activities and their implications for sustainable soil management. This paper is structured according to the IMRAD format, beginning with a comprehensive review of the existing literature, followed by a description of the methodology, a detailed presentation and analysis of the results, a discussion of their implications, and concluding with a synthesis of the findings and recommendations for future action.

2. Literature Review

A comprehensive understanding of the current state of soils in the Tashkent region requires a thorough examination of the foundational pedological literature, coupled with a deep dive into decades of research on the specific anthropogenic pressures that have shaped this landscape. The literature review is structured to first establish the baseline characteristics of the region's soils, followed by a systematic analysis of the impacts of the primary anthropogenic drivers: long-term irrigation, intensive agricultural practices, urbanization, and industrial pollution.

2.1. Pedogenesis, Classification, and Baseline Characteristics of Serozems

The foundational soils of the Tashkent oasis, and indeed much of Central Asia's irrigated plains, belong to the Serozem soil group, a term first introduced into the Russian classification system to describe the typical soils of sub-boreal deserts and semi-deserts [7]. These soils have formed primarily on loess and loess-like loam deposits, which define the geology of the Chirchiq-Ahangaran basin [6]. The pedogenesis of Serozems is intrinsically linked to the arid continental climate, characterized by low annual precipitation (200-400 mm), high summer temperatures, and high potential evapotranspiration. Natural vegetation consists primarily of ephemeral and ephemeroid species, which have a short life cycle in the cool, moist spring, contributing a relatively small amount of organic matter to the soil annually [14]. Consequently, natural or "typical" Serozems are fundamentally characterized by a very low humus content in the upper horizon, often ranging from just 0.5% to 1.5%. This humus is, however, well-distributed through the profile. A second defining characteristic is the high carbonate content (calcareousness) throughout the soil profile, often with a distinct horizon of calcium carbonate accumulation. This buffering capacity results in a soil reaction that is consistently neutral to slightly alkaline, typically with a pH ranging from 7.5 to 8.5 [7, 15].

The classification of Serozems has been a subject of extensive study by Russian and Uzbek pedologists, including prominent figures like Gerasimov and Rozanov. They are often subdivided into 'light' (svetly), 'typical' (obyknovenny), and 'dark' (temny) Serozems based on elevation and associated moisture regimes, with the Tashkent oasis predominantly featuring typical and light Serozems [15]. From an agricultural perspective, these soils, despite their low organic matter, possess favorable physical properties due to their loessial parent material, including good water-holding capacity and aeration when not compacted. However, the most critical transformation of these soils began with the advent of large-scale irrigation, which has been practiced in this oasis for millennia but was dramatically intensified during the 20th century [4]. This has led to the formation of what are termed "Agro-irrigated soils" or "oasis-agricultural soils." These are essentially anthrosols, where human activity has been the dominant soil-forming factor, superseding natural pedogenesis. These soils are often characterized by a noticeable "aggradation horizon" or "cultural layer" resulting from the deposition of sediments from irrigation water and the deep plowing and amendment practices over centuries [13]. However, this anthropogenic transformation is not universally positive, as it introduces a new set of pedological processes, primarily driven by water, salt, and nutrient management, which form the core of the region's soil degradation problem [9].

2.2. The Impact of Long-Term Irrigation: Salinization and Hydromorphism

The single most dominant anthropogenic factor shaping soil properties in the agricultural landscapes of the Tashkent region is irrigation. While irrigation is the prerequisite for agriculture in this arid climate, its long-term application, especially without adequate management, initiates a cascade of detrimental processes [10]. The most pervasive and well-documented of these is secondary salinization. This process was extensively studied and modeled by V.A. Kovda, who established the fundamental principles of salt accumulation in irrigated arid lands [9]. Secondary salinization occurs when the application of irrigation water, which always contains some dissolved salts, coupled with insufficient natural or artificial drainage, causes the groundwater table to rise. In the Tashkent region, the groundwater table, which was naturally deep (10-20 meters), has risen in many areas to within 1-3 meters of the surface [13]. When this mineralized groundwater approaches the capillary fringe, the intense evaporative demand at the surface wicks the water upwards, where it evaporates, leaving the dissolved salts (chlorides, sulfates, and carbonates of sodium, magnesium, and calcium) to accumulate in the root zone and at the soil surface [10]. This process progressively increases the soil's electrical conductivity (EC), creating osmotic stress that hinders water uptake by plants, and at higher concentrations, causes direct ion toxicity, leading to crop yield failure [16].

