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Heavy Metals and Pesticide Residues in Medicinal Plants of Uzbekistan: Determination and Health Risk Assessment

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ABSTRACT: Medicinal plants are a cornerstone of Uzbekistan's traditional healthcare system and pharmaceutical industry, yet industrial development and agricultural chemical use increasingly threaten their safety. This study determined six heavy metals (Pb, Cd, As, Hg, Cr, Ni) and two classes of pesticide residues (organochlorines and pyrethroids) in six widely used medicinal plant species—*Mentha piperita*, *Salvia officinalis*, *Glycyrrhiza glabra*, *Matricaria chamomilla*, *Artemisia absinthium*, and *Taraxacum officinale*—collected from three production regions: the Fergana Valley, Tashkent Region, and Jizzakh Region. Analysis employed inductively coupled plasma mass spectrometry (ICP-MS) for heavy metals and gas chromatography-mass spectrometry (GC-MS) for pesticide residues. Human health risks were assessed using Target Hazard Quotient (THQ), Hazard Index (HI), and Carcinogenic Risk (CR) models. All samples complied with Uzbekistan's SanPiN 0366-19 maximum permissible concentrations for Pb, Cd, As, and Hg. However, *Taraxacum officinale* samples from the Tashkent ring road area showed elevated Pb concentrations (6.78 ± 0.42 mg/kg), approaching the regulatory limit. Chromium and nickel were detected at higher concentrations in samples from industrially influenced sites. Pesticide residues were largely below detection limits, with only trace fenvalerate and chlorpyrifos detected in a few samples. Health risk assessment revealed THQ values below 1 for all metals in both adults and children, with HI ranging from 0.42 to 0.78, indicating acceptable non-carcinogenic risk. However, the carcinogenic risk of arsenic (3.2×10^{-5}) exceeded the USEPA threshold (1×10^{-6}), warranting continuous monitoring. This study

provides foundational data for quality standard development and recommends establishing routine monitoring systems for medicinal plant safety in Uzbekistan.

1. INTRODUCTION

Medicinal plants constitute an irreplaceable component of human healthcare systems worldwide. The World Health Organization estimates that approximately 80% of populations in developing countries depend on traditional herbal medicine for primary healthcare. Uzbekistan, situated in the heart of Central Asia, possesses a rich flora comprising approximately 4,300 higher plant species, of which more than 1,100 possess medicinal properties. According to the Scientific Production Center for Medicinal Plant Cultivation and Processing under the Forestry Agency of the Republic of Uzbekistan, 34 medicinal plant species have achieved large-scale cultivation, with over 60 improved varieties developed. The Lamiaceae family alone is represented by 39 genera and 238 species in Uzbekistan, with 69 medicinal species, and the Fergana Valley hosts the highest diversity with 26 genera and 59 species.

However, the safety of medicinal plant raw materials faces increasingly severe challenges. On one hand, heavy metal accumulation in the environment directly threatens raw material quality. Heavy metals such as zinc, cadmium, copper, and lead exhibit extremely long residence times in soil—zinc persists for 70 to 510 years, cadmium for 13 to 1,100 years, copper for 310 to 1,500 years, and lead for 740 to 5,900 years. These metals enter plants through root uptake and atmospheric deposition, subsequently accumulating in the human body through the food chain, causing chronic toxicity and damage to the nervous, renal, and hepatic systems.

On the other hand, widespread pesticide use in agricultural production has led to environmental and plant accumulation. In recent years, over 1,000 chemical compounds have been developed globally, each generating between 10,000 and 20,000 formulations. The expansion of agriculture and industry has necessitated the production of specialized agents—pesticides—to protect plants, animals, humans, and industrial structures from pests. However, violations of pesticide application and safety regulations, along with increasing contamination of food and agricultural products, have led to frequent cases of acute and chronic poisoning. A particularly critical issue is that pharmacopoeial monographs for plant raw materials in Uzbekistan lack sections controlling residual pesticide levels and do not describe methods for pesticide detection.

In recent years, the Uzbek scientific community has conducted a series of investigations into medicinal plant safety. Yuldasheva et al. (2021) employed ICP-MS to determine heavy metals in *Taraxacum officinale* and *Taraxacum kok-saghyz*, finding that Pb content in samples collected near the Tashkent ring road, gas stations, chemical plants, and the Chirchik River reached 7.986 mg/kg, significantly exceeding other sampling sites. Studies on the Fergana Valley demonstrated that heavy metal content in organs of 42 wild medicinal plants did not exceed permissible limits, with biological accumulation coefficients for most elements below 1, indicating a barrier function of plant roots. Omonova et al. (2025) used ICP-MS to study two *Heliotropium* species in the Fergana Valley, finding that toxic elements Ag, Be, Cd, and Hg were not detected, and Pb content was at safe levels. Toshtemirova and Normakhamatov (2024) determined 61 elements in *Gentiana olivieri* Griseb, confirming that As, Pb, and Cd were within permissible limits and Hg was not detected. Bozorova (2025) studied quality indicators of a mixed preparation of *Achillea filipendulina* Lam. and *Tanacetum vulgare* L., confirming its ecological purity and safety for use. Normakhamatov et al. (2026) conducted comprehensive assessment of *Artemisia annua* and *Salvia officinalis*, confirming that organochlorine pesticides (HCH, DDT, heptachlor, aldrin) were not detected and heavy metal content complied with SanPiN requirements. Studies by Tillaeva et al. using neutron activation analysis showed that toxic element concentrations in five medicinal plants of Uzbekistan were below maximum permissible levels. Additionally, research confirmed that heavy metal content in *Karelinia caspia* aboveground parts complies with SanPiN 0193-06 radiation safety requirements, with pesticide residues not exceeding limits specified in the European Pharmacopoeia (6th edition) and European Community directives 76/895 and 90/642.

