

Growth Responses and Phytoremediation Capacity of *Colocasia esculenta* under Drought Conditions in Pb-Contaminated Soil

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ABSTRACT

Phytoremediation is an effective, plant-based strategy for removing heavy metals from contaminated environments under various conditions. This study examines how lead (Pb) pollution and drought stress affect *Colocasia esculenta*'s physiological reactions and capacity to accumulate Pb. Plants were grown for 45 days under two soil moisture conditions (100% and 50% field capacity) and treated with 100 mg/kg Pb. The findings indicated that drought stress significantly diminished root growth, whereas Pb exposure exhibited no significant effect ($p > 0.05$). No significant differences were observed in stem height, dry plant biomass, and relative growth rate (RGR) values ($p > 0.05$). Under the combined Pb exposure and drought condition, the chlorophyll content and chlorophyll fluorescence parameters (PI and Fv/Fm) did not change. Under drought conditions, translocation factor (TF) levels were less than 1 (0.45-0.56) for the first 30 days; yet, following 45 days, they were more than 1 (1.17). Under drought stress, the bioaccumulation factor (BAF) values were over 1 (1.99-5.14), suggesting a high potential for Pb accumulation. All of these indicate that *C. esculenta* is resistant to Pb and has the capacity to phytoremediate Pb-contaminated dry soils.

HIGHLIGHTS

- *Colocasia esculenta* was assessed for Pb phytoextraction under drought conditions.
- A 45-day pot experiment mixed 100 mg/kg of Pb with two levels of soil moisture.
- Drought impeded root development, but Pb alone had no significant effect on growth.
- Chlorophyll, Fv/Fm, and PI demonstrated stability under drought and Pb stress.
- BAF remained above 1; TF increased to 1.17 by day 45 during drought conditions.

1. INTRODUCTION

Lead (Pb) is classified as a hazardous heavy metal because of its severe toxicity and environmental persistence, making it a major environmental pollutant of global concern (Qi et al., 2018). Pb poisoning in agricultural soils is frequently caused by long-term farming practices, industrial emissions, or excessive pesticide use. This poses serious risks to crop output, soil quality, and human health (Kumar et al., 2020; Rahman et al., 2024). Pb pollution in agricultural areas has become an increasingly serious environmental problem in Thailand. For example, industrial activities

in Rayong Province have resulted in Pb accumulation in soils and crops, with some fruit samples containing Pb levels exceeding the national safety limit of 1 mg/kg for food crops, according to the Ministry of Public Health Announcement, while vegetable cultivation in Phitsanulok Province has been reported to contain Pb concentrations up to 8.29 mg/kg (Apilux et al., 2023). This contamination puts food safety at risk and pinpoints how urgently sustainable soil remediation techniques are needed.

Phytoremediation is one of the remediation strategies that has drawn the most attention as a

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sustainable, economical, and ecologically friendly way to reduce heavy metal contamination. This plant-based method takes advantage of some species' innate ability to absorb, store, and fix hazardous metals from polluted soils in both controlled and field settings (Jabeen et al., 2009). Even though phytoremediation is a promising and eco-friendly method, inorganic limitations like drought or water scarcity can restrict plant growth and biomass production, which lowers pollutant uptake and remediation efficiency (Tangahu et al., 2011). Seasonal drought, especially in the summer months, can limit the effectiveness of phytoremediation in soils contaminated with heavy metals. Plants under drought stress undergo complex physiological and biochemical changes, such as osmotic imbalance and decreased biomass (Ozturk et al., 2021). Therefore, choosing the right plant species for metal extraction and cleanup requires drought tolerance (Qi et al., 2018).