Associated with the rising groundwater table is the problem of waterlogging, or hydromorphism. When soils are persistently saturated, oxygen diffusion is inhibited, leading to anaerobic or sub-oxic conditions [4]. This triggers reductive chemical processes, known as gleying, which are visible as mottled gray and reddish-brown patches in the soil profile. These anaerobic conditions are detrimental to the roots of most crops (excluding rice) and fundamentally alter the soil's biogeochemistry [17]. For example, nitrate (NO_3^-), the primary form of nitrogen available to plants, is rapidly converted by denitrifying bacteria into nitrogen gas (N_2) and nitrous oxide (N_2O), a potent greenhouse gas, resulting in a net loss of soil fertility [18]. Similarly, sulfate (SO_4^{2-}) can be reduced to toxic hydrogen sulfide (H_2S). Furthermore, the solubility and mobility of minerals like iron and manganese increase under reduced conditions, which can lead to toxicity issues. The physical structure of the soil also suffers; water-saturated loess soils lose their aggregation and are highly susceptible to compaction by agricultural machinery, further exacerbating poor drainage in a vicious cycle [19]. In some cases, high levels of sodium (Na^+) from irrigation water or groundwater can lead to sodification, where sodium ions displace calcium and magnesium on the soil's cation exchange complex. This deflocculates clay particles, destroying soil structure, sealing soil pores, and making the soil virtually impermeable to water and air [9, 16].

2.3. Agricultural Intensification: Nutrient Depletion and Compaction

While irrigation alters the soil's hydrological and saline regime, the practices of intensive agriculture directly impact its chemical and physical fertility. The agricultural model implemented in Uzbekistan during the Soviet period, and largely continued thereafter, was dominated by the cotton monoculture, a system that places extreme demands on soil nutrients [20]. This system prioritized yield maximization through the heavy application of synthetic mineral fertilizers (nitrogen, phosphorus, and potassium - NPK) while often neglecting the replenishment of soil organic matter (SOM) [21]. Humus, or SOM, is the cornerstone of soil fertility; it improves soil structure, water retention, and cation exchange capacity, and is the primary reservoir of soil nitrogen [1]. The continuous cultivation of crops like cotton and wheat, where most of an above-ground biomass is removed from the field, combined with the practice of burning or removing crop residues, has led to a steady decline in soil humus content. Studies across Central Asia have documented a significant decrease in humus levels in long-term irrigated Serozems compared to their virgin counterparts, often falling below a critical 1% threshold [22]. This depletion of organic matter not only reduces the soil's natural nutrient-supplying capacity but also degrades its physical structure, making it more prone to crusting and erosion.

The reliance on synthetic NPK fertilizers, while necessary to sustain yields, has created its own set of agrochemical imbalances. The overuse of nitrogen fertilizers, particularly ammonium-based forms, can lead to localized soil acidification. While Serozems are highly buffered by carbonates, the nitrification process itself releases H+ ions, which can, over decades, consume the carbonate buffer in the topsoil [18]. More significantly, excess nitrate is highly mobile and prone to leaching, meaning a large fraction of the applied fertilizer can be washed below the root zone by inefficient furrow irrigation, wasting resources and contributing to the nitrate contamination of the rising groundwater [23]. Phosphorus fertilizers, in contrast, are not mobile. In the alkaline, calcareous Serozems, applied phosphate (P) rapidly reacts with calcium to form insoluble calcium phosphates, a process known as P-fixation [24]. This renders a large portion of the fertilizer unavailable to plants, requiring farmers to apply ever-increasing amounts to achieve the same agronomic effect, while leading to an accumulation of non-labile phosphorus in the soil. Furthermore, the decades-long use of pesticides, particularly persistent organic pollutants (POPs) like DDT and HCH, which were heavily applied during the Soviet era for cotton pest control, has left a toxic legacy. These compounds are hydrophobic and bind strongly to soil organic matter and clay particles, persisting in the environment for decades and posing risks as they slowly enter the food chain [25].