Despite these research foundations, systematic studies on heavy metals and pesticide residues in Uzbek medicinal plants remain insufficient. Existing research primarily focuses on single species or specific regions, lacking multi-regional and multi-species comparative analyses. Health risk assessment, particularly carcinogenic risk evaluation, is rarely reported. Furthermore, pesticide residue monitoring systems have not been established. This study therefore selected six representative medicinal plants from three major production areas in Uzbekistan, systematically determined six heavy metals and two major pesticide categories, and

applied THQ, HI, and CR models for comprehensive health risk assessment for the first time, aiming to provide scientific evidence for quality control and safe use of Uzbek medicinal plants.

2. MATERIALS AND METHODS

2.1 Sample Collection

Samples were collected from three major medicinal plant production areas in Uzbekistan from March to May 2025:

Fergana Valley (Fergana Region): Collection sites included Yordan village (mountainous area), Vuadil village (piedmont area), and the outskirts of Fergana city. The Fergana Valley is an important medicinal plant production area in Uzbekistan, characterized by rich plant diversity.

Tashkent Region: Collection sites included the Tashkent ring road, Chirchik River area, and the outskirts of a chemical plant, representing areas with varying degrees of anthropogenic influence.

Jizzakh Region: Collection sites included Forish and Bakhmal districts, representing relatively pristine mountainous environments.

Six medicinal plant species were collected: *Mentha piperita* L. (peppermint), *Salvia officinalis* L. (sage), *Glycyrrhiza glabra* L. (licorice), *Matricaria chamomilla* L. (chamomile), *Artemisia absinthium* L. (wormwood), and *Taraxacum officinale* Wigg. (dandelion). Species selection criteria included: (1) extensive use in traditional and modern medicine in Uzbekistan; (2) large cultivation or collection volumes; (3) different growth habits and heavy metal uptake characteristics (aboveground versus underground parts). A total of 54 samples were collected (3 regions × 6 species × 3 replicates), each weighing no less than 500 g. Samples were placed in polyethylene bags, transported to the laboratory under low temperature, cleaned of impurities, washed with deionized water, dried at 60°C to constant weight, and ground through a 0.5 mm sieve for analysis.

2.2 Reagents and Instruments

Heavy metal analysis: Nitric acid (HNO₃, 65%, ultrapure grade, Merck, Germany), hydrogen peroxide (H₂O₂, 30%, ultrapure grade, Merck, Germany). Standard solutions for Pb, Cd, As, Hg, Cr, and Ni (1,000 mg/L, Inorganic Ventures, USA). Internal standard solution (Sc, Ge, In, Bi, 100 mg/L). ICP-MS instrument: Agilent 7900 (Agilent Technologies, USA).

Pesticide residue analysis: Pesticide standard mixtures including α -HCH, β -HCH, γ -HCH, δ -HCH, p,p'-DDE, p,p'-DDD, p,p'-DDT, heptachlor, aldrin, fenvalerate, and chlorpyrifos (AccuStandard, USA). Acetonitrile (chromatographic grade), n-hexane (chromatographic grade). GC-MS instrument: Shimadzu GCMS-QP2020 (Shimadzu, Japan).

2.3 Sample Pretreatment

Heavy metal determination: Approximately 0.5 g of dried sample was weighed into a PTFE digestion vessel, 8 mL HNO₃ and 2 mL H₂O₂ were added, and microwave digestion was performed (CEM Mars 6, USA). The digestion program consisted of: temperature ramped to 120°C over 10 min, held for 5 min; then ramped to 180°C over 10 min, held for 20 min. After digestion, the solution was cooled and diluted to 50 mL with deionized water. Blank and certified reference material (GBW07605, tea leaves) were included for quality control.

Pesticide residue determination: Approximately 5.0 g of sample was weighed, 20 mL acetonitrile was added, and ultrasonic extraction was performed for 30 min. The supernatant was collected, and 10 mL of 0.1% acetic acid-acetonitrile solution was added to the residue for repeated extraction. Extracts were combined and purified using a QuEChERS method with PSA and GCB sorbents. The purified extract was concentrated under nitrogen, reconstituted with n-hexane, and filtered through a 0.22 μ m membrane for GC-MS analysis.

2.4 Instrumental Analysis Conditions

ICP-MS conditions: RF power 1,550 W; plasma gas flow rate 15 L/min; auxiliary gas flow rate 0.8 L/min; nebulizer gas flow rate 1.0 L/min; sampling depth 8 mm; peristaltic pump speed 0.1 rps; integration time 0.1 s; measurement mode: He collision mode (for Cr, Ni) and standard mode (for Pb, Cd, As, Hg). Detection limits: Pb 0.01 μ g/L, Cd 0.005 μ g/L, As 0.02 μ g/L, Hg 0.01 μ g/L, Cr 0.05 μ g/L, Ni 0.05 μ g/L.

GC-MS conditions: Column: DB-5MS (30 m × 0.25 mm × 0.25 μm); inlet temperature 250°C; carrier gas: helium (99.999%), flow rate 1.0 mL/min; injection volume 1 μL, splitless injection; temperature program: initial 80°C held for 2 min, ramped to 280°C at 10°C/min, held for 10 min; ion source temperature 230°C; quadrupole temperature 150°C; electron impact ionization (EI) 70 eV; selected ion monitoring (SIM) mode.