Some drought-resistant species, like Bermuda grass (*Cynodon dactylon*) (Sekabira et al., 2011) and shrub violet (*Hybanthus floribundus*) (Kachenko et al., 2011), exhibit the ability to accumulate heavy metals; nevertheless, their restricted biomass and slow growth limit extensive utilization. Finding new plant species with higher biomass output, drought tolerance, and the ability to accumulate metals is therefore crucial for phytoremediation research (Sarma, 2011). Pb-contaminated soils usually have seasonal water constraints, such as droughts or inconsistent rainfall, which restrict plant development. Since phytoremediation efficacy depends on plant biomass production and transpiration-driven mass flow, prospective species must be assessed under metal and water deficiency conditions, not just single-stress conditions. In tropical and subtropical regions, *Colocasia esculenta* (L.) Schott belongs to the family Araceae and is a wetland plant that has demonstrated tolerance to environmental stress and a notable ability to absorb heavy metals in both roots and shoots (Davis et al., 2023; Mariwy et al., 2024). However, little is known about how drought stress affects *C. esculenta*'s photochemical efficiency and capacity for Pb accumulation. This study aims to examine the drought tolerance, photosynthetic efficacy, and phytoremediation capabilities of *C. esculenta* in Pb-contaminated soil under controlled soil-moisture regimes (100% and 50% pot capacity) to develop recommendations for sustainable soil management and phytoremediation in drought-affected agricultural areas of Thailand.

2. METHODOLOGY

2.1 Plant, soil material, and experimental design

Colocasia esculenta was obtained from regions without a history of contamination near Mae Tao Creek, Phra That Pha Daeng Subdistrict, Tak Province, Northern Thailand. To ensure constant growth, plants were cultivated in a greenhouse for a month on soil completely devoid of heavy metals before the experiment. Uniform plants of similar size were chosen for the experiment; each had an average shoot length of around 21-23 cm and a root length of about 10 cm. Soil with a low background Pb concentration (<11 mg/kg) and no fertilizer amendment was obtained from Chatuchak Market, Bangkok, Thailand (Table 1). Soaking the soil in water allowed for the determination of the pot's field capacity (PC). The water was drained for a whole day after the plastic pots were covered with plastic sheets. By subtracting the dry weight of the soil from the weight of the soil after draining, the water content in PC was determined (Khamsuk et al., 2018). To achieve 100% PC and 50% PC, 930 mL and 465 mL of water were added to the pots; an initial assessment revealed that plants endured at 50% PC, establishing the maximum drought level they can withstand. The plants were relocated into plastic pots filled with soil at 100% PC and 50% PC. The pots were covered with plastic sheets to stop evaporation. By monitoring the overall weight of the pots on day 0, the water level in the pots was maintained throughout the 45-day experiment. After that, the weight was noted every day, and water was added to return the entire weight to its starting point. Additionally, moisture levels were regulated; the 50% PC treatment was maintained at a gravimetric soil water content of 24% (w/w), whereas the 100% PC treatment was maintained at 48% (w/w).

To achieve Pb contamination, 100 mg/kg of dry soil containing lead carbonate (PbCO_3) was added to the homogenized soil. The experimental conditions included (1) soil moisture, comprising two levels (100% and 50% PC), and (2) Pb addition, consisting of two levels (0 and 100 mg/kg). The pot experiment was arranged in 4 treatments: 0 mg/kg Pb with 100% PC (T1; control), 0 mg/kg Pb with 50% PC (T2; drought), 100 mg/kg Pb with 100% PC (T3; Pb + no drought), and 100 mg/kg Pb with 50% PC (T4; Pb + drought). Three repetitions of each treatment were conducted, with one plant per pot serving as a duplicate. The experiment was conducted using a fully

randomized approach. Plants were grown in the greenhouse under normal natural environment conditions for 45 days (28-32°C, 60% humidity, natural sunshine, and a 12/12 h photoperiod). During the trial period, all clearly visible symptoms of drought, such as wilting, leaf rolling, loss of turgor, leaf drooping, and margin drying or browning, as well as Pb-toxicity symptoms, such as chlorosis, necrotic lesions, and stunting or decreased leaf size in the plants, were documented. Plant growth and Pb accumulation were measured after 30 and 45 days, and the performance index (PI) and photosynthetic pigments were evaluated at the end of the experiment.

2.2 Growth measurement

Plant samples were gathered, cleaned twice with tap water, rinsed with distilled water, and then divided into shoots and roots before being oven-dried for 72 h at 65°C until their weight remained consistent. Plants' dry weights were measured and evaluated for Pb accumulation. By measuring the distance from the tip of the stem to the region above ground, the stem height was determined. Poisoning symptoms were observed during the experiment, and a ruler was used to measure the root length from the root ends to the stem base.