A final, critical impact of intensive agriculture is soil compaction. The loessial soils of the Tashkent region are structurally vulnerable, particularly when wet. The repeated use of heavy machinery—tractors for tillage, planters, sprayers, and harvesters—exerts significant pressure on the soil, destroying macropores and creating a dense, restrictive layer known as a "plow pan" at a depth of 20-40 cm [19]. This compacted layer severely impedes root penetration, limits the infiltration of water, and exacerbates surface water runoff and erosion. It also creates a perched water table above the pan, worsening anaerobic conditions in the root zone and further contributing to the problems of waterlogging and denitrification [17]. This physical degradation works in synergy with chemical degradation (salinization and nutrient depletion) to create a progressively less productive and resilient agricultural environment.

2.4. Urbanization and its Pedological Footprint

The rapid and often poorly regulated expansion of Tashkent city represents a completely different, yet equally destructive, set of anthropogenic pressures on the soil. The most direct and irreversible impact is soil sealing [8]. As the city expands, residential areas, commercial centers, and transportation infrastructure (roads, parking lots) cover productive agricultural Serozems with impervious surfaces. This process completely destroys the soil's capacity to perform its essential ecosystem services: it nof longer supports vegetation, infiltrates water (leading to increased flood risk), biodegrades waste, or sequesters carbon [26]. The land is, for all practical purposes, permanently lost from a pedological and agricultural standpoint. This urban sprawl disproportionately consumes the most fertile alluvial and loess soils located in the flat, accessible river basins, forcing agriculture onto more marginal, less productive lands [27].

Where soils are not sealed, such as in urban parks, residential gardens, and vacant lots, they are fundamentally transformed into "urban soils" or "Technosols" [28]. These soils are characterized by extreme spatial heterogeneity. Their profiles are often truncated (topsoil removed) or buried under layers of fill material. This "urban fill" is a chaotic mixture of natural soil and anthropogenic artifacts, including construction debris (brick, concrete, mortar, glass), industrial slag, ash, and domestic waste [29]. The chemical properties of these soils are drastically altered. The presence of concrete and mortar debris can significantly increase soil pH and calcium carbonate content, making the soil even more alkaline than its Serozem progenitor [30]. Conversely, soils in older urban cores may show acidification from atmospheric deposition of SO2 and NOx (from heating and transport) over long periods, though this is less common in high-carbonate systems [31].

From a chemical fertility standpoint, urban soils are a study in contrasts. They are often heavily contaminated but can also be "over-fertilized." Leakage from aging sewage infrastructure, the application of compost and fertilizers in parks and gardens, and atmospheric nitrogen deposition can create hotspots of nitrogen and phosphorus [32]. However, the more pressing concern is contamination. The most ubiquitous urban soil pollutants are heavy metals, particularly lead (Pb) and zinc (Zn) [33]. Legacy lead from the historical use of leaded gasoline has accumulated in roadside soils for decades and, being immobile, remains in the topsoil. Zinc is associated with tire wear (zinc oxide is used in vulcanization) and the corrosion of galvanized metal (fences, roofs) [34]. Copper (Cu) from vehicle brake pads and cadmium (Cd) from various industrial and domestic sources also accumulate. Beyond metals, urban soils are often sinks for organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), which are products of incomplete combustion from vehicle exhaust, asphalt, and coal burning [35]. These contaminants pose a direct health risk through inhalation of soil dust, dermal contact, and, critically, through the consumption of vegetables grown in urban and peri-urban gardens (*tomorqa*), a common practice in the region [36].

2.5. Industrial Pollution and Atmospheric Deposition

The Tashkent region is not just a residential and agricultural hub; it is the industrial heartland of Uzbekistan. Major industrial complexes in cities surrounding Tashkent, suchas Almalyk, Chirchiq, and Bekabad, are significant point sources of atmospheric pollution [11]. The Almalyk Mining and Metallurgical Complex (AGMK) is one of the largest non-ferrous metal producers in

Central Asia, processing copper, zinc, lead, and molybdenum ores. Decades of smelting operations, particularly in older facilities, have released massive quantities of particulate matter containing these metals, as well as sulfur dioxide (SO2) [37]. The chemical plant in Chirchiq has historically been a major producer of nitrogen fertilizers (ammonia, ammonium nitrate) and other chemicals, with potential emissions including fluoride, ammonia, and nitrogen oxides [38]. Bekabad is a center for steel production and cement manufacturing, contributing its own profile of dust and metal emissions.

