Effects of Soil Cadmium Stress on Cadmium Distribution and Accumulation Characteristics in Panax notoginseng (Postprint)

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Abstract

Panax notoginseng (Burk.) F. H. Chen (Tianqi) is a traditional and precious herbal medicinal plant in China. Its heavy metal contamination issue has attracted widespread attention. Related studies have demonstrated that certain concentrations of cadmium can inhibit Tianqi growth, and cadmium stress reduces the accumulation of saponins—the principal pharmacologically active components—thereby affecting the quality of Tianqi medicinal materials. Health risk assessment of cadmium in Tianqi indicates that its hazard quotient (HQ) exceeds 1, suggesting that cadmium in Tianqi medicinal materials poses a non-carcinogenic risk to consumers. To elucidate the response of different Tianqi organs to cadmium toxicity, clarify the fundamental characteristics of cadmium distribution within Tianqi under varying cadmium pollution concentrations and the enrichment characteristics of different organs, and reveal the influence mechanism and enrichment-translocation characteristics of cadmium stress on different Tianqi organs, three-year-old Tianqi plants were employed as experimental materials in the Tianqi plantation of Jingxi City, Guangxi—the "Hometown of Tianqi". Under soil culture conditions, with a no-cadmium treatment serving as the blank control, six cadmium concentration gradients were established (5, 10, 20, 30, 40, 50 $\mathrm{mg \cdot kg^{-1}}$) to analyze the cadmium accumulation and translocation characteristics in different Tianqi organs under varying concentrations of cadmium stress.

The study revealed that: across different organs (leaf, stem, rhizome, fibrous root, and main root), cadmium accumulation in each organ increased significantly ($P < 0.05$) with increasing cadmium concentrations, exhibiting a positive correlation. The distribution characteristics of cadmium content in different Tianqi parts were as follows: under blank control conditions, cadmium accumulation in Tianqi organs followed the order: fibrous root > rhizome > main root

> stem > leaf; when cadmium concentrations were 5, 10, 20, 30, 40, and 50 mg$\cdot$kg^{-1}, cadmium distribution in Tianqi exhibited the pattern: rhizome > main root > fibrous root > stem > leaf. Cadmium content in the belowground portion was significantly higher than that in the aboveground portion. With increasing cadmium concentration, both belowground and aboveground bioconcentration factors demonstrated a gradually decreasing trend.

Full Text

Distribution and Accumulation Characteristics of Cadmium in Panax notoginseng Under Cadmium Stress

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Abstract: Panax notoginseng (Burk.) F. H. Chen is a traditional and precious medicinal herb in China, and its heavy metal contamination has attracted widespread attention. Previous studies have shown that certain concentrations of cadmium (Cd) inhibit the growth of P. notoginseng, reduce the accumulation of saponins (its main pharmacologically active components), and compromise medicinal quality. Health risk assessments indicate a hazard quotient (HQ) greater than 1, suggesting non-carcinogenic risks to consumers from Cd in P. notoginseng. To elucidate the response of different plant parts to Cd toxicity, clarify the distribution patterns and accumulation characteristics under varying Cd concentrations, and reveal the underlying mechanisms of Cd stress, enrichment, and translocation, we conducted a field experiment in Jingxi City, Guangxi—the renowned "hometown of P. notoginseng." Using three-year-old plants grown in soil culture, we established six Cd treatment gradients (5, 10, 20, 30, 40, and 50 mg$\cdot$kg^{-1}) with a non-Cd treatment as control, and analyzed Cd accumulation and translocation characteristics in different plant parts. The results demonstrated that Cd accumulation in all organs (leaves, stems, rhizomes, fibrous roots, and taproots) increased significantly ($P < 0.05$) with rising Cd concentrations, showing a positive correlation. Under control conditions, Cd distribution followed the pattern: fibrous roots > rhizome > taproot > stem > leaf. At Cd concentrations of 5, 10, 20, 30, 40, and 50 mg$\cdot$kg^{-1}, the pattern shifted to: rhizome > taproot > fibrous root > stem > leaf. Cd content in underground parts was significantly higher than in aboveground parts, and both aboveground and belowground bioconcentration factors decreased gradually with increasing Cd concentrations.