2.3 Determination of Pb in the plant tissue

The 0.5 g of plant samples were digested in a 2:1 ratio of HNO₃ to HClO₄ (v/v) using the open tube digestion technique (Simmons et al., 2005). A flame atomic absorption spectrophotometer (FAAS, Varian AA-220FS) was used to measure the amount of Pb present in plants. Hollow cathode lamps were run at 7.5 mA, and the wavelengths were set at 283.3 nm. Quantification was performed using a calibration curve derived from a series of diluted standard solutions, exhibiting a coefficient of determination (r²) exceeding 0.995.

2.4 Chlorophyll fluorescence and pigment measurement

At day 45, the performance index (PI), photosynthetic pigments, and chlorophyll fluorescence (Fv/Fm) of plants in all four treatments (T1-T4) were determined. These parameters were determined by the two factors: soil moisture (100% and 50% PC) and Pb addition (0 and 100 mg/kg). Chlorophyll fluorescence was measured on fully expanded leaves using a chlorophyll fluorometer (Pocket PEA, Hansatech Instruments Ltd., King's

Lynn, Norfolk, UK). Leaves were dark-adapted for 30 min using leaf clips prior to measurement. Minimal fluorescence (Fo) and maximal fluorescence (Fm) were recorded, and variable fluorescence was calculated as Fv = Fm - Fo. The maximum quantum yield of PSII was calculated as Fv/Fm = (Fm - Fo)/Fm (Maxwell and Johnson, 2000; Strasser et al., 2000; Stirbet and Govindjee, 2011). Plant samples were collected, cleansed twice with tap water, and then rinsed with distilled water to determine photosynthetic pigments. The samples were then oven-dried at 65°C for 3 days and homogenized with a mill (IKA: Japan). To measure the quantity of chlorophyll (Chl) a and Chl b, fresh leaf samples were obtained from each pot in the dark, cleaned with deionized water, and then 0.5 g of fresh leaf was chopped into tiny pieces and homogenized with 5 mL of acetone (80% v/v). The chlorophyll content was calculated according to the equations of Porra et al. (1989) and Holm (1954) based on mg chl/g fresh weight (FW) (Korkmaz et al., 2010):

$$\text{Chl a (mg/g FW)} = 12.25 \times A_{663.6} - 2.55 \times A_{646.6}$$

$$\text{Chl b (mg/g FW)} = 20.31 \times A_{646.6} - 4.91 \times A_{663.6}$$

$$\text{Chl a+b (mg/g FW)} = 17.76 \times A_{646.6} + 7.34 \times A_{663.6}$$

Where: Chl a and b are the chlorophyll a and chlorophyll b, respectively.

2.5 Data analysis

The bioaccumulation factor (BAF) was calculated according to Wilson and Pyatt (2007) as follows:

$$\text{BAF} = \frac{\text{Pb concentration in the plant}}{\text{Pb concentration in the soil}}$$

The translocation of Pb from roots to shoots was measured using the translocation factor (TF), which was calculated as follows (Cui et al., 2007):

$$\text{TF} = \frac{\text{Pb concentration in the shoot}}{\text{Pb concentration in the root}}$$

Relative growth rate (RGR) was calculated according to Hunt's equation (Hunt, 1978):

$$\text{RGR} = \frac{\ln W_2 - \ln W_1}{T_2 - T_1}$$

Where; RGR is the relative growth rate (g/g/d), and W₁, T₁, and W₂, T₂ are the initial and final dry weights and times for each treatment, respectively.

2.6 Statistical analysis

The mean and standard error of three replicates were computed. Data were analyzed using ANOVA in SPSS (version 21.0; SPSS Inc., Chicago, IL, USA). When ANOVA indicated significant differences ($p < 0.05$), mean comparisons were performed using Dunnett's post hoc test to compare each treatment with the control ($\alpha = 0.05$). The relationships between Pb concentrations in plant tissues at $p < 0.05$ were evaluated using Pearson's correlation.