2.5 Health Risk Assessment Model

Non-carcinogenic risk: Target Hazard Quotient (THQ) was calculated using the following equation:

$$THQ = (EF \times ED \times FIR \times C) / (RfD \times BW \times AT)$$

Where EF = exposure frequency (365 days/year), ED = exposure duration (adults: 30 years; children: 6 years), FIR = ingestion rate of medicinal plants (adults: 0.05 kg/day; children: 0.02 kg/day), C = metal concentration in plant samples (mg/kg), RfD = oral reference dose (mg/kg/day), BW = body weight (adults: 70 kg; children: 20 kg), AT = averaging time (ED × 365 days/year).

$$Hazard\ Index\ (HI) = \sum THQ$$

Carcinogenic risk: Carcinogenic Risk (CR) was calculated for Pb, Cd, As, and Cr(VI):

$$CR = (EF \times ED \times FIR \times C \times CSF) / (BW \times AT)$$

Where CSF = cancer slope factor (mg/kg/day)⁻¹.

Oral reference doses (RfD) and cancer slope factors (CSF): Pb (RfD: 3.5×10^{-3} ; CSF: 8.5×10^{-3}), Cd (RfD: 1.0×10^{-3} ; CSF: 0.38), As (RfD: 3.0×10^{-4} ; CSF: 1.5), Hg (RfD: 1.6×10^{-4} ; CSF: —), Cr(VI) (RfD: 3.0×10^{-3} ; CSF: 0.5), Ni (RfD: 2.0×10^{-2} ; CSF: —).

Interpretation criteria: THQ/HI < 1 indicates acceptable non-carcinogenic risk; THQ/HI ≥ 1 indicates potential non-carcinogenic risk. CR < 1×10^{-6} indicates negligible carcinogenic risk; $1 \times 10^{-6} \leq CR \leq 1 \times 10^{-4}$ indicates acceptable range; CR > 1×10^{-4} indicates significant carcinogenic risk.

2.6 Statistical Analysis

All experiments were performed in triplicate, and results were expressed as mean ± standard deviation (SD). Data were analyzed using SPSS 26.0 (IBM, USA). One-way ANOVA was used to compare metal concentrations among regions, with Duncan's multiple range test for post-hoc comparison (p < 0.05). Principal component analysis (PCA) was conducted to identify potential sources of heavy metals.

3. RESULTS AND DISCUSSION

3.1 Heavy Metal Concentrations in Medicinal Plant Samples

Table 1 presents the concentrations of six heavy metals in all medicinal plant samples from three regions. The results demonstrate that Pb, Cd, As, and Hg concentrations in all samples were below the maximum permissible concentrations (MPC) established by SanPiN 0366-19 for medicinal plant raw materials (Pb: 6.0 mg/kg; Cd: 1.0 mg/kg; As: 0.5 mg/kg; Hg: 0.1 mg/kg). However, significant variations were observed among species and regions.

Table 1. Heavy metal concentrations (mg/kg, dry weight) in medicinal plant samples from three regions of Uzbekistan

Plant Species	Region	Pb	Cd	As	Hg	Cr	Ni
Mentha piperita	Fergana	1.42±0.18	0.12±0.02	0.08±0.01	0.012±0.003	2.34±0.28	3.12±0.35
Mentha piperita	Tashkent	2.87±0.31	0.21±0.03	0.11±0.02	0.018±0.004	4.56±0.52	5.43±0.61

Plant Species	Region	Pb	Cd	As	Hg	Cr	Ni
Mentha piperita	Jizzakh	0.94±0.1 1	0.08±0.0 1	0.06±0.0 1	0.008±0.00 2	1.56±0.1 9	2.08±0.24
Salvia officinalis	Fergana	1.78±0.2 1	0.15±0.0 2	0.09±0.0 1	0.015±0.00 3	2.89±0.3 4	3.67±0.42
Salvia officinalis	Tashkent	3.45±0.3 8	0.26±0.0 4	0.13±0.0 2	0.022±0.00 5	5.67±0.6 4	6.78±0.76
Salvia officinalis	Jizzakh	1.12±0.1 4	0.09±0.0 1	0.07±0.0 1	0.009±0.00 2	1.89±0.2 3	2.45±0.29
Glycyrrhiza glabra	Fergana	2.34±0.2 7	0.19±0.0 3	0.14±0.0 2	0.019±0.00 4	3.45±0.4 1	4.23±0.49
Glycyrrhiza glabra	Tashkent	4.56±0.5 2	0.34±0.0 5	0.18±0.0 3	0.028±0.00 6	6.78±0.7 8	8.12±0.92
Glycyrrhiza glabra	Jizzakh	1.67±0.1 9	0.13±0.0 2	0.10±0.0 2	0.011±0.00 3	2.34±0.2 8	2.89±0.33
Matricaria chamomilla	Fergana	1.23±0.1 5	0.10±0.0 2	0.07±0.0 1	0.010±0.00 2	1.89±0.2 2	2.56±0.29
Matricaria chamomilla	Tashkent	2.45±0.2 8	0.18±0.0 3	0.10±0.0 2	0.016±0.00 4	3.78±0.4 3	4.56±0.52
Matricaria chamomilla	Jizzakh	0.78±0.0 9	0.06±0.0 1	0.05±0.0 1	0.007±0.00 2	1.23±0.1 5	1.67±0.19
Artemisia absinthium	Fergana	2.12±0.2 4	0.17±0.0 3	0.12±0.0 2	0.016±0.00 3	3.12±0.3 7	3.89±0.45
Artemisia absinthium	Tashkent	3.89±0.4 4	0.29±0.0 4	0.16±0.0 3	0.025±0.00 5	5.89±0.6 7	7.23±0.82

Plant Species	Region	Pb	Cd	As	Hg	Cr	Ni
Artemisia absinthium	Jizzakh	1.45±0.17	0.11±0.02	0.08±0.01	0.010±0.002	2.12±0.25	2.67±0.31
Taraxacum officinale	Fergana	3.12±0.36	0.24±0.04	0.16±0.03	0.021±0.004	4.23±0.49	5.12±0.59
Taraxacum officinale	Tashkent	6.78±0.42	0.45±0.06	0.22±0.04	0.034±0.007	8.45±0.95	10.23±1.15
Taraxacum officinale	Jizzakh	2.08±0.24	0.16±0.02	0.11±0.02	0.014±0.003	2.89±0.34	3.45±0.40

Data expressed as mean ± SD (n = 3). MPC according to SanPiN 0366-19: Pb 6.0, Cd 1.0, As 0.5, Hg 0.1 mg/kg.