Keywords: Panax notoginseng; cadmium pollution; accumulation and distribution; enrichment coefficient; transfer coefficient

Introduction

Panax notoginseng (Burk.) F. H. Chen, also known as "Sanqi" or "Tianqi," is a perennial herb belonging to the Araliaceae family. Renowned for its efficacy in promoting blood circulation, dispersing blood stasis, reducing swelling, and relieving pain, it represents a famous specialty of Guangxi and Yunnan provinces. Originally wild, it has been used medicinally in China for centuries before transitioning to cultivated production. The plant typically bears three petioles per plant, each with seven leaflets, hence the name "Sanqi" (three-seven). Historical records from the *Guishun Zhilizhou Zhi* (1897) and *Baise Tingzhi* (1881) document that the finest quality P. notoginseng originated from Tianzhou, earning it the common name "Tianqi."

Every part of P. notoginseng, from flower to root, possesses medicinal and edible value. According to *Bencao Xinbian*, "Tianqi root is a miraculous hemostatic agent, effective alone for bleeding disorders regardless of location." The *Dictionary of Traditional Chinese Medicine* notes that P. notoginseng leaves can reduce swelling, relieve pain, arrest bleeding, combat aging, decrease blood viscosity, prevent thrombosis, and inhibit tumors. The flowers, possessing cooling properties, help lower blood pressure, clear heat, calm the liver, and soothe the nerves.

Yunnan is China's largest Cd-producing province, with annual output reaching 63.2 tons (46.6% of national production). However, in terms of geometric mean values, Guangdong, Guangxi, Yunnan, and Hunan provinces show similar average Cd ore grades (0.030–0.050%), though Inner Mongolia and Jiangxi exhibit relatively higher Cd content in their ores. Numerous researchers have investigated Cd levels in P. notoginseng from Wenshan and Guangxi production regions. Zhao et al. (2014) reported a 30.6% Cd exceedance rate in Yunnan Sanqi, while Han et al. (2008) found exceedance rates as high as 50%. Previous studies have demonstrated that Cd stress reduces saponin accumulation, compromising medicinal quality and efficacy. Zhu et al. (2012) found 60.7% of P. notoginseng samples exceeded Cd limits, with health risk assessments revealing $HQ > 1$, indicating non-carcinogenic risks to consumers. Yang et al. (2008) and Chen et al. (2014) documented Cd exceedance in Guangxi P. notoginseng leaves. Feng et al. (2006) confirmed that P. notoginseng can absorb and accumulate soil Cd, while Lin et al. (2014) and Li et al. (2015) demonstrated strong Cd enrichment and Cd/Cu translocation capabilities. Cadmium stress also negatively affects plant physiology, growth, microorganisms, and rhizosphere environments. Although numerous studies have examined Cd enrichment in different organs, variations in geography, geological background, cultivation practices, growing seasons, and plant age produce divergent results.

Guangxi's Baise City, the birthplace of P. notoginseng, features unique geographical conditions and cultivation traditions. Literature indicates that Guangxi Tianqi differs from Yunnan Sanqi in fibrous root characteristics: Tianqi has fewer, thicker fibrous roots, while Yunnan Sanqi possesses numerous fine, velvety fibrous roots. Tianqi taproots are conical or short cylindrical, whereas Yunnan Sanqi taproots are conical or elongated. These morphological differences likely relate to cultivation practices and environmental conditions, necessitating further investigation into how Cd affects growth and organ-specific Cd distribution in Tianqi.

Most previous Cd-P. notoginseng research has focused on greenhouse simulations. This study, conducted in situ in a farmer's greenhouse in Jingxi City, Guangxi during the rainy season (July–September) when pests and diseases are prevalent, examined three-year-old plants to investigate Cd distribution, translocation, and enrichment characteristics across different organs. The findings aim to provide guidance for safe cultivation and quality assurance of Guangxi P. notoginseng.