3. RESULTS AND DISCUSSION

3.1 Physico-chemical properties of the experimental soils

As shown in Table 1, the experimental soils had a neutral pH (7.1). The cation exchange capacity (CEC) values were 31.4 cmol/kg, and the soil had a clay texture with modest amounts of organic matter (2.44 g/kg). Essential nutrient levels were comparatively high, particularly available P (40 mg/kg) and K (159 mg/kg), while total N (0.11%) was at a moderate level. These nutrients are essential for promoting the growth of roots and the absorption of metals. The soil's overall background Pb content was 10.86 mg/kg. The soil's EC value was 0.81 dS/m.

3.2 Combined effects of Pb and drought on plant growth

The plants were cultivated at a concentration of 100 mg/kg Pb, either by itself or in conjunction with

drought stress. In comparison to the control groups (T1 and T3), the drought treatments (T2 and T4) demonstrated a minor reduction in root length as the trial progressed, with a significant difference ($p < 0.05$) (Figure 1(a) and (b)). However, as compared to the control group, the stem height of plants exposed to Pb during drought circumstances showed no adverse effects. According to Table 2, there was no significant mean difference ($p > 0.05$) in the RGR and dry plant biomass data for any treatment. In the Pb-treated plants under well-watered conditions (T3; Pb + 100% PC), RGR decreased significantly with exposure time, from 0.058 ± 0.0066 at day 30 to 0.044 ± 0.0017 g/g/day at day 45 ($p < 0.05$; Table 2). The reduction in root length at the end of the trial was significantly impacted by drought stress, even though Pb had no effect ($p < 0.05$).

Table 1. Physico-chemical properties of the experimental soils

Characteristics	Value
1. Soil pH	7.1
2. Organic matter	2.44 g/kg
3. Soil texture	Clay
4. CEC	31.40 cmol/kg
5. Total nitrogen	0.11 %
6. Available phosphorus	40 mg/kg
7. Available potassium	159 mg/kg
8. Electrical conductivity	0.81 dS/m
9. Pb	10.86 mg/kg

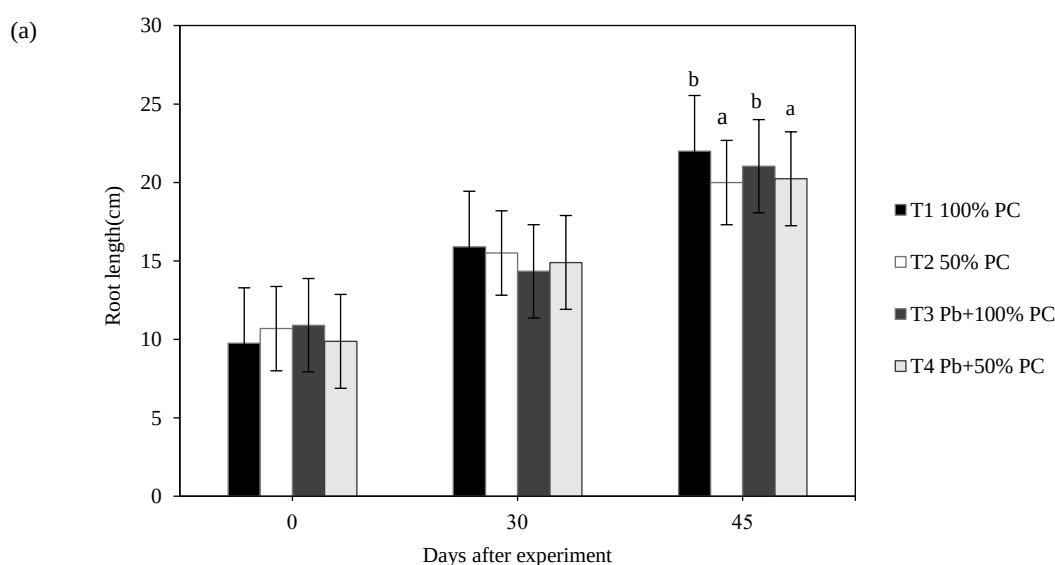


Figure 1. Root length (a) and stem height (b) of *C. esculenta* under conditions of no drought and drought, with or without Pb, at 0, 30, and 45 days. Data are mean $\pm$ SD ($n = 3$), and different letters indicate significant differences ($p < 0.05$).