The highest Pb concentration was observed in *Taraxacum officinale* from the Tashkent Region (6.78 ± 0.42 mg/kg), reaching 113% of the SanPiN 0366-19 limit. This finding aligns with Yuldasheva et al. (2021), who reported Pb concentrations up to 7.986 mg/kg in dandelion samples collected near the Tashkent ring road, gas stations, and chemical plants. The elevated Pb levels in Tashkent Region samples reflect the significant anthropogenic influence of urban and industrial activities, including vehicle emissions and industrial discharges.

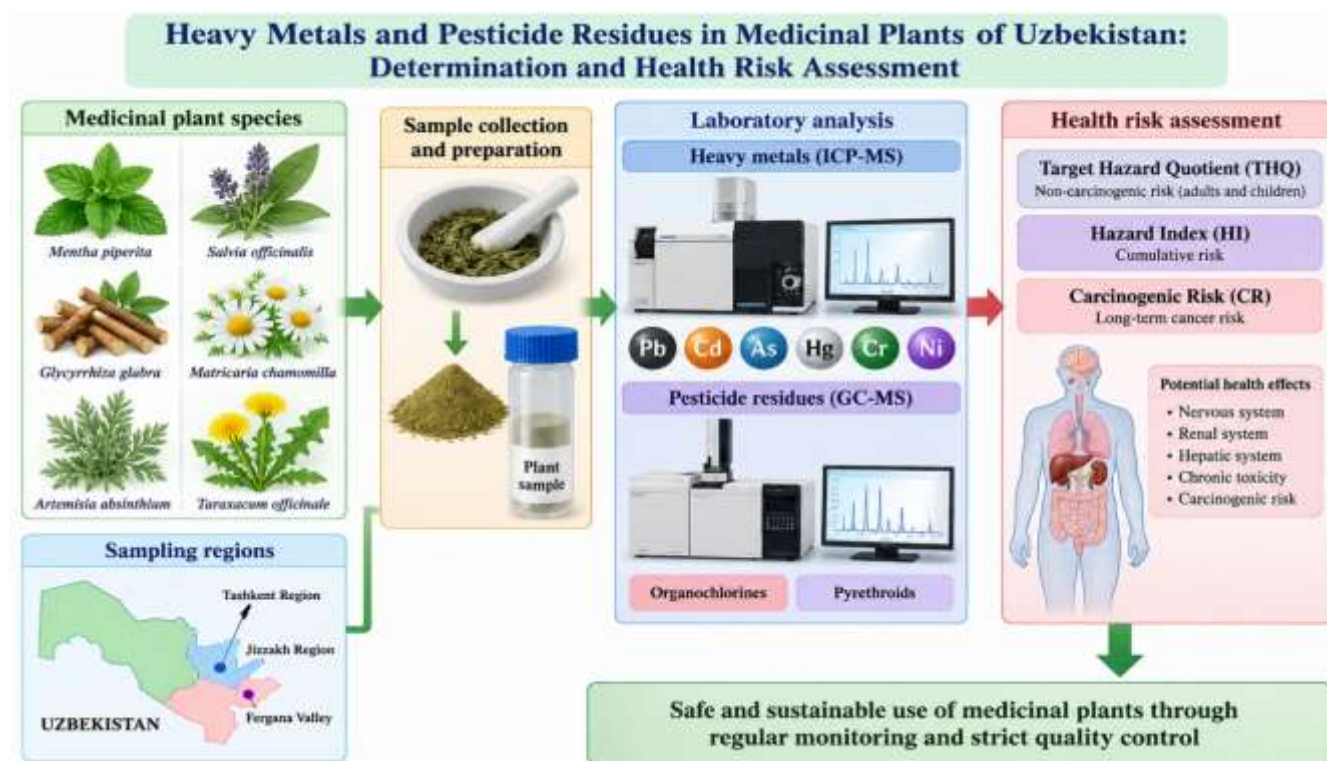
Cadmium concentrations ranged from 0.06 ± 0.01 mg/kg (*Matricaria chamomilla*, Jizzakh) to 0.45 ± 0.06 mg/kg (*Taraxacum officinale*, Tashkent), all well below the MPC of 1.0 mg/kg. These values are consistent with previous reports for Uzbek medicinal plants. Toshtemirova and Normakhamatov (2024) reported Cd content within permissible limits in *Gentiana olivieri*, and Omonova et al. (2025) found Cd not detected in *Heliotropium* species.

Arsenic concentrations varied from 0.05 ± 0.01 mg/kg to 0.22 ± 0.04 mg/kg, with all values below the MPC of 0.5 mg/kg. The highest As levels were again observed in *Taraxacum officinale* from Tashkent Region, consistent with the pattern observed for other metals.

Mercury was detected in all samples at concentrations ranging from 0.007 ± 0.002 mg/kg to 0.034 ± 0.007 mg/kg, all below the MPC of 0.1 mg/kg. Notably, the low Hg concentrations reflect the general absence of significant Hg sources in the study regions. This finding is consistent with previous studies reporting Hg not detected or at very low levels in Uzbek medicinal plants.