Materials and Methods

1.1 Experimental Materials and Treatments

Three-year-old P. notoginseng plants were cultivated in a farmer's garden in Potianjiang, Jingxi City (opposite Qingshe Mountain) at 758 m elevation. Management practices followed local conventions.

Soil for the pot experiment was collected from actual P. notoginseng fields using an S-shaped sampling method from the 0–20 cm plow layer. After air-drying and passing through a 10-mesh sieve, appropriate $CdCl_2$ solutions were prepared and sprayed onto 5 kg dry soil portions, mixed thoroughly, and potted. Seven Cd treatments were established: 0 (control), 5, 10, 20, 30, 40, and 50 $mg \cdot kg^{-1}$, with three replicates per treatment and three similarly-sized plants per replicate. The cultivation period ran from July 9 to September 9, 2018, with management consistent with local practices. Soil agrochemical properties were: pH 4.86, organic matter 43.30 $mg \cdot kg^{-1}$, available N 178.11 $mg \cdot kg^{-1}$, available P 48.80 $mg \cdot kg^{-1}$, available K 203.70 $mg \cdot kg^{-1}$, and background Cd 0.44 $mg \cdot kg^{-1}$.

One week after Cd treatment, soil samples were collected and analyzed, yielding measured concentrations of 0.46, 5.07, 11.47, 20.89, 28.53, 39.60, and 51.02 $mg \cdot kg^{-1}$. These values fitted the equation $y = 0.9898x + 0.5182$ ($R^2 = 0.9972$).

1.2 Sample Collection and Processing

Whole plants were harvested, washed with tap water to remove soil, rinsed three times with deionized water, and separated into leaves, stems, rhizomes, taproots, and fibrous roots. Samples were killed at 105 °C for 30 minutes, dried to constant weight at 65 °C, ground into powder, and passed through a 50-mesh sieve for analysis.

1.3 Measurement Methods

1. **Agronomic traits**: Stem height (from rhizome to flower stalk), stem diameter (averaged from three measurement points), leaf length (leaflet length), leaf width (leaflet width), fibrous root number, root weight, and leaf area (leaf length × leaf width × 0.6134).
2. **Soil agrochemical properties**: Determined according to *Soil Agrochemical Analysis* (Bao, 2008).
3. **Soil Cd**: Determined by graphite furnace atomic absorption spectrophotometry per GB/T 17141-1997.
4. **Plant Cd**: Determined by graphite furnace atomic absorption spectrophotometry per GB/T 5009.15-2014.

1.4 Data Processing

Data were analyzed using Microsoft Office Excel 2007 and DPS 7.5 software, with significance testing by Duncan's new multiple range test (P < 0.05).

Results

2.1 Effects of Cadmium Stress on Cadmium Distribution in Panax notoginseng

Table 1 Cadmium content in different parts of Panax notoginseng

<table>
<tr><th>Cd concentration ($mg \cdot kg^{-1}$)</th><th>Leaf Cd content ($mg \cdot kg^{-1}$)</th><th>Stem Cd content ($mg \cdot kg^{-1}$)</th><th>Rhizome Cd content ($mg \cdot kg^{-1}$)</th><th>Fibrous root Cd content ($mg \cdot kg^{-1}$)</th><th>Ttaproot Cd content ($mg \cdot kg^{-1}$)</th></tr>
<tr><td>0 (control)</td><td>0.20$±0.02g|0.38±0.02g|0.64±0.02g|1.39±0.07g|0.44±0.02g||5|0.32±0.03f|0.59±0.03e|0.87±0.02d</td><td></td><td></td><td></td><td></td></tr>
</table>

Note: Different lowercase letters indicate significant differences among treatments (P < 0.05).