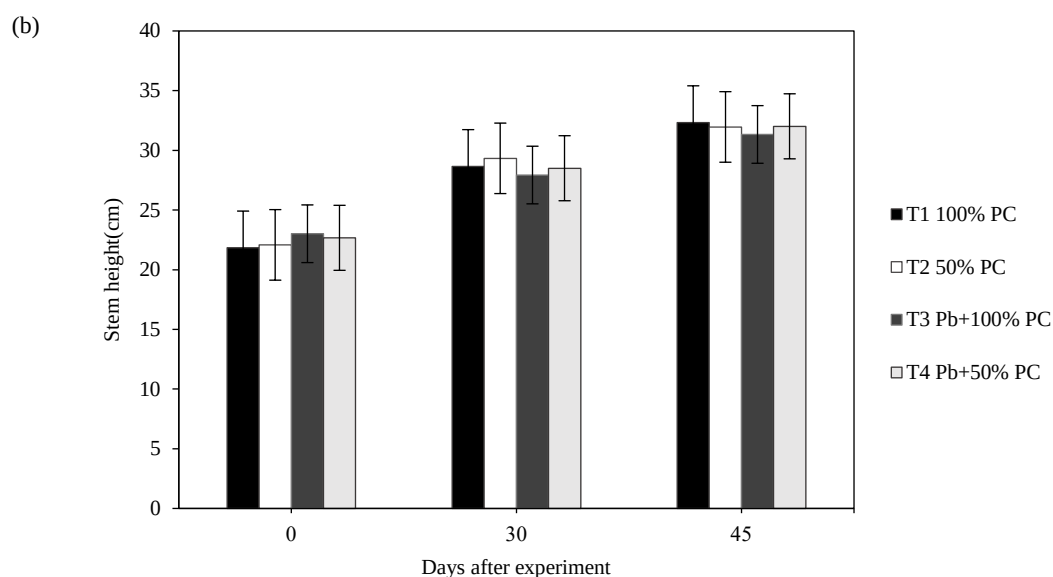


Figure 1. Root length (a) and stem height (b) of *C. esculenta* under conditions of no drought and drought, with or without Pb, at 0, 30, and 45 days. Data are mean $\pm$ SD (n=3), and different letters indicate significant differences ($p<0.05$) (cont.).

Table 2. Dry biomass production (DW, g) and relative growth rate (RGR, g/g/day) of *C. esculenta* grown in various soil treatments for 30 and 45 days

Treatments	Exposure time (days)				
	0	30		45	
	DW	DW	RGR	DW	RGR
T1: 100% PC	2.62 ^A ± 0.09	14.53 ^{a,B} ± 0.64	0.057 ^{a,A} ± 0.0076	19.53 ^{b,C} ± 2.41	0.045 ^{a,A} ± 0.0012
T2: 50% PC	3.36 ^A ± 0.11	13.48 ^{a,B} ± 0.99	0.046 ^{a,A} ± 0.0066	18.50 ^{c,C} ± 1.27	0.038 ^{a,A} ± 0.0006
T3: Pb + 100% PC	2.63 ^A ± 0.18	15.13 ^{a,B} ± 0.24	0.058 ^{a,B} ± 0.0066	19.14 ^{a,C} ± 1.49	0.044 ^{a,A} ± 0.0017
T4: Pb + 50% PC	2.84 ^A ± 0.27	16.79 ^{a,B} ± 0.68	0.059 ^{a,A} ± 0.0058	18.77 ^{a,C} ± 2.44	0.042 ^{a,A} ± 0.0002

Values are mean $\pm$ SE (n=3). Those with the same letter did not differ, while small letters indicated treatment differences and capital letters showed exposure time differences ($p<0.05$).

The drought treatment (50% PC) was selected in accordance with a mild-to-moderate water deficit that preserves plant viability and biomass for Pb uptake and phytoremediation testing based on our preliminary screening. In addition, this moisture level is relevant to field conditions, as the Thai Meteorological Department (TMD) reported that the Northern region experienced variable rainfall in 2025, including periods of below- and above-normal rainfall (TMD, 2025). The effects of Pb and drought stress on *C. esculenta* growth performance were examined throughout a 45-day pot experiment. The findings demonstrated that modest drought stress significantly reduced root length, yet plants were still able to grow under all treatments. However, neither Pb contamination nor drought stress significantly affected stem height or dry biomass. The findings show that