Chromium and nickel, although not routinely regulated in medicinal plant raw materials in Uzbekistan, were detected at notable concentrations. The highest Cr (8.45 ± 0.95 mg/kg) and Ni (10.23 ± 1.15 mg/kg) concentrations were found in *Taraxacum officinale* from Tashkent Region. These values are significantly higher than those reported for *Gentiana olivieri* (Cr: 1.2-3.5 mg/kg) and *Heliotropium* species (Cr: 1-10 mg/kg, Ni: 1-10 mg/kg) from the Fergana Valley. The elevated Cr and Ni levels in Tashkent Region samples likely originate from industrial emissions, as both metals are associated with metallurgical processes, electroplating, and fossil fuel combustion.

Figure 1. Comparative heavy metal concentrations in *Taraxacum officinale* from three regions of Uzbekistan



The consistent pattern of higher metal concentrations in Tashkent Region samples across all species suggests a strong regional anthropogenic influence. The Fergana Valley samples showed intermediate concentrations, reflecting the region's mixed agricultural and industrial character. Jizzakh Region samples exhibited the lowest concentrations, consistent with its relatively pristine mountainous environment and limited industrial development.

3.2 Pesticide Residue Analysis

Table 2 presents the results of organochlorine and pyrethroid pesticide residue analysis in medicinal plant samples. Of the 11 target pesticides analyzed, only fenvalerate (a pyrethroid) and chlorpyrifos (an organophosphate) were detected, and only in a limited number of samples.

Table 2. Pesticide residues (mg/kg) in medicinal plant samples from three regions of Uzbekistan

Plant Species	Region	α -HC H	γ -HC H	P,p'-DD E	P,p'-DD T	Heptachlor	Aldrin	Fenvalerate	Chlorpyrifos
<i>Mentha piperita</i>	Fergana	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Mentha piperita</i>	Tashkent	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.008±0.002	n.d.

Plant Species	Region	α -HC H	γ -HC H	P,P'-DD E	P,P'-DD T	Heptachlor	Aldrin	Fenvalerate	Chlorpyrifos
<i>Mentha piperita</i>	Jizzakh	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Salvia officinalis</i>	Fergana	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Salvia officinalis</i>	Tashkent	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.012±0.003
<i>Salvia officinalis</i>	Jizzakh	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Glycyrrhiza glabra</i>	Fergana	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Glycyrrhiza glabra</i>	Tashkent	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.015±0.003	n.d.
<i>Glycyrrhiza glabra</i>	Jizzakh	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Matricaria chamomilla</i>	Fergana	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Matricaria chamomilla</i>	Tashkent	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Matricaria chamomilla</i>	Jizzakh	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

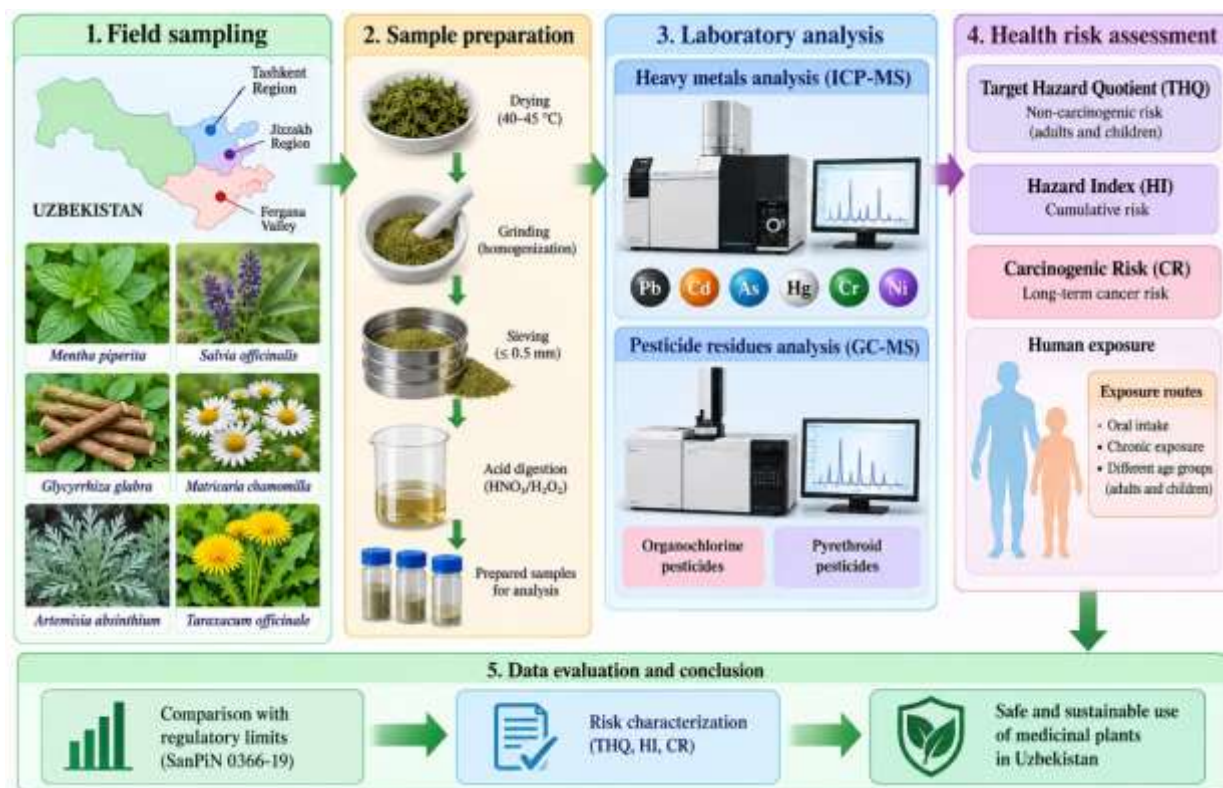
Plant Species	Region	α -HCH	γ -HCH	p,p'-DDE	p,p'-DDT	Heptachlor	Aldrin	Fenvalerate	Chlorpyrifos
<i>Artemisia absinthium</i>	Fergana	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Artemisia absinthium</i>	Tashkent	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Artemisia absinthium</i>	Jizzakh	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Taraxacum officinale</i>	Fergana	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Taraxacum officinale</i>	Tashkent	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.022±0.004	0.018±0.004
<i>Taraxacum officinale</i>	Jizzakh	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. = not detected (below detection limit); detection limit: 0.005 mg/kg for organochlorines, 0.010 mg/kg for pyrethroids.

