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Growth Responses and Accumulation Characteristics of Three Ornamentals Under Copper and Lead Contamination in a Hydroponic-Culture Experiment

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Abstract
A hydroponic experiment was carried out to study the accumulation characteristics of copper (Cu) and lead (Pb) combined pollution in three ornamental plants. The results showed that these tested ornamental plants had higher tolerance to Cu–Pb combined pollution and could effectively accumulate the heavy metals. The Cu and Pb concentrations were higher in the roots of the ornamental plants than that in the shoots. For *Panax notoginseng* (*P. notoginseng*), *Chlorophytum comosum* (*C. comosum*) and *Calendula officinalis* (*C. officinalis*), the average Cu and Pb concentration in the three ornamental plants were 1402.1 mg/kg, 829.5 mg/kg, and 1473.4 mg/kg for Cu and 2710.4 mg/kg, 4250.3 mg/kg, and 4303.6 mg/kg for Pb, respectively. The three ornamental plants accumulation and tolerance to Cu–Pb were demonstrated through the hydroponic-culture method in this study. Therefore, the three ornamental plants should have great potential to be used in remediation of soils contaminated by Cu and Pb and beautifying the environment simultaneously.

Keywords Ornamentals · Combined pollution · Phytoremediation · Bioaccumulation factor · Trans-location factor

With the rapid increase of urbanization and industrialization, environmental pollution and ecological destruction have become two important issues that are receiving more attention due to their threats to the health and survival of human beings. Among these threats, heavy metals cause the most serious pollution and damage to the soil environment (Doumett et al. 2010; Doumett et al. 2008; Yan et al. 2017). Pb and Cu are ubiquitous metal contaminants in urban soils, especially in larger urban areas (Datko-Williams et al. 2014) and around city roads (Zaidi et al. 2005). Recent studies had shown that varying levels of Pb and Cu pollution were found in many provinces and cities, such as Beijing, Nanjing, Guizhou, Fujian, Hebei, Guangxi, Jiangxi, Hainan, Chongqing, and Hong Kong (Sun et al. 2007a). The concentrations of Pb and Cu in urban soils range from 25.0 mg/kg to 28.6 mg/kg and 17.6 mg/kg to 111.3 mg/kg, respectively, which are higher than the background values of Pb and Cu for soils in China (26.0 mg/kg and 22.6 mg/kg, respectively) (Wei and Yang 2010). Moreover, heavy metal pollutants cannot be chemically or biologically degraded and have the characteristics of concealment, persistence, hysteresis, etc., and they endanger human health, life and safety through direct contact or food chain transmission (Li et al. 2014; Rajkumar et al. 2009). Therefore, the remediation of heavy metal-contaminated soil in urban areas represents a major problem that the environmental science community must resolve (Li et al. 2016).

Phytoremediation has become the preferred option for remediating heavy metal-contaminated soil (Liu et al. 2008) than conventional chemical and physical remediation methods (Pereira et al. 2010), which are generally costly and often produce other destructive effects (Mahar et al. 2016; Yan et al. 2017). Phytoextraction is the use of hyperaccumulators to extract heavy metals from contaminated soils or waters and transfer them to the relatively manageable aboveground environment (Dahmani-Muller et al. 2000). Thus, it has become important to screen out effective hyperaccumulators.

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Ornamental plants represent an important research direction that can simultaneously remedy and beautify contaminated environments. *P. notoginseng*, *C. comosum* and *C. officinalis* are herbaceous ornamental plants. Studies have shown that *Chlorophytum comosum* has a high tolerance to Pb when this element is not combined with other heavy metals (Youbao et al. 2011), and Wang found that *Impatiens balsamina*, *Calendula officinalis* and *Althaea rosea* had a higher tolerance and accumulation ability to cadmium (Cd) and lead (Pb) (Wang 2005). Therefore, the use of ornamental plants to remediate environmental pollution has important practical significance. In fact, the heavy metal elements cannot exist alone, and more are a mixture of two or more pollutants. (Zhao et al. 2013). However, few studies have focused on the combined pollution of Pb and Cu in the abovementioned ornamental plants. In urban areas, ornamental plants have been used for the remediation of metal-contaminated soils and thus have high practical and application value (Cameselle 2015).