C. esculenta can withstand the combined stress, especially when it comes to sustaining aboveground growth in spite of limited root formation. Similar findings from earlier research have shown that while shoot development is frequently preserved under mild stress, drought stress mostly impacts root elongation due to changed water availability and osmotic adjustment (Gupta et al., 2020). The shoot tissues of *C. esculenta* can maintain growth for a longer period because of osmotic adjustment and water storage in petioles and corms. However, drought-induced inhibition of root elongation may result from limited carbohydrate allocation to belowground tissues and a decrease in root hydraulic conductivity (Vásquez et al., 2025). Similar results have been seen in other crops, such as wheat and cassava, where dryness considerably decreased root density and length, but

stem height was mostly unchanged (Bacher et al., 2022). These findings demonstrated that whereas stem height is unaffected by drought and Pb, restricted root development may indicate drought stress.

3.3 Effects of Pb and drought on chlorophyll contents and fluorescence parameters

Table 3 illustrates the chlorophyll and fluorescence of well-watered and moderate drought plants with and without 100 mg/kg Pb. After 45 days,

there was no discernible change in total chlorophyll and chlorophyll a+b ($p>0.05$), and all treatments showed chlorophyll a predominating over chlorophyll b. Likewise, no significant alterations were noted in chlorophyll fluorescence parameters (PI and Fv/Fm) between drought-treated and unstressed plants, irrespective of Pb contamination ($p>0.05$). The findings imply that fluorescence characteristics and chlorophyll contents were unaffected by Pb exposure or dryness ($p>0.05$; Table 3).

Table 3. Chlorophyll and fluorescence of *C. esculenta* growing in well-watered and severe drought conditions with and without Pb contamination after 45 days. All parameters were measured on the second fully expanded leaf beneath the growing point (values are mean $\pm$ SE; n=3)

Treatments	Chlorophyll content (mg/g FW)			PI	Fv/Fm
	Total	a	b		
T1: 100% PC	20.40 $\pm$ 1.62	12.34 $\pm$ 1.17	8.06 $\pm$ 1.04	6.42 $\pm$ 0.002	0.80 $\pm$ 0.001
T2: 50% PC	19.77 $\pm$ 0.88	12.89 $\pm$ 0.66	7.88 $\pm$ 0.94	6.38 $\pm$ 0.007	0.82 $\pm$ 0.006
T3: Pb + 100% PC	18.96 $\pm$ 1.14	11.03 $\pm$ 2.01	7.93 $\pm$ 0.15	5.97 $\pm$ 0.004	0.79 $\pm$ 0.007
T4: Pb + 50% PC	20.69 $\pm$ 1.97	12.68 $\pm$ 2.09	8.01 $\pm$ 0.88	5.98 $\pm$ 0.009	0.83 $\pm$ 0.003

C. esculenta has physiological tolerance mechanisms that protect the photosynthetic machinery from oxidative stress, according to the current study's constant fluorescence metrics (Fv/Fm and PI) and notably unchanged chlorophyll levels. Fv/Fm indicates the maximum quantum yield of PSII in dark-adapted leaves, whereas PI is an integrative index of PSII performance that is often more sensitive to stress and typically decreases under stress conditions (Baker, 2008). The maintenance of chlorophyll pigments under drought is indicative of effective osmotic adjustment and antioxidant activity, which sustain photosystem II and support continuous carbon uptake (Li et al., 2024). These findings suggest that *C. esculenta* can maintain performance under coupled Pb+drought by adjusting root development and biochemically protecting the photosynthetic apparatus.

Moreover, prior research has demonstrated that, depending on the length and intensity of the stress, drought stress can either maintain or lower chlorophyll levels (Song et al., 2026). Plant adaptability may have helped maintain high PSII efficiency under drought, as Fv/Fm values remained around 0.80 over 45 days. In healthy plants, Fv/Fm typically ranges from 0.75 to 0.85 and declines under stress (Guidi et al., 2019). The consistent Fv/Fm of *C. esculenta* may suggest effective photoprotection via antioxidant activity and non-photochemical quenching (Pluciński et al., 2023).

