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## Phytoextraction Potential of *Colocasia esculenta* for Cadmium- and Zinc-contaminated Soils under Moderate Drought Stress: A Short-Term Pot Study

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### Abstract

This study investigates the effects of moderate drought on growth, physiology, and heavy metal accumulation in *Colocasia esculenta* cultivated in cadmium (Cd) and zinc (Zn) contaminated soils. Plants were grown for 30 days under moisture levels of 100% (well-watered), 60%, and 40% field capacity (FC), representing moderate drought, in soils containing 100 mg/kg Cd and Zn. Drought had no impact on the relative growth rate (RGR), whereas metal exposure significantly reduced dry weight and stem height ( $p < 0.05$ ) of the plants. The photochemical efficiency of PSII (Fv/Fm) and chlorophyll content remained stable ( $p > 0.05$ ), but the water content (WC) of the leaves decreased under drought stress ( $p < 0.05$ ). Translocation factors (TF) for both metals were above 1 in all treatments, indicating that heavy metal predominantly accumulated in shoots, with Cd exhibiting greater bioaccumulation factors (BAF) (2.40–3.03) than Zn (1.39–2.98). Overall, moderate drought limited biomass production but enhanced the accumulation of Cd and Zn and translocation to the shoots. These findings suggest that *C. esculenta* is suitable for the phytoextraction of Cd- and Zn-contaminated soils under drought-stress conditions after short-term exposure of 30 days. However, reduced biomass under drought may decrease overall phytoextraction despite higher tissue concentrations. Therefore, field-scale investigations under variable rainfall conditions are still required.

**Keywords:** cadmium, *Colocasia esculenta*, drought stress, metal stress, phytoremediation, zinc

### 1. Introduction

Drought has been demonstrated to exacerbate heavy metal uptake in plants, especially when soil moisture levels drop below certain thresholds (Muhammad et al., 2024). The interaction between drought stress and heavy metal pollution presents a compound threat to food safety, plant productivity, and soil health. Because heavy metals persist in the environment for a long time, phytoremediation—the use of plants to remove or stabilize contaminants—has emerged as a widely used and cost-effective approach to environmental remediation. (Bhat et al., 2022; Yan et al., 2020). According to the Thai

Meteorological Department (TMD, 2025), drought frequency and intensity in northern and northeastern Thailand have increased in recent years. Due to long-term fertilizer use and other inputs, cadmium (Cd) and zinc (Zn) accumulated in agricultural soils and residual pore water under low soil moisture, affecting their mobility and bioavailability and endangering crops and ecosystems (Angon et al., 2024; Kumar et al., 2020; Rashid et al., 2023; Wang et al., 2020).

Phytoremediation mechanisms, such as phytoextraction and phytostabilization, can decrease the bioavailability of metals in soils. Hyperaccumulator species are capable of absorbing large quantities of

metals (Tan et al., 2023). However, drought conditions significantly affect the efficacy of phytoremediation and are increasingly prevalent due to climate change. According to Muhammad et al. (2024), drought stress can modify plant physiology and decrease transpiration and biomass, subsequently influencing the assimilation and translocation of heavy metals. Previous research has indicated that drought may decrease phytoextraction efficiency by restricting metal mobility in arid soils, while other studies have increased accumulation because of stress-induced changes in root permeability (Peng et al., 2022). Therefore, choosing the right plant species for metal extraction and remediation requires drought tolerance.

Species associated with wetlands can frequently endure varying water conditions, from saturated to water-limited environments, making them suitable candidates for assessing metal uptake and tolerance during water scarcity. *Colocasia esculenta* (L.) Schott belongs to the family Araceae and is a tropical food crop known for its resilience to diverse environmental conditions and its ability to uptake and accumulate metals in contaminated soils (Kundu et al., 2024; Mariwy et al., 2024). Moreover, previous studies have suggested the use of *C. esculenta* for phytoremediation in heavy metal-contaminated soils and sediments under non-drought conditions (Chayapan et al., 2015). However, evidence is still scarce concerning the association between moderate water shortage and Cd and Zn contamination and its effects on growth and Cd–Zn uptake/translocation in soil-cultivated *C. esculenta*. Therefore, it is important to assess chlorophyll content and chlorophyll fluorescence parameters as indicators of photosystem II performance under water-deficit conditions. Our hypothesis is that a moderate water deficit impacts the uptake of Cd and Zn and root-to-shoot translocation in *C. esculenta* by affecting plant water status and photosynthetic performance, thereby influencing phytoextraction efficacy. Thus, this study investigated growth responses, plant water content, photosynthetic performance, and Cd–Zn accumulation parameters in *C. esculenta* under moderate drought in soil contaminated with Cd and Zn.

## 2. Objectives

This study investigated the phytoextraction potential of *C. esculenta* for Cd and Zn in contaminated soil under moderate drought conditions. It also examined the relationship between Cd–Zn uptake and translocation with plant water status and photosynthetic performance, including water content

(WC), chlorophyll (Chl) content, and chlorophyll fluorescence parameters.