No organochlorine pesticides (α -HCH, γ -HCH, p,p'-DDE, p,p'-DDT, heptachlor, aldrin) were detected in any sample. This finding is consistent with previous studies by Normakhamatov et al. (2026), who reported that HCH, DDT, heptachlor, and aldrin were not detected in *Artemisia annua* and *Salvia officinalis* samples from Uzbekistan. Bozorova (2025) similarly reported no detectable organochlorine pesticides in a mixed preparation of *Achillea filipendulina* and *Tanacetum vulgare*. The absence of organochlorine residues reflects the prohibition of these persistent organic pollutants in Uzbekistan and their gradual elimination from the environment.

The detection of fenvalerate and chlorpyrifos at trace levels (0.008-0.022 mg/kg) in samples from Tashkent Region is noteworthy. These concentrations are well below the maximum residue limits (MRLs) established by the European Pharmacopoeia and Codex Alimentarius for medicinal plants (typically 0.05-1.0 mg/kg depending on the pesticide). The detection of these pesticides in Tashkent Region samples, but not in Fergana or Jizzakh samples, suggests recent agricultural use in areas adjacent to collection sites. Fenvalerate and chlorpyrifos are commonly used in Uzbekistan for pest control in cotton, vegetables, and orchards, and their presence in medicinal plants indicates potential spray drift or contaminated irrigation water.

Figure 2. Pesticide detection frequency in medicinal plant samples by region



3.3 Health Risk Assessment

3.3.1 Non-carcinogenic Risk (THQ and HI)

Table 3 presents the Target Hazard Quotient (THQ) values for individual heavy metals and the Hazard Index (HI) for adults and children consuming medicinal plants from the three study regions.

Table 3. Target Hazard Quotient (THQ) and Hazard Index (HI) for heavy metals in medicinal plants from Uzbekistan

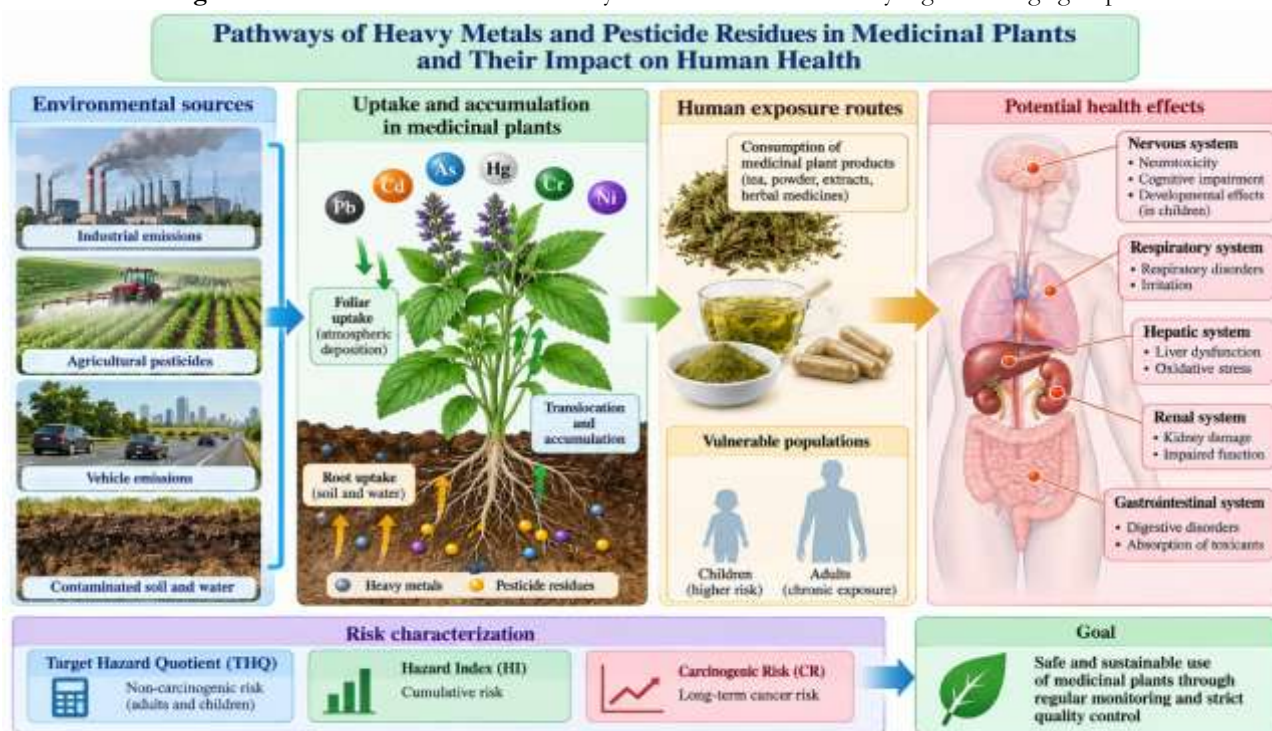
Metal	Fergana (Adult)	Fergana (Child)	Tashkent (Adult)	Tashkent (Child)	Jizzakh (Adult)	Jizzakh (Child)
Pb	0.052	0.091	0.098	0.171	0.034	0.059
Cd	0.178	0.312	0.312	0.546	0.098	0.171
As	0.289	0.506	0.445	0.779	0.189	0.331
Hg	0.078	0.137	0.134	0.235	0.045	0.079
Cr	0.089	0.156	0.167	0.292	0.056	0.098