Interestingly, combined drought and Pb does not negatively affect PI, indicating adaptive adjustments in PSII energy fluxes that sustain photosynthesis (Li et al., 2024). Overall, steady Fv/Fm and PI show that *C. esculenta* can withstand mild drought and Pb, which is in line with findings that drought-tolerant species preserve PSII stability through improved antioxidants, osmotic adjustment, and chloroplast integrity (Ozturk et al., 2021). This pinpoints how *C. esculenta* uses biochemical compounds with antioxidant capacity to maintain the photosynthetic process to survive under stressful environments.

3.4 Pb accumulation in plant tissues

The accumulation of Pb by *C. esculenta* is presented in Table 4. When compared to control groups, Pb accumulation was noticeably higher under combined stress circumstances (T3; Pb+100% PC) ($p<0.05$). With a concentration of 513.66 mg/kg at the conclusion of the trial, plants under drought stress showed the greatest accumulation of Pb. During the first 30 days of exposure, the concentration of Pb is higher in the roots than in the shoots. After 45 days of exposure, plants in the drought-treated condition (T4) showed higher BAF levels (5.14) than those in the well-watered treatment (T3). All TF values for *C. esculenta* were less than 1.0, except for the combined stress treatment (Pb+drought) observed in a 45-day experiment. This suggests that after 45 days of

exposure, mild dryness did not affect Pb translocation, confirming its potential for phytoextraction.

According to this study, Pb translocation to shoots in *C. esculenta* was lower at 30 days than at 45 days, indicating increased root-to-shoot Pb translocation with exposure time. This pattern implies that during the early exposure period, Pb was first bound in the roots, restricting its movement to the shoots. Ahmad et al. (2011) found reduced Pb translocation in maize (*Zea mays* L.) during early stress exposure, demonstrating the plant's ability to detoxify Pb in root tissues. Similar findings were seen in a 15-day hydroponic test on Siam weed (*Chromolaena odorata*), where PEG-induced stress limited translocation to the shoots while increasing Pb absorption into the roots. This reduction in *C. esculenta* was caused by either sequestration in the root vacuoles or the precipitation of insoluble Pb salts in intercellular gaps (Yongpisanphop et al., 2017;

Srirueang et al., 2022). Pb has limited root-to-shoot translocation and is typically less mobile in plants than essential minerals, particularly during early exposure under water scarcity. By attaching to negatively charged functional groups in cell-wall pectins, restricted xylem loading, transporter control, and quick Pb retention in roots may immobilize Pb in the apoplast and decrease the mobile Pb fraction available for translocation (Rahman et al., 2024). Partial saturation of binding sites and/or alterations in root permeability and xylem loading may enhance Pb transport to shoots with prolonged exposure. According to Baker (1981), *C. esculenta* is an accumulator because $TF > 1$ after 45 days. This result implies that prolonged drought stress may raise Pb mobilization in aerial tissues, possibly as a result of drought-induced changes in xylem loading and root permeability (Rahman et al., 2024).

Table 4. Dry biomass, Pb accumulation, translocation factor (TF) and bioaccumulation factor (BAF) values of *C. esculenta* grown in contaminated soil for 0, 30 and 45 days

Treatment	Day	Dry biomass (g/plant)	Pb accumulation (mg/kg)			TF	BAF
			Shoot	Root	Total		
T3: Pb + 100% PC	0	2.63±0.18	0.00±0.00	0.00±0.00	0.00±0.00	0.00	0.00
	30	15.13±0.24	61.33±2.85 ^{a,A}	137.66±14.11 ^{a,B}	199.00±15.18 ^{a,A}	0.45	1.99
	45	19.14±1.49	168.66±11.26 ^{b,C}	277.66±1.76 ^{b,C}	446.33±12.47 ^{b,C}	0.61	4.46
T4: Pb + 50% PC	0	2.84±0.27	0.00±0.00	0.00±0.00	0.00±0.00	0.00	0.00
	30	16.79±0.68	116.33±23.85 ^{a,B}	208.33±1.45 ^{a,B}	324.66±22.73 ^{a,B}	0.56	3.25
	45	18.77±2.44	277.33±28.67 ^{b,D}	236.33±2.03 ^{b,C}	513.66±30.38 ^{b,D}	1.17	5.14

Values are mean±SE (n=3). Those with the same letter did not differ, while small letters indicated treatment differences and capital letters indicated exposure time differences at p<0.05.