These pollutants are transported by prevailing winds and deposited onto soils in the surrounding areas, creating a "pollution halo" that often overlaps with residential and agricultural lands [12]. The impact of heavy metal deposition on soil agrochemical properties is multifaceted. Unlike organic pollutants, metals do not biodegrade and are permanent additions to the soil [33]. They accumulate in the topsoil, where they bind strongly to organic matter and clay particles. Their mobility and bioavailability (the fraction available for plant uptake) are highly dependent on soil pH. In the alkaline Serozems (pH > 8), most heavy metals (like Pb, Cu, Zn) are relatively immobile, as they precipitate as carbonates, hydroxides, or oxides [39]. While this reduces their immediate risk of leaching into groundwater, it does not mean they are harmless. They remain in the root zone, and plant roots can excrete organic acids (exudates) that create acidic micro-sites, mobilizing and absorbing these metals [40]. Cadmium (Cd) is a particular concern as it tends to be more mobile and bioavailable in a wider pH range than other metals and is highly toxic, accumulating in crops and posing a severe risk to kidney function in humans [41].

The co-deposition of sulfur dioxide (SO2) from smelting and burning high-sulfur coal or fuel oil introduces another stressor. When SO2 dissolves in soil moisture, it forms sulfurous and sulfuric acid. In the highly buffered calcareous Serozems, this acid is quickly neutralized by calcium carbonate [31]. However, this "acid rain" effect, even if it doesn't lower the bulk soil pH, accelerates the weathering of carbonate minerals and can mobilize certain elements. More importantly, the constant deposition of these pollutants can severely impact soil biology. High concentrations of heavy metals are toxic to the soil microbial community (bacteria and fungi) that is responsible for all critical nutrient cycling processes, including the decomposition of organic matter (humus formation) and nitrogen fixation [42]. A reduction in microbial activity and diversity can lead to a decline in soil "health" and fertility, even if NPK levels appear sufficient.

2.6. Synthesis and Knowledge Gaps

The literature review reveals that the soils of the Tashkent region are under a complex and severe siege from multiple, overlapping anthropogenic forces. The agricultural soils in the rural parts of the province are primarily afflicted by processes relatedim to water and nutrient mismanagement—namely, secondary salinization, waterlogging, humus depletion, and compaction. The soils of the urban agglomeration, in contrast, are being lost to sealing or fundamentally transformed into Technosols, characterized by high heterogeneity and, most alarmingly, contamination with heavy metals and organic pollutants from transport, waste, and industry. The peri-urban zone represents the most complex battleground, where these forces collide: agricultural practices persist on the urban fringe, but these soils are simultaneously subjected to atmospheric deposition from both urban and industrial sources.

While a substantial body of research exists, it is often fragmented. Many studies [e.g., 10, 13, 16] focus intensely on salinization within specific irrigation schemes. Other studies [e.g., 11, 37] provide valuable data on heavy metal pollution, but often only in the immediate vicinity of a major industrial source like Almalyk. Research on the specific properties of Tashkent's urban soils [e.g., 28, 30] is a more recent but growing field. What is critically lacking is a single, coherent study that synchronously samples and analyzes the full spectrum of degradation indicators (agrochemical fertility, salinity, *and* heavy metal contamination) across the entire land-use gradient, from the urban core of Tashkent, through the peri-urban industrial belt, and out to the intensive rural agricultural landscapes. Such a study is essential to compare the relative magnitudes of these different degradation pathways, to identify potential synergistic interactions (e.g., how does salinization affect heavy metal mobility?), and to provide a holistic evidence base for policymakers tasked with managing land use in this vital and densely populated region. This research is designed to directly address this critical knowledge gap.

3. Methodology

This study was designed as a comparative cross-sectional analysis to investigate the impact of different anthropogenic land uses on soil agrochemical properties in the Tashkent region. The methodology encompassed a stratified field sampling design, standardized laboratory analyses, and statistical evaluation of the resultant data.

- **3.1. Study Area and Sampling Design**

The study was conducted within the Tashkent metropolitan area (Tashkent city) and the surrounding districts of the Tashkent region, located in the Chirchiq-Ahangaran river basin (approximately 40°50' – 41°55' N, 68°40' – 70°10' E). The climate is arid continental, and the dominant natural soils are Typical Serozems formed on loess deposits. To capture the influence of distinct anthropogenic pressures, a stratified random sampling approach was implemented. The study area was divided into three primary land-use zones:

1. **Urban Zone (UZ):** This zone included areas within the Tashkent city limits characterized by high population density and urban infrastructure. Sampling sites (n=30) were selected from public parks, green spaces, and residential areas, chosen to represent soils under typical urban management but not sealed by infrastructure.
2. **Peri-urban Zone (PUZ):** This transitional zone (n=30) represented the interface of urban, industrial, and agricultural land uses. Sites were selected in areas with proximity to major industrial centers (e.g., Chirchiq, Almalyk) and transportation corridors, as well as areas of small-scale suburban agriculture (*tomorqa*).
3. **Rural Agricultural Zone (RAZ):** This zone (n=30) consisted of large, intensively cultivated fields in the rural districts of the Tashkent region, dominated by long-term irrigated agriculture, primarily under wheat and cotton rotation.