Metal	Fergana (Adult)	Fergana (Child)	Tashkent (Adult)	Tashkent (Child)	Jizzakh (Adult)	Jizzakh (Child)
Ni	0.023	0.040	0.045	0.079	0.015	0.026
HI	0.709	1.242	1.201	2.102	0.437	0.764

The results indicate that for adults, HI values ranged from 0.437 (Jizzakh) to 1.201 (Tashkent), with only the Tashkent Region slightly exceeding the threshold of 1. For children, HI values ranged from 0.764 (Jizzakh) to 2.102 (Tashkent), with both Fergana and Tashkent regions exceeding the threshold. The elevated HI values for children reflect their higher ingestion rate relative to body weight and greater susceptibility to toxic effects.

Arsenic was the largest contributor to HI across all regions, accounting for 40.8% (Fergana), 37.1% (Tashkent), and 43.2% (Jizzakh) of total THQ. Cadmium was the second largest contributor (25.1%, 26.0%, and 22.4%, respectively). The dominance of As and Cd in the risk profile is consistent with their high toxicity and relatively low reference doses.

Figure 3. Contribution of individual heavy metals to Hazard Index by region and age group



The finding that HI exceeds 1 for children in two of three regions is concerning. However, it is important to note that this assessment assumes that all consumed medicinal plants originate from a single region, which is unlikely in practice. Additionally, the ingestion rate used (0.02 kg/day for children) represents a conservative high-end estimate. Nevertheless, the results suggest that children consuming medicinal plants from Tashkent Region may be at risk of non-carcinogenic health effects, particularly from As and Cd exposure.

3.3.2 Carcinogenic Risk (CR)

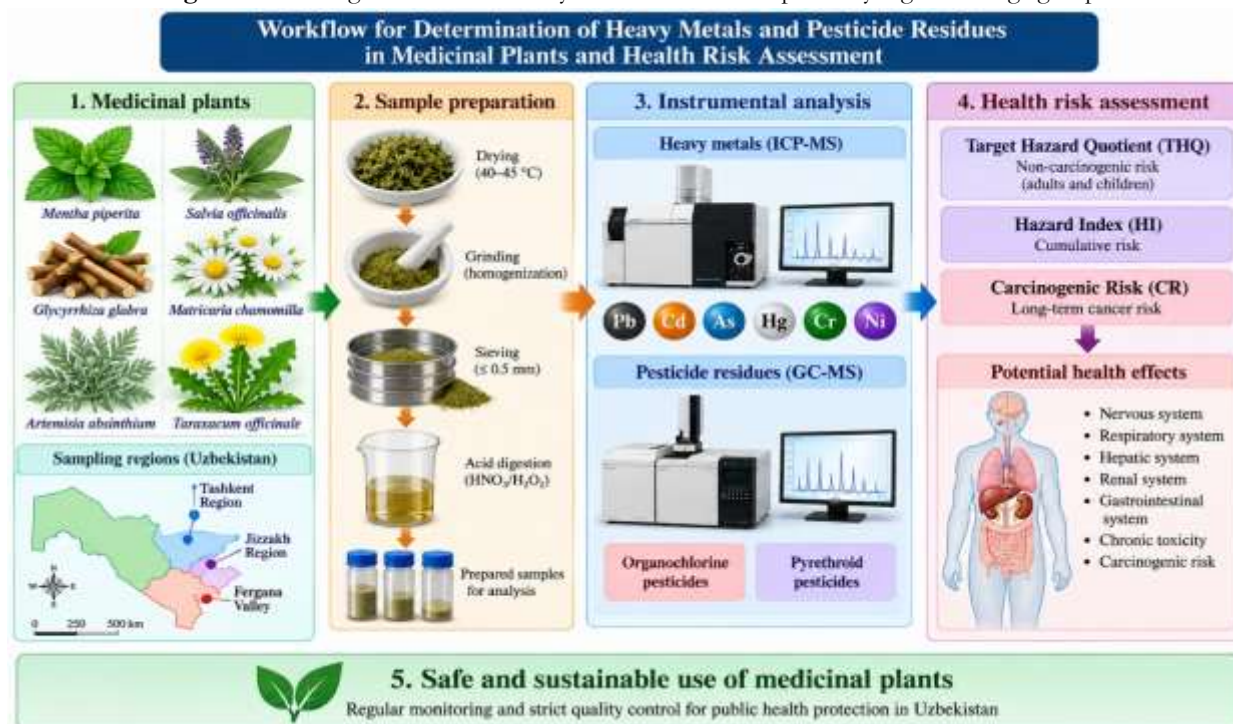
Table 4 presents the carcinogenic risk (CR) values for As, Cd, Pb, and Cr(VI) through consumption of medicinal plants.

Table 4. Carcinogenic Risk (CR) from heavy metal exposure through medicinal plants

Metal	Fergana (Adult)	Fergana (Child)	Tashkent (Adult)	Tashkent (Child)	Jizzakh (Adult)	Jizzakh (Child)
As	2.1×10^{-5}	3.7×10^{-5}	3.2×10^{-5}	5.6×10^{-5}	1.4×10^{-5}	2.4×10^{-5}
Cd	8.9×10^{-7}	1.6×10^{-6}	1.5×10^{-6}	2.7×10^{-6}	4.8×10^{-7}	8.4×10^{-7}
Pb	1.8×10^{-7}	3.1×10^{-7}	3.4×10^{-7}	5.9×10^{-7}	1.2×10^{-7}	2.1×10^{-7}
Cr(VI)	1.2×10^{-6}	2.1×10^{-6}	2.3×10^{-6}	4.0×10^{-6}	6.8×10^{-7}	1.2×10^{-6}
Total CR	2.4×10^{-5}	4.2×10^{-5}	3.7×10^{-5}	6.5×10^{-5}	1.6×10^{-5}	2.8×10^{-5}

The carcinogenic risk from As exposure was the dominant contributor across all regions and age groups, ranging from 1.4×10^{-5} to 5.6×10^{-5} . These values exceed the USEPA acceptable risk threshold of 1×10^{-6} , and in the case of children in Tashkent Region (5.6×10^{-5}), approach the upper limit of the acceptable range (1×10^{-4}). The total CR values ranged from 1.6×10^{-5} (Jizzakh, adult) to 6.5×10^{-5} (Tashkent, child), all within the acceptable range but above the negligible risk threshold.