Prior research has demonstrated that Pb and drought have an impact on the absorption and distribution of heavy metals in plants, including transpiration rate and water usage efficiency, which were also noted in citrus (*Citrus aurantium* L.) (Giannakoula et al., 2021). It has been demonstrated that drought stress alters the metabolism of starch in *C. esculenta* (Zhang et al., 2024), possibly having an indirect impact on metal absorption and translocation. Furthermore, it has been discovered that native *C. esculenta* wetland populations may act as bioaccumulators of Pb and other metals in contaminated soils (Chayapan et al., 2015; Davis et al., 2023). This species' capacity to transfer Pb to aboveground tissues during drought conditions points to an adaptive detoxifying mechanism that enables the safe disposal of contaminated biomass.

The overall BAF values are greater than 1 in both drought-treated and untreated plants,

demonstrating the capacity of the growing plants for Pb uptake. To combat the harmful effects of metal ions, plants often trigger antioxidative reactions (Rahman et al., 2024). According to phytochemical investigations, *C. esculenta* has a high antioxidant capacity and is known to be rich in phenolic and flavonoid compounds, which supports the idea that these metabolites aid in its tolerance mechanisms (Nugroho et al., 2025). Heavy metal toxicity often causes oxidative stress, which plants respond to by increasing peroxidase (POD)-related activities to maintain cellular integrity and photosynthetic activity (Rahman et al., 2024). Some Araceae species, such as elephant foot yam (*Amorphophallus paeoniifolius*), have been reported to accumulate heavy metals through similar enzyme-mediated detoxification responses, which implies that metal tolerance and sequestration characteristics may be present within this family (Singh et al., 2017). Therefore, the Pb

tolerance and accumulation observed in *C. esculenta* in the present study reflect similar family-level traits.

Studies showing that BAF and TF can demonstrate their phytoremediation potential for Pb-contaminated soils are supported by the Pb accumulation in *C. esculenta* throughout the course of the 45-day treatment. Our results indicate that drought-induced increases in Pb mobility and plant adaptation mechanisms enhance phytoextraction efficacy (Acharya et al., 2025). *C. esculenta* is therefore a viable option for phytoremediation techniques in regions with fluctuating water levels because of its Pb tolerance, drought adaptability, and translocation capabilities. Wetland plants that are not intended to be hyperaccumulators are examples of wild native or indigenous species that often adapt to the natural habitat and may have unexplored potential to clean up the environment. Hence, Chayapan et al. (2015) suggest *C. esculenta* for heavy metal-contaminated soil/sediments. Growing *C. esculenta* in Pb-contaminated soils could jeopardize food safety, even though it can absorb and translocate Pb. Clearly separating remediation plots from areas used for food production, harvesting at the best times to maximize metal removal, handling contaminated biomass safely and regulating its disposal or treatment, and managing risks to avoid livestock grazing and unintentional exposure are all important aspects of practical phytoremediation applications. Water-saving management can enhance phytoremediation and contain pollutants in drought-prone locations.

4. CONCLUSION

This experiment demonstrated that *C. esculenta* can withstand 45 days of combined drought and Pb stress while maintaining growth, photosynthetic efficiency, and chlorophyll integrity. Even though Pb's mobility was restricted after its initial exposure at 30 days, the quick translocation of Pb to aerial tissues during a protracted mild drought gives evidence of accumulator properties. The results of the study demonstrate the promising capacity of *C. esculenta* as a phytoextraction agent for Pb in dry polluted soils. These results shed important light on *C. esculenta*'s potential for phytoremediation, especially in drought-prone areas.

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AUTHOR CONTRIBUTIONS

Jampasri K. conceptualized the study, developed the methodology, supervised the research, managed project administration, acquired funding, and performed a writing-review and editing. Saeng-ngam S. conceptualized the study, developed the methodology, and performed writing—original draft preparation and writing—review and editing. Larpkern P. developed the methodology, conducted the investigation, curated the data, and performed formal analysis, and prepared figures and visualizations. Moungrimuangdee B. developed the methodology, conducted the investigation, curated the data, performed formal analysis, and performed a writing review and editing.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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