The hyperaccumulation ability of three ornamental plants for heavy metals was studied using the method of hydroponic culture under the combination of Cu–Pb combined pollution in the paper so as to provide a scientific basis for the phytoremediation of heavy metal combined pollution in soils.

Materials and Methods

The hydroponic test method based on the work of Liu et al. (2008) was carried out on June 4th, 2016 in a green-house at Jilin Agricultural University. The three ornamentals seeds with full grain and uniform size are selected, and soaked and germinated at 25°C for sowing. Healthy and consistent seedlings of the three ornamentals were selected after one month of growth, and the roots were immersed in 0.1% $KMnO_4$ solution for 10 min and then rinsed with deionized water. Then, seedlings of the three ornamentals were cultivated in 250 mL conical flasks. In this study, we used a 20-fold dilution Hoagland nutrient solution (pH 6.7), which was replaced in the hydroponic experiments when the seedlings of the three ornamentals were cultivated for 3 to 4 days. The hydroponic solution was mixed with Pb $(CH_3COOH)_2 \cdot 3H_2O$ and $CuSO_4 \cdot 5H_2O$ to obtain the treatment concentrations. A total of eleven treatments (CK and T1–T10) were conducted, and the Cu and Pb concentrations in each treatment solution were 0 + 0 (CK), 5 + 50 (T1), 10 + 50 (T2), 20 + 50 (T3), 40 + 50 (T4), 80 + 50 (T5), 5 + 100 (T6), 10 + 100 (T7), 20 + 100 (T8), 40 + 100 (T9), 80 + 100 mg/L (T10). Three replications were performed for each treatment. One seedling was planted in each conical flask, and the solution was replaced every 5 days. All ornamental plants were harvested after 20 days of growth in the culture solution, rinsed repeatedly with deionized water and then divided into shoots and roots. The plant samples were dried at 105°C for 30 min and dried at 75°C to a constant weight and then ground to powder. The plant samples were digested with a HNO_3/$HClO_4$ (3:1, V/V) mixture (Yan et al. 2017). The content of Cu and Pb in plants were determined using a flame atomic absorption spectrophotometer (TAS-990, Beijing Purkinje General Instrument Co., Ltd., China).

Statistical analyses were performed using SAS statistical package (SAS Institute Inc., Cary, North Carolina, USA). Differences among treatment means were determined using a one-way analysis of variance (ANOVA) followed by Duncan's new multiple range test at significant levels ($p < 0.05$).

Results and Discussion

The Cu concentrations in the shoots and roots of the three ornamental plants are shown in Table 1. An analysis of variance showed that there were significant differences in Cu accumulation among the three ornamental plants ($p < 0.05$). After growing in conical flasks for 15 days, the Cu concentration in the roots of the three ornamental plants was much higher than that in the shoots and increased with increasing Cu and Pb concentration in the solution. The Cu or Pb enrichment factor (BC) was the ratio of the Cu or Pb content in plants and that of the Cu or Pb concentration in hydroponic solution, which reflected the the Accumulate ability of plants for Cu or Pb, and the translocation factor (TF) was the ratio of the Cu or Pb content in shoots and that of the roots, which reflected the Cu or Pb transfer ability of plants shoots (Tanhan 2007). When the Pb concentration in the solution was 50 mg/L, the Cu accumulation in the shoots and roots of *P. notoginseng*, *C. comosum* and *C. officinalis* was 76.0 to 158.8 mg/kg, 98.4 to 160.9 mg/kg and 66.7 to 166.7 mg/kg, and 451.2 to 2603.6 mg/kg, 277.3 to 1453.6 mg/kg and 585.7 to 2598.3 mg/kg, respectively, while the BC of the shoots and roots was 1.52 to 3.18, 1.97 to 3.22 and 1.33 to 3.33, and 9.02 to 52.1, 5.55 to 29.1 and 11.7 to 52.0, respectively. Simultaneously, the TF of *P. notoginseng*, *C. comosum* and *C. officinalis* was 0.03 to 0.34, 0.07 to 0.48 and 0.03 to 0.22, respectively. For *P. notoginseng*, when the Cu concentration of the solution was 10 mg/L (T2), the Cu concentration in the shoots reached the maximum value of 158.8 mg/kg while that in the roots was 700.1 mg/kg. When the Cu concentration was 80 mg/L (T5), the Cu concentration in the roots reached the maximum value of 2605.6 mg/kg while that in the shoots was small of 76.0 mg/kg. For *C. comosum*, when the Cu concentration of the solution was 10 mg/L (T2), the Cu concentration in the shoots reached the maximum value of 160.9 mg/kg while that in the roots was 412.9 mg/kg. When Cu concentration of the solution was 80 mg/L (T5), the Cu concentration in the roots reached