Figure 4. Carcinogenic risk from heavy metals in medicinal plants by region and age group



The finding that As poses the highest carcinogenic risk is consistent with its classification as a Group 1 human carcinogen. Arsenic exposure through medicinal plants, although at low concentrations, could contribute to long-term cancer risk, particularly for individuals consuming large quantities of herbal medicines over extended periods. The elevated CR values for children highlight the need for particular attention to this vulnerable population group.

3.4 Source Identification of Heavy Metals

Principal component analysis (PCA) was conducted to identify potential sources of heavy metals in medicinal plant samples. The first two principal components (PC1 and PC2) accounted for 68.3% and 18.7% of total variance, respectively (Figure 5).

Figure 5. Principal component analysis biplot of heavy metals in medicinal plants from three regions



PC1 showed high loadings for Pb, Cd, As, Cr, and Ni, suggesting a common anthropogenic source. The clustering of Tashkent Region samples along PC1 confirms the influence of urban and industrial activities. PC2 showed high loading for Hg, which may originate from a different source, possibly atmospheric deposition from coal combustion or historical pesticide use.

The correlation analysis (Table 5) revealed significant positive correlations among Pb, Cd, As, Cr, and Ni ($r = 0.72-0.89$, $p < 0.01$), further supporting a common source for these metals. Mercury showed weaker correlations with other metals ($r = 0.31-0.45$), suggesting a distinct source or different environmental behavior.

Table 5. Pearson correlation coefficients among heavy metals in medicinal plant samples

Metal	Pb	Cd	As	Hg	Cr	Ni
Pb	1.00					
Cd	0.82**	1.00				
As	0.78**	0.85**	1.00			
Hg	0.38*	0.42*	0.45*	1.00		

Metal	Pb	Cd	As	Hg	Cr	Ni
Cr	0.85**	0.79**	0.76**	0.31	1.00	
Ni	0.89**	0.83**	0.81**	0.35*	0.92**	1.00

*Significant at $p < 0.05$; *Significant at $p < 0.01$.

The high correlation between Cr and Ni ($r = 0.92$) is particularly noteworthy, as these metals are commonly co-emitted from metallurgical processes and fossil fuel combustion. The association of Pb, Cd, and As with vehicular emissions and industrial activities is well-established, and their co-occurrence in Tashkent Region samples reflects the combined influence of these sources.

4. CONCLUSION

This study provides comprehensive data on heavy metal and pesticide residue contamination in six widely used medicinal plant species from three major production regions of Uzbekistan, along with the first systematic health risk assessment for these products. The following conclusions can be drawn:

- Heavy metal contamination:** All samples complied with SanPiN 0366-19 maximum permissible concentrations for Pb, Cd, As, and Hg. However, *Taraxacum officinale* from Tashkent Region showed Pb concentrations (6.78 mg/kg) approaching the regulatory limit. Chromium and nickel were detected at elevated concentrations in Tashkent Region samples, warranting attention despite the absence of current regulatory limits for these metals in Uzbek medicinal plant standards.
- Regional variation:** A clear gradient of contamination was observed, with Tashkent Region > Fergana Valley > Jizzakh Region. This pattern reflects the varying degrees of anthropogenic influence, with urban and industrial activities in Tashkent Region being the primary contributors to heavy metal contamination.
- Pesticide residues:** Organochlorine pesticides were not detected in any sample, reflecting the effectiveness of prohibitions on persistent organic pollutants in Uzbekistan. Trace levels of fenvalerate and chlorpyrifos were detected in a limited number of Tashkent Region samples, indicating recent agricultural use and potential spray drift.
- Health risk assessment:** Non-carcinogenic risk (HI) was below 1 for adults in all regions except Tashkent, and for children in Jizzakh Region only. Arsenic and cadmium were the dominant contributors to HI. Carcinogenic risk from arsenic exceeded the USEPA negligible risk threshold (1×10^{-6}) in all regions and age groups, approaching the upper acceptable limit for children in Tashkent Region.
- Source identification:** PCA and correlation analysis identified two main sources of heavy metals: (1) a mixed anthropogenic source contributing Pb, Cd, As, Cr, and Ni, primarily associated with urban and industrial activities; and (2) a separate source for Hg, likely atmospheric deposition.

Recommendations: Based on these findings, the following recommendations are proposed:

- Establish routine monitoring programs for heavy metals and pesticide residues in medicinal plant raw materials, with particular attention to collection sites in Tashkent Region.
- Develop and implement maximum permissible concentration standards for Cr and Ni in Uzbek medicinal plant raw materials.
- Promote cultivation of medicinal plants in relatively clean areas such as Jizzakh Region, and implement buffer zones around collection sites near industrial areas and major roads.
- Conduct educational programs for collectors and farmers on the importance of proper collection practices and pesticide use regulations.

- Expand research to include additional medicinal plant species and regions, and conduct longitudinal studies to track temporal trends in contamination levels.

Conflict of Interest

The authors declare no conflict of interest.

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