At each of the 90 sampling sites, a composite soil sample was collected from the plow layer (0–30 cm depth), which is the most agronomically and environmentally active horizon. Each composite sample consisted of 5 to 7 sub-samples taken in a "W" or "X" pattern over a 100 m x 100 m area, which were then thoroughly mixed to ensure representativeness. The precise geographic coordinates of each site were recorded using a GPS.

- **3.2. Laboratory Analysis**

All collected soil samples were transported to the laboratory, air-dried at room temperature, gently crushed to break up aggregates, and passed through a 2-mm sieve to remove stones and large organic debris. The sieved samples were then subjected to a suite of standardized agrochemical analyses.

Soil pH and electrical conductivity (EC) were measured in a 1:5 soil-to-deionized water suspension using a calibrated combination pH/EC meter. Soil organic matter (humus) content was determined using the Tyurin method, which involves wet oxidation with a potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4) solution, followed by titration [15]. Total nitrogen (N) was determined by the Kjeldahl method, involving acid digestion and distillation. Plant-available phosphorus (P) and potassium (K) were extracted using the Machigin method, a 1% ammonium carbonate solution, which is standard in the region for calcareous soils [15]. The extracted P was quantified colorimetrically, and K was measured using flame photometry.

For heavy metal analysis, a subset of samples was prepared for total metal content. Soil (0.5 g) was digested using a strong acid mixture (e.g., concentrated HNO_3 and $HClO_4$) on a hot plate until clear. The digested solution was then filtered, diluted to a known volume (50 ml) with deionized water, and analyzed for total concentrations of Lead (Pb), Zinc (Zn), Copper (Cu), and Cadmium (Cd) using an Atomic Absorption Spectrometer (AAS) against certified calibration standards.

- **3.3. Statistical Analysis**

All data generated from the laboratory analyses were organized and statistically processed using SPSS software (Version 25.0). Descriptive statistics (mean, standard deviation) were calculated for each parameter within each of the three land-use zones (UZ, PUZ, RAZ). To test for statistically significant differences in soil properties between the zones, a one-way Analysis of Variance (ANOVA) was performed. When the ANOVA F-test was significant ($p < 0.05$), a post-hoc Tukey's Honestly Significant Difference (HSD) test was used to identify which specific zones differed from each other. Finally, Pearson correlation analysis was conducted to explore the relationships between different soil properties, such as the correlation between pH and heavy metal concentrations or between humus and nutrient levels.

4. Results and Analysis

The analysis of soil samples from the urban, peri-urban, and rural agricultural zones of the Tashkent region reveals profound and statistically significant differences in key agrochemical properties and contaminant levels. The results clearly quantify the divergent degradation pathways driven by different forms of anthropogenic land use.

- **4.1. General Agrochemical Properties and Fertility Status**

The fundamental indicators of soil health and fertility—pH, Electrical Conductivity (EC), humus, and primary nutrients (N, P, K)—are presented in **Table 1**. The data highlights a clear differentiation among the three zones. Soil pH remained alkaline across all zones, consistent with the calcareous Serozem parent material, but with a statistically significant trend ($p < 0.05$). The Rural Agricultural Zone (RAZ) was the most alkaline (mean pH 8.3), likely due to the evaporative accumulation of basic salts (carbonates) through long-term irrigation. The Urban Zone (UZ) was significantly less alkaline (mean pH 7.9), which may reflect a minor acidifying influence from urban atmospheric deposition or the use of different landscaping inputs.

The most dramatic difference was observed in Electrical Conductivity (EC), a direct proxy for soil salinity. The RAZ exhibited the highest mean EC (3.1 dS/m), significantly higher ($p < 0.01$) than both the peri-urban (2.5 dS/m) and urban (1.8 dS/m) zones. An EC of 3.1 dS/m is already in the range considered slightly to moderately saline, posing osmotic stress to many sensitive crops. This result empirically confirms that secondary salinization, driven by long-term irrigation and inadequate drainage, is the dominant degradation process in the intensive agricultural landscapes. The PUZ also showed elevated salinity, indicating that irrigation in these fringe areas is also problematic.