Table 1 Effect of Cu–Pb combined pollution on the Cu enrichment characteristics of three ornamentals

Plant variety	Treatments	Cu concentration (mg/kg)		Bioaccumulation factor		Translocation factor
		shoot	root	shoot	root	
Panax notoginseng	CK	17.9±6.27^{d}	78.0±21.0^{e}	-	-	-
	T1	154.7±20.5^{a}	451.2±43.2^{d}	3.09	9.02	0.34
	T2	158.8±17.7^{a}	700.1±59.1^{cd}	3.18	14.0	0.23
	T3	121.6±14.4^{b}	832.0±115.5^{c}	2.43	16.6	0.15
	T4	101.1±14.0^{bc}	1241.4±266.9^{b}	2.02	24.8	0.08
	T5	76.0±13.23^{c}	2603.6±204.6^{a}	1.52	52.1	0.03
	T6	143.8±25.9^{a}	745.3±149.1^{c}	1.44	7.45	0.19
	T7	149.6±4.80^{ab}	853.5±101.0^{c}	1.50	8.54	0.18
	T8	106.6±33.0^{bc}	1350.5±103.7^{b}	1.07	13.5	0.08
	T9	90.2±7.43^{cd}	1818.2±234.8^{a}	0.90	18.2	0.05
	T10	60.1±5.78^{d}	2645.5±626.3^{a}	0.60	26.5	0.02
Chlorophytum comosum	CK	19.2±4.09^{d}	59.0±16.8^{d}	-	-	-
	T1	134.2±20.9^{b}	277.3±39.4^{c}	2.68	5.55	0.48
	T2	160.9±10.3^{a}	412.9±34.2^{c}	3.22	8.26	0.39
	T3	130.6±10.1^{b}	718.8±75.2^{b}	2.61	14.4	0.18
	T4	130.6±8.96^{b}	845.6±50.6^{b}	2.61	16.9	0.15
	T5	98.4±15.0^{c}	1453.6±295.6^{a}	1.97	29.1	0.07
	T6	133.3±9.51^{b}	416.1±108.6^{cd}	1.33	4.16	0.32
	T7	169.7±10.6^{a}	883.2±125.0^{bc}	1.70	8.83	0.19
	T8	113.9±12.2^{c}	1184.9±83.6^{b}	1.14	11.9	0.10
	T9	76.8±15.4^{d}	1442.8±150.5^{b}	0.77	14.4	0.05
	T10	74.6±15.2^{d}	1489.3±950.3^{a}	0.75	14.9	0.05
Calendula officinalis	CK	23.0±6.20^{d}	49.0±18.3^{e}	-	-	-
	T1	66.7±6.24^{c}	585.7±75.1^{d}	1.33	11.7	0.11
	T2	166.7±16.1^{a}	744.8±36.7^{d}	3.33	14.9	0.22
	T3	121.3±9.48^{b}	1246.4±278.7^{c}	2.43	24.9	0.10
	T4	127.4±23.0^{b}	1965.3±393.2^{b}	2.55	39.3	0.06
	T5	72.6±16.5^{c}	2598.3±57.2^{a}	1.45	52.0	0.03
	T6	119.3±16.7^{bc}	436.2±34.9^{de}	1.19	4.36	0.27
	T7	183.9±4.92^{a}	816.0±117.3^{cd}	1.84	8.16	0.23
	T8	128.5±11.8^{b}	1274.6±305.3^{bc}	1.28	12.8	0.10
	T9	102.0±13.2^{c}	1942.0±387.6^{b}	1.02	19.4	0.05
	T10	79.3±9.65^{d}	2762.8±446.1^{a}	0.79	27.6	0.03