Table 1 shows that Cd content in each organ increased significantly (P < 0.05) with increasing Cd concentration, though accumulation patterns varied among organs. Under control conditions, Cd distribution followed: fibrous roots > rhizome > taproot > stem > leaf. At Cd concentrations of 5, 10, 20, 30, 40, and 50 $mg \cdot kg^{-1}$, the pattern became: rhizome > taproot > fibrous root > stem > leaf. Significant differences existed among treatments within each organ. Compared with the control, aboveground leaf and stem Cd contents increased by 1.60, 2.95, 4.35, 6.25, 7.55, and 8.55-fold, and 3.74, 2.53, 8.11, 10.92, 21.24, and 24.76-fold, respectively. Belowground rhizome, fibrous root, and taproot Cd contents increased by 9.61, 14.59, 20.69, 38.81, 46.66, and 59.11-fold; 3.77, 5.06, 8.16, 9.75, 11.08, and 13.19-fold; and 10.27, 18.16, 25.73, 31.98, 39.25, and 49.55-fold, respectively. Notably, Cd accumulation in leaves and fibrous roots showed relatively smaller increases.

To quantify the relationship between Cd treatment concentration and accumulation in different organs, linear regression was performed with organ Cd content (y) versus soil Cd concentration (x). All organs showed significant linear increases: leaf ($y = 0.0314x + 1.023$, $R^2 = 0.9819$), stem ($y = 0.1829x + 0.0688$, $R^2 = 0.9607$), rhizome ($y = 0.7306x + 1.023$, $R^2 = 0.9813$), fibrous root ($y = 0.3184x + 3.1842$, $R^2 = 0.9572$), and taproot ($y = 0.3950x + 2.1978$, $R^2 = 0.9781$). These relationships indicate significant positive correlations between Cd treatment concentration and accumulation in all organs. The slope coefficients reflect differential Cd uptake rates: 0.0314 (leaf), 0.1829 (stem), 0.7306 (rhizome), 0.3184 (fibrous root), and 0.3950 (taproot), suggesting the stability of Cd accumulation follows the order: leaf > stem > fibrous root > taproot > rhizome.

2.2 Effects of Cadmium Stress on Cadmium Enrichment and Aboveground Translocation

Table 2 Enrichment coefficients of Cd in different parts of Panax notoginseng

Cd concentration ($mg \cdot kg^{-1}$)	Rhizome enrichment coefficient	Fibrous root enrichment coefficient	Ttaproot enrichment coefficient
5	0.87	1.25	1.51
10	1.42	6.15	4.52
20	3.08	13.24	11.32
30	4.15	24.84	13.55
40	8.07	29.86	15.40
50	9.41	37.83	18.33

The bioconcentration factor (BCF), defined as the ratio of element concentration in plant tissue to that in soil, reflects heavy metal uptake and storage capacity. Table 2 shows that all tissues exhibited decreasing BCFs with increasing soil Cd concentrations. Among organs at the same treatment level, the rhizome showed the highest BCF. At 5 $mg \cdot kg^{-1}$ Cd, the fibrous root BCF exceeded that of the taproot, but at higher concentrations, the taproot BCF surpassed the fibrous root. At 5 $mg \cdot kg^{-1}$ Cd, both rhizome and fibrous root BCFs exceeded 1.0, with the taproot BCF reaching 0.9, indicating stronger Cd enrichment in underground parts, particularly the rhizome. Overall, P. notoginseng showed relatively weak Cd enrichment capacity that decreased rather than increased with Cd concentration.

Table 3 Transfer coefficients of Cd in Panax notoginseng under cadmium stress

Cd concentration ($mg \cdot kg^{-1}$)	Aboveground Cd content ($mg \cdot kg^{-1}$)	Belowground Cd content ($mg \cdot kg^{-1}$)	Transfer coefficient
0 (control)	0.29	0.82	0.35
5	0.46	2.88	0.16
10	3.77	26.71	0.14
20	7.16	41.90	0.17
30	8.70	57.73	0.15
40	18.97	82.53	0.23
50	23.62	112.90	0.21

The transfer coefficient, calculated as the ratio of aboveground to belowground Cd content, indicates translocation efficiency from roots to shoots. Table 3 shows a wave-like decreasing trend in transfer coefficients with increasing Cd concentration, displaying irregular patterns. The control treatment exhibited the highest transfer coefficient (0.35), with subsequent treatments showing values of 0.16, 0.14, 0.17, 0.15, 0.23, and 0.21. Tables 2 and 3 suggest a corresponding relationship between enrichment and transfer coefficients under certain conditions.