Conversely, soil fertility in terms of organic matter and nutrients showed an inverse trend. Soil humus content was critically low in the RAZ (mean 1.1%), significantly lower than in the UZ (1.9%). This confirms the hypothesis that intensive monoculture farming practices, with insufficient return of organic residues, have severely depleted the soil's organic matter reserves. The surprisingly high humus level in the UZ is likely an artifact of urban landscaping management, where parks and green spaces receive imported topsoil, compost, and irrigation, creating localized 'oases' of fertility. Total Nitrogen followed the same pattern as humus, to which it is intrinsically linked. Available Phosphorus (P) and Potassium (K) were also highest in the UZ, likely dueto the regular application of fertilizers in gardens and parks, whereas the RAZ soils showed lower levels, possibly reflecting nutrient export by crops and fixation processes.

Table 1: Comparison of key agrochemical properties across different land-use zones in Tashkent region (Mean ± Standard Deviation)

Parameter	Urban Zone (UZ) (n=30)	Peri-urban Zone (PUZ) (n=30)	Rural Agricultural Zone (RAZ) (n=30)	ANOVA (p-value)
pH (1:5 H_2O)	7.9 ± 0.3	8.1 ± 0.2	8.3 ± 0.4	< 0.05
EC (dS/m)	1.8 ± 0.9	2.5 ± 1.1	3.1 ± 1.4	< 0.01
Humus (%)	1.9 ± 0.8	1.4 ± 0.5	1.1 ± 0.4	< 0.01
Total N (%)	0.11 ± 0.04	0.09 ± 0.03	0.08 ± 0.02	< 0.05
Available P (mg/kg)	35.5 ± 10.2	28.1 ± 8.5	22.4 ± 7.9	< 0.01
Available K (mg/kg)	310 ± 50	290 ± 45	265 ± 60	< 0.05

- **4.2. Heavy Metal Contamination Status**

The analysis of total heavy metal concentrations provides a starkly different picture of soil degradation, one focused on technogenic contamination rather than agricultural depletion. The results, summarized in **Table 2**, show that the urban and peri-urban zones are significantly contaminated compared to the rural agricultural soils, which largely reflect the natural background levels of Serozems.

Lead (Pb) concentrations were highest in the UZ (mean 75.8 mg/kg), more than triple the level found in the RAZ (22.4 mg/kg) and significantly exceeding the regional background level (15-20 mg/kg). This pattern is a classic signature of urban pollution, primarily attributable to the legacy of leaded gasoline emissions, which accumulated in roadside soils for decades. Zinc (Zn) showed a similar urban-centric pattern, with the UZ (180.4 mg/kg) and PUZ (130.1 mg/kg) having dramatically elevated levels. This is consistent with Zn sources related to urbanization, such as tire wear and the corrosion of galvanized materials.

Copper (Cu) presented a slightly different spatial distribution. While elevated in the UZ (90.1 mg/kg), the highest concentrations were found in the PUZ (110.5 mg/kg). This suggests a strong influence from the industrial centers located in the peri-urban belt, particularly the Almalyk mining and metallurgical complex, a major emitter of copper particulates. The RAZ (45.2 mg/kg) was also elevated above the background (20-30 mg/kg), which may be due to the long-term use of copper-based fungicides or impurities in phosphate fertilizers, in addition to atmospheric deposition.

Cadmium (Cd), a highly toxic metal, showed the most alarming trend. Its concentration was highest in the UZ (1.5 mg/kg) and PUZ (1.1 mg/kg), both of which are significantly ($p < 0.01$) higher than the RAZ (0.4 mg/kg) and the background level (< 0.3 mg/kg). The mean concentration in the UZ is approaching the common international Maximum Allowable Concentration (MAC) of 2.0 mg/kg, indicating that some hotspots within the city likely exceed this critical threshold. This Cd accumulation is a clear marker of industrial and urban waste streams.

Table 2: Heavy metal concentrations (mg/kg) in topsoil (0-30 cm) across land-use zones.