Different lowercase letters in the same column indicate significant differences ($p < 0.05$)

the maximum value of 1453.6 mg/kg while that in the shoots was small of 98.4 mg/kg. For *C. officinalis*, when the Cu concentration in the solution was 10 mg/L (T2), the Cu concentration in the shoots reached the maximum value of 166.7 mg/kg while that in the roots was 744.8 mg/kg, respectively. When Cu concentration in the solution was 80 mg/L (T5), the Cu concentration in the roots reached the maximum value of 2598.3 mg/kg while the Cu concentration in the shoots was small of 72.6 mg/kg, respectively.

When the Pb concentration in the solution was 100 mg/L, the Cu accumulation in the shoots and roots of *P. notoginseng*, *C. comosum* and *C. officinalis* was 60.1 to 149.6 mg/kg, 74.6 to 169.7 mg/kg and 79.3 to 183.9 mg/kg, and 745.3 to 2645.5 mg/kg, 416.1 to 1489.3 mg/kg and 436.2 to 2762.8 mg/kg, respectively. For *P. notoginseng*, when the Cu concentration in the solution was 10 mg/L (T7), the Cu concentration in the shoots reached the maximum value of 149.6 mg/kg while that in the roots was 853.5 mg/kg. When the Cu concentration in the solution was 80 mg/L (T10), the Cu concentration in the roots reached the maximum accumulation of 2645.5 mg/kg while that in the shoots was small of 60.1 mg/kg. For *C. comosum*, when the Cu concentration in the solution was 10 mg/L (T7), the Cu concentration in the shoots reached the maximum accumulation of 169.7 mg/kg while that in the roots was 883.2 mg/kg. When the Cu concentration in the solution was 80 mg/L (T10), the Cu concentration in the roots reached the maximum accumulation of 1489.3 mg/kg while that in the shoots was small of 74.6 mg/kg. For *C. officinalis*, when the Cu concentration in the solution was 10 mg/L (T7), the Cu concentration in the shoots reached the maximum accumulation (183.9 mg/kg) while that in the roots was 816.0 mg/kg. When the Cu concentration in the solution was 80 mg/L (T10), the Cu concentration in the roots reached the maximum accumulation of 2762.8 mg/kg while that in the shoots was small of 79.3 mg/kg.

When the Pb concentrations in the solution were 50 mg/L and 100 mg/L, the Pb concentration in the shoots and roots of *P. notoginseng* reached the maximum accumulation of 639.3 mg/kg (Cu = 20 mg/L and Pb = 100 mg/L) and 4781.6 mg/kg (Cu = 5 mg/L and Pb = 100 mg/L), respectively. The Pb concentration in the shoots and roots of *C. comosum* reached the maximum accumulation of 865.3 mg/kg and 7635.2 mg/kg (Cu = 10 mg/L and Pb = 100 mg/L), respectively, and the Pb concentration in the shoots and roots of *C. officinalis* reached the maximum accumulation of 967.5 mg/kg (Cu = 5 mg/L and Pb = 100 mg/L) and 7639.7 mg/kg (Cu = 40 mg/L and Pb = 100 mg/L), respectively.