Discussion

3.1 Effects of Cadmium Stress on Cadmium Accumulation and Distribution in Panax notoginseng

Heavy metal content in P. notoginseng varies among production regions, likely related to local temperature, geography, soil conditions, previous crops, and genetic factors. Even within the same region, where climatic and soil conditions are similar, individual growth status contributes to heavy metal content variation among samples.

This study found significant positive correlations between soil Cd content and Cd concentrations in different organs, with accumulation stability following the order: leaf > stem > fibrous root > taproot > rhizome. However, organ-specific accumulation patterns differed. Under control conditions, Cd distribution was: fibrous roots > rhizome > taproot > stem > leaf, consistent with Li et al. (2015) who reported fibrous roots > rhizome > taproot > leaf > stem, though our leaf and stem distribution differed. Our findings align with Chen et al. (2014), who demonstrated stem Cd content exceeding leaf Cd content. At Cd treatments of 5–50 $mg \cdot kg^{-1}$, distribution shifted to: rhizome > taproot > fibrous root > stem > leaf, matching Huang et al. (2014).

These discrepancies may arise from several factors: First, regional differences between Guangxi Tianqi and Yunnan Sanqi affect temperature, moisture, evapotranspiration, nutrient availability, base saturation, and altitude. Second, this field study employed local cultivation practices without controlled temperature or moisture, unlike greenhouse experiments. Third, the experimental period (July 9–September 9, 2018) coincided with peak pest, disease, and rainfall seasons, with occasional waterlogging that may have affected Cd transport and accumulation. Fourth, altitude, shading rate, shade house type, and plant age influence organ-specific Cd accumulation. Fifth, different plant ages show varying mineral element absorption, translocation, and accumulation patterns. This study used three-year-old plants, differing from the two-year-old plants used in some studies—a key factor since most plants exhibit age-dependent differences in mineral uptake.

3.2 Effects of Cadmium Stress on Cadmium Enrichment and Aboveground Translocation

Within the experimental range, enrichment coefficients for leaves, stems, rhizomes, fibrous roots, and taproots all decreased with increasing Cd concentration, consistent with Zhu et al. (2014). Among organs, the rhizome showed the highest BCF, followed by fibrous roots and taproots. At 5 $\mathrm{mg \cdot kg^{-1}}$ Cd, fibrous root BCF exceeded taproot BCF, but at 20–50 $\mathrm{mg \cdot kg^{-1}}$, taproot BCF surpassed fibrous root BCF, with both equal at 20 $\mathrm{mg \cdot kg^{-1}}$ Cd. Leaves showed the lowest BCF, contrasting with some studies reporting fibrous roots > rhizome > taproot > leaf > stem. This discrepancy likely stems from methodological differences, plant age, and management practices. Field surveys revealed that Guangxi Baise P. notoginseng growers exclusively use organic fertilizers, as chemical fertilizers reportedly cause plant death and root rot. This organic cultivation may influence Cd accumulation patterns.

Transfer coefficients exhibited wave-like, irregular trends but remained below control values across all Cd treatments. The overall trend suggested relative increases with Cd concentration. The correspondence between enrichment and transfer coefficients aligns with studies on heavy metal lead translocation in fennel (Gan et al., 2018).

Conclusion

1. Cadmium stress significantly increased Cd content in all P. notoginseng organs, with significant positive correlations between Cd concentration and accumulation.
2. Under control conditions, Cd distribution was: fibrous roots > rhizome > taproot > stem > leaf. At Cd concentrations of 5, 10, 20, 30, 40, and 50 $\mathrm{mg \cdot kg^{-1}}$, distribution became: rhizome > taproot > fibrous root > stem > leaf.
3. Belowground Cd content was significantly higher than aboveground content, with both aboveground and belowground bioconcentration factors

decreasing gradually as Cd concentration increased.

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Note: Figure translations are in progress. See original paper for figures.