Metal	Urban Zone (UZ) (n=30)	Peri-urban Zone (PUZ) (n=30)	Rural Agricultural Zone (RAZ) (n=30)	Background Level (Typical Serozem)	MAC (Example EU Limit)
Lead (Pb)	75.8 ± 25.1	50.3 ± 18.2	22.4 ± 5.6	15–20	100
Zinc (Zn)	180.4 ± 60.5	130.1 ± 45.0	70.3 ± 20.1	50–70	300
Copper (Cu)	90.1 ± 30.2	110.5 ± 40.8	45.2 ± 15.3	20–30	150
Cadmium (Cd)	1.5 ± 0.7	1.1 ± 0.5	0.4 ± 0.2	< 0.3	2.0

- **4.3. Analysis of Degradation Pathways**

The synthesis of these two datasets (Table 1 and Table 2) allows for a clear analysis of the distinct degradation pathways. The Rural Agricultural Zone (RAZ) soils are being degraded primarily through **agricultural-hydrological processes**. The key symptoms are a critical loss of soil organic matter (humus) and a significant build-up of salts (high EC). This combination leads to soils that are structurally poor, chemically imbalanced, and less resilient, with diminishing productive capacity. This is a classic pathway of "desertification" of irrigated lands.

In stark contrast, the Urban Zone (UZ) soils are being degraded through **technogenic-chemical processes**. These soils are not (on average) suffering from salinization or humus depletion; in fact, they are often artificially enriched. Their degradation is defined by the accumulation of toxic heavy metals (Pb, Zn, Cd) to levels that pose a significant environmental and human health risk. This chemical contamination renders the soil unsafe for urban agriculture (a common practice) and compromises its function as a healthy urban ecosystem component.

The Peri-urban Zone (PUZ) represents a "hybrid" degradation model. It suffers from *both* sets of problems. It shows moderate salinization (EC 2.5 dS/m) from agricultural activities that persist on the urban fringe, while *also* exhibiting severe heavy metal contamination (especially Cu and Zn) due to its proximity to both urban transport corridors and major industrial point sources. This makes the peri-urban soil environment the most complex and, arguably, the most degraded from a multi-faceted perspective.

The correlation analysis further supported these findings, showing a strong positive correlation between humus and N ($r = 0.78$, $p < 0.01$) across all samples, and a strong positive correlation between Pb and Zn ($r = 0.85$, $p < 0.01$), confirming their shared urban/transport origin.

5. Discussion

The results of this study provide robust, quantitative evidence for the multifaceted and spatially divergent impacts of anthropogenic activities on the soils of the Tashkent region. The primary finding—that urban and agricultural land uses create distinct degradation pathways—has significant implications for soil science and environmental management. The agricultural degradation pathway, characterized by humus depletion and secondary salinization, aligns perfectly with decades of research on irrigated Serozems in Central Asia [9, 10, 13, 22]. Our finding of a mean humus content of 1.1% in the rural agricultural zone (RAZ) confirms the critical depletion of organic matter documented by scholars [21], who have long warned that the cotton-wheat monoculture system is inherently unsustainable without massive organic matter replenishment. The mean EC of 3.1 dS/m in the RAZ is a clear indicator that secondary salinization is not a historical problem but an active, ongoing process, threatening the long-term viability of this agricultural oasis. This confirms the models of Kovda [9] and the field observations of regional scientists [16] who link this salinization directly to inefficient furrow irrigation and inadequate drainage infrastructure.

The second degradation pathway, technogenic chemical pollution in the urban and peri-urban zones, tells a different story. The high levels of Pb and Zn found in the Urban Zone (UZ) are a classic fingerprint of urbanization, consistent with findings from countless cities worldwide [26, 33, 34]. The legacy of leaded gasoline is a persistent global problem, and our data confirms it is a significant issue in Tashkent. The elevated Copper (Cu) in the Peri-urban Zone (PUZ) strongly supports studies that have modeled atmospheric deposition from the Almalyk industrial complex [11, 37]. This finding is critical, as it demonstrates that industrial emissions are not a localized problem but are impacting the wider peri-urban environment, which includes residential areas and small farms. The most alarming finding is the accumulation of Cadmium (Cd) in the UZ and PUZ. As Cd is highly mobile and toxic [41], its presence at levels approaching international limits (Table 2) poses a direct food chain risk. This is particularly relevant in the context of Uzbekistan, where urban and peri-urban vegetable gardens (*tomorqa*) are a vital source of food and income. Vegetables grown in these contaminated soils could be accumulating dangerous levels of heavy metals, creating a direct pathway for human exposure [36].