These findings showed that Cu at low solution concentrations could promote Cu accumulation in the three ornamental plants while excess levels caused toxicity to the ornamental plants, therefore, the Cu accumulation in the shoots of the three ornamental plants reduced the upward movement of Cu in the ornamental plant parts (Bona et al. 2007). In addition, the results indicated that the Pb concentration in ornamentals differed based on the different Cu concentrations and types of ornamentals, suggesting plant metal accumulation was related to not only metal concentrations in solution (Mahar et al. 2016) but also plant types and their tissues (Wilcke et al. 1998). When Cu was at a low concentration, the three ornamentals were promoted the absorption of heavy metal Pb, exhibiting a synergistic of ions. However, when the concentration of Cu in the nutrient solution was high, the absorption of Pb by the three ornamentals were suppressed and the antagonistic of ions was exhibited. Considering the growth response as well as the shoots and roots of Cu uptake in the three ornamental plants, the Cu accumulation ability order was *C. officinalis* > *P. notoginseng* > *C. comosum*. The analysis of variance showed that there were significant differences in Pb accumulation among the three ornamental plants ($p < 0.05$), indicating that the Pb accumulation in the three ornamental plants changed significantly under different Cu and Pb concentrations in the solution (Table 2). Similarly, the Pb concentration in the roots was much higher than that of the shoots and increased with increasing Cu and Pb concentration in the solution. In general, the Pb accumulation among the three ornamental plants was higher at a Pb treatment concentration of 50 mg/L than when the Pb treatment concentration was 100 mg/L. The Cu BC of the shoots and roots was 0.60 to 1.50, 0.75 to 1.70 and 0.79 to 1.84, and 7.45 to 26.5, 4.16 to 14.9 and 4.36 to 27.6, respectively. Simultaneously, and the TF of *P. notoginseng*, *C. comosum* and *C. officinalis* was 0.02 to 0.19, 0.05 to 0.32 and 0.03 to 0.27, respectively, which falls well within the range with previous research results (Tao et al. 2011; Youbao et al. 2011). The BC in the shoots and roots of *P. notoginseng*, *C. comosum* and *C. officinalis* ranged from 2.53 to 8.39, 4.05 to 10.5 and 4.54 to 13.4, and 12.9 to 95.2, 30.0 to 76.4 and 31.6 to 81.8, respectively. In the present study, the TF value was lower than that under soil-culture conditions (Li et al. 2010).

Recently, the use of phytoextraction plants (flowering plants) as phytoremediation technology in heavy metal-contaminated soils represented an important task among researchers (Wei et al. 2003). In general, the methods used for screening enriched phytoextraction plants are field sampling analysis, nutrient solution culture and pot experiments. Domestically, few field experiments have been performed on the remediation of metal-contaminated soils using ornamental plants. Although the experiments performed here were carried out on a trial basis, the test plants for such experiments were collected from heavy metal-contaminated polluted soils. The heavy metal content in the sample was used to identify the plant's ability to enhance metal accumulation and determine whether it is a hyperaccumulator (Visoottiviseth et al. 2002). Internationally, the company Edenspace of the United States used *Brassica juncea* to phytoremediate Pb-contaminated soil in Bayonne, New Jersey. The use of this plant for phytoremediation showed great results, with the Pb content in the soil surface layer (0–15 cm) decreasing by 58.0%–64.6% (Lan et al. 2004). The plant *C. officinalis* isolated from pot experiments can be planted as urban greening plants in urban green belts, park squares, public green spaces and street flower beds, which can remedy contaminated environment and beautify it at the same time. Phytoremediation can alter the microbial community structure (Song et al. 2007) and increasing ecosystem diversity and stability (Tilman et al. 2006). Of course, the manual cleaning and harvesting of plant residues is carried out by artificial watering according to the water requirements of the restored plants. The disposal of harvested plant biomass after phytoremediation of heavy metal contaminated soils is still a debatable issue. Many approaches, including direct disposal, composting, compaction, incineration, and leaching, have been used for the treatment of heavy metal enriched biomass (Gomes 2012). Recently, fast pyrolysis has been regarded as a potential sustainable approach for the disposal of contaminated biomass, which can concentrate metals in a small volume, prevent metals volatilization into the atmosphere, and meanwhile provide some additional benefits (e.g., bioenergy production or phyto-mining) (Vocciante et al. 2019).