The "hybrid" degradation observed in the PUZ is perhaps the most complex management challenge. These soils are being "squeezed" from both sides: they suffer from the agricultural mismanagement common to the rural zone (salinization) while simultaneously acting as a sink for urban and industrial pollutants. This synergy may create novel risks; for example, the complex interactions between salinity (high ion concentration) and heavy metal mobility are poorly understood. While high pH and carbonates in Serozems generally immobilize metals [39], the high chloride concentrations in saline soils could potentially form mobile metal-chloride complexes, increasing their bioavailability—a hypothesis that requires further investigation [43].

The limitations of this study must be acknowledged. This was a cross-sectional study providing a snapshot in time; a longitudinal study monitoring these sites over several years would provide deeper insights into the *rates* of degradation. Furthermore, we measured *total* heavy metal concentrations. While this is a standard indicator of pollution, future research should focus on *bioavailable* fractions (e.g., using DTPA extraction) to more accurately assess the immediate risk of plant uptake. We also did not analyze for organic pollutants (PAHs, pesticides), which represent another significant, unquantified aspect of anthropogenic impact [25, 35]. Despite these limitations, this study successfully synthesizes the major chemical and agrochemical stressors, providing a holistic baseline that was previously lacking in the literature [as identified in the gap, 2.6].

6. Conclusion

This comprehensive study set out to evaluate the influence of dominant anthropogenic factors on the agrochemical properties and fertility of soils in Tashkent city and region. Through a stratified analysis of urban, peri-urban, and rural agricultural land-use zones, our research has successfully quantified the severe and divergent degradation pressures acting on this critical soil resource. The findings compellingly demonstrate that the soils of the Tashkent oasis are simultaneously under attack from two distinct fronts: a crisis of fertility depletion in agricultural areas and a crisis of toxic contamination in urbanized areas.

The rural agricultural soils, the bedrock of the region's food production, are characterized by a classic syndrome of irrigated arid-land degradation. We found they are afflicted by critically low humus content (mean 1.1%) due to decades of intensive monoculture and a significant level of secondary salinization (mean EC 3.1 dS/m) resulting from inefficient water management. This combination is progressively diminishing the soil's productive capacity, undermining long-term food security, and contributing to the desertification of this vital oasis.

Conversely, the urban and peri-urban soils, while often artificially enriched with nutrients like phosphorus and organic matter, are serving as sinks for dangerous technogenic pollutants. We recorded significantly elevated concentrations of heavy metals, particularly lead (up to 75.8 mg/kg) and zinc (up to 180.4 mg/kg) from transport and urban sources, and copper (up to 110.5 mg/kg) and cadmium (up to 1.5 mg/kg) linked to the region's powerful industrial centers. These contaminant levels, especially for cadmium, are approaching or exceeding safe limits, posing a direct and tangible threat to human health via the consumption of produce from ubiquitous urban and peri-urban gardens. The peri-urban zone is uniquely vulnerable, exhibiting a hazardous combination of both salinization and high metal contamination.

The scientific contribution of this work lies in its synchronous and comparative assessment, which moves beyond single-issue studies (e.g., only salinity or only metals) to provide a holistic diagnostic of the health of the entire soil system across the Tashkent agglomeration. The clear differentiation of these degradation pathways is not merely an academic exercise; it is a critical finding for policy and governance. It demonstrates unequivocally that a "one-size-fits-all" approach to soil management will fail.

Therefore, we propose a two-pronged policy recommendation. First, for the rural agricultural zone, policy must urgently prioritize a transition to sustainable water and soil management. This includes aggressive investment in water-saving technologies (e.g., drip irrigation, laser land-leveling) to combat salinization, coupled with mandatory conservation agriculture practices, such as crop rotation with legumes, planting cover crops, and retaining crop residues to rebuild soil organic matter. Second, for the urban and peri-urban zones, the priority must be human health protection and remediation. This requires stricter enforcement of industrial emission controls, comprehensive soil testing in all residential and gardening areas, and the active remediation of known hotspots, potentially through low-cost, sustainable methods like phytoremediation. Furthermore, stringent land-use planning must be enacted to protect the remaining high-quality agricultural Serozems from irreversible urban sealing. Failure to address these dual crises will not only compromise the agricultural potential of the Tashkent region but also exacerbate public health risks for its growing population.

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