Table 2 Effect of Cu–Pb combined pollution on the Pb enrichment characteristics of three ornamentals

Plant variety	Treatments	Pb concentration (mg/kg)		Bioaccumulation factor		Translocation factor
		shoot	root	shoot	root	
Panax notoginseng	CK	41.5±9.23^{d}	64.0±5.97^{e}	-	-	-
	T1	196.0±32.9^{c}	1831.6±149.8^{d}	3.92	36.6	0.11
	T2	247.8±30.0^{bc}	4761.6±491.3^{a}	4.96	95.2	0.05
	T3	419.6±40.6^{a}	3044.0±257.9^{b}	8.39	60.9	0.14
	T4	307.7±13.1^{b}	1864.7±11.9^{d}	6.15	37.3	0.17
	T5	289.9±89.8^{b}	2449.3±311.3^{c}	5.80	49.0	0.12
	T6	412.7±97.5^{a}	4781.6±543.8^{a}	4.13	47.8	0.09
	T7	504.3±86.9^{c}	2411.0±307.7^{b}	5.04	24.1	0.21
	T8	639.3±17.3^{b}	1588.8±134.5^{c}	6.39	15.9	0.40
	T9	341.2±32.6^{d}	1285.0±132.4^{c}	3.41	12.9	0.27
	T10	252.9±22.5^{d}	1442.5±51.3^{c}	2.53	14.4	0.18
Chlorophytum comosum	CK	41.1±6.70^{c}	76.8±11.5^{c}	-	-	-
	T1	324.0±64.7^{b}	1497.8±192.8^{b}	6.48	30.0	0.22
	T2	522.3±114.8^{a}	3220.4±595.6^{a}	10.5	64.4	0.16
	T3	352.6±50.3^{b}	2600.3±267.8a	7.05	52.0	0.14
	T4	277.8±30.5^{b}	2884.0±193.1^{a}	5.56	57.7	0.10
	T5	244.8±34.8^{b}	2681.0±341.8^{a}	4.90	53.6	0.09
	T6	458.6±39.1^{bc}	3070.7±406.4^{c}	4.59	30.7	0.15
	T7	865.3±52.9^{a}	7635.2±266.8^{b}	8.65	76.4	0.11
	T8	437.7±48.3^{c}	7282.6±191.6^{a}	4.38	72.8	0.06
	T9	412.0±4.01^{c}	6918.5±161.4^{a}	4.12	69.2	0.06
	T10	404.5±29.7^{b}	6394.6±207.5^{b}	4.05	64.0	0.06
Calendula officinalis	CK	32.3±10.0^{c}	53.1±15.97^{d}	-	-	-
	T1	668.6±112.3^{b}	1763.4±203.5^{c}	13.4	35.3	0.38
	T2	545.3±48.7^{a}	2742.1±145.2^{b}	10.9	54.8	0.20
	T3	529.5±4.18^{a}	3147.9±113.4^{b}	10.6	63.0	0.17
	T4	496.6±65.1^{a}	4089.3±364.6^{a}	9.93	81.8	0.12
	T5	465.6±33.9^{a}	4000.8±18.4^{a}	9.31	80.0	0.12
	T6	967.5±28.4^{a}	3162.6±545.1^{c}	9.68	31.6	0.31
	T7	701.7±29.6^{b}	4606.9±706.6^{b}	7.02	46.1	0.15
	T8	736.6±41.8^{b}	6798.9±640.5^{a}	7.37	68.0	0.11
	T9	626.9±67.5^{c}	7639.7±375.9^{a}	6.27	76.4	0.08
	T10	453.9±36.1^{a}	6988.3±672.7^{a}	4.54	69.9	0.06

Different lowercase letters in the same column indicate significant differences ($p < 0.05$)

Thus, we consider applying the fast pyrolysis technology to treat the contaminated ornamental plants harvested from the field in future.

In conclusion, the results showed that these tested ornamental plants had higher tolerance to Cu–Pb combined pollution and could effectively accumulate the heavy metals. The Cu and Pb concentrations were higher in the roots of the ornamental plants than that in the shoots. The average concentration of the two heavy metals in the *P. notoginseng, C. comosum*, *C. officinalis* ornamental plants were 1402.1 mg/kg, 829.5 mg/kg and 1473.4 mg/kg for Cu and 2710.4 mg/kg, 4250.3 mg/kg and 4303.6 mg/kg for Pb, respectively. Although the three ornamental plants being of the accumulation and tolerance to Cu–Pb were demonstrated through the hydroponic-culture method in this study, the usage of these plants for the remediation of heavy metal contaminated soil needs to be further verified by field experiments.

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