## 3. Materials and Methods

### 3.1 Plants Materials and Soil Preparation

The experimental soil was obtained from areas that have not been previously contaminated with heavy metals. The soil had a neutral pH of 7.0 and a comparatively low organic matter concentration of 2.08 g/kg. It was classified as clay, exhibiting a high cation exchange capacity (CEC) of 36.01 cmol/kg. It had 0.14% total nitrogen, 65 mg/kg of available phosphorus, and 151 mg/kg of available potassium. The experimental soil was initially air-dried, sieved through a 2 mm mesh, and homogenized before being transferred into plastic containers. The field capacity (FC) of the pot (PC) was determined by soaking the soil with water, following the method outlined by Khamsuk et al. (2018). Briefly, pots filled with soil were saturated with distilled water and allowed to drain freely for 24 h while covered with plastic sheets to minimize evaporation. The PC value was calculated as the difference between the weight of the drained soil and the oven-dried soil weight (105°C for 24 h). The containers were filled with 930, 558, and 372 mL of water for 100%, 60%, and 40% PC, respectively. The experiment maintained soil moisture by weighing pots daily and replenishing water to compensate for evapotranspiration losses at 48%, 28.8%, and 19.2%. *C. esculenta* was obtained near the Zn mine in Tak province, in the Mae Tao River basin of northern Thailand. These PC levels represent relative water limitation that occurs during dry seasons or reduced irrigation (TMD, 2025). Plant background Cd concentrations were  $1.29 \pm 0.31$  mg/kg in root and  $24.62 \pm 2.85$  mg/kg in the shoot, whereas Zn concentrations were  $1.38 \pm 1.03$  and  $26.36 \pm 5.02$  mg/kg, respectively. Uniformly sized plants were transplanted into the pots after being precultivated in a nursery for three weeks.

### 3.2 Experimental Design

Six experimental treatments and three control treatments were performed. Each treatment was prepared in five replicates, each consisting of one plantlet. A randomized complete block design was used to study drought-metal stress. Plants were grown in well-watered conditions (100% PC) and moderate drought conditions (40% and 60% PC), with 100 mg/kg of Cd for treatments T1–T3 and Zn at 100 mg/kg for treatments T4–T6 by spiking the soil with aqueous solution of  $\text{CdCl}_2 \cdot 2.5\text{H}_2\text{O}$  and  $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ ,

respectively. For artificially contaminated soil preparation, each heavy metal was spiked into the experimental soil and then homogenized. The spiked soil was aged for two weeks before transplantation to facilitate metal–soil interactions and stabilization without chemical fertilizers. The control groups (C1–C3) did not receive any metals. A bench-scale pot experiment was conducted in a greenhouse (12/12 h photoperiod). All pot experiments were set up without the addition of chemical fertilizer during the 30-day experimental period. Plant growth, WC, performance index (PI), chlorophyll pigments, and PSII photochemical efficiency (Fv/Fm) were assessed. Heavy metal accumulation was also evaluated.

### 3.3 Cd and Zn Analysis

The plant samples were harvested, washed with tap water, rinsed with distilled water, oven-dried at 65°C for three days, and ground to a fine powder. Dried plants (0.5 g) were digested with 5 mL of 69% HNO<sub>3</sub> in a digestion block until the solution was clear. The digests were filtered using Whatman No. 42 filter paper and subsequently diluted to a final volume of 25 mL with deionized water. Cd and Zn concentrations were determined using a flame atomic absorption spectrometer (SpectrAA 55B, Varian) equipped with hollow cathode lamps set at 228.8 nm (Cd, 4 mA) and 213.9 nm (Zn, 5 mA). A calibration curve was generated from standard solutions (2–10 mg/L) with  $r^2 > 0.995$ , and the detection limits were determined accordingly (0.002–0.003 mg/L). Furthermore, stem height and root length were measured, and toxicity symptoms were visually monitored throughout the experiment.

### 3.4 Phytoremediation and Photosynthesis Potential

The following equations (Cui et al., 2007; Hunt, 1978; Wilson & Pyatt, 2007) were used to assess the phytoremediation efficiency of the plants:

$$BAF = \frac{M_{shoot} \text{ or } M_{root}}{M_{soil}} \quad (1)$$

$$TF = \frac{M_{shoot}}{M_{root}} \quad (2)$$

where  $M_{shoot}$  (mg/kg),  $M_{root}$  (mg/kg) and  $M_{soil}$  (mg/kg) represent the metal concentration in the shoot (stem and leaf tissues), the root, and the metal concentration of soil, respectively.

$$RGR = \frac{\ln W_2 - \ln W_1}{T_2 - T_1} \quad (3)$$

Where RGR is the relative growth rate (g/g/d);  $W_1$  and  $T_1$  and  $W_2$  and  $T_2$  are the initial and final dry weights and times for each treatment, respectively.

Chlorophyll fluorescence was assessed using a portable photosynthesis meter. The photochemical efficiency of PSII (Fv/Fm) in dark-adapted leaves was determined based on the measured parameters (Maxwell & Johnson, 2000). Photosynthetic efficiency was evaluated using a chlorophyll fluorometer (Pocket PEA, Hansatech Instruments Ltd, King's Lynn, Norfolk, UK). A minimum of 30 readings from a leaf were collected to derive a single final average reading.

The chlorophyll content was determined using the following equations by Korkmaz et al. (2010), which were based on mg chl/g fresh weight (FW):

$$\text{Chl a} = 12.25 \times A_{663.6} - 2.55 \times A_{646.6},$$

$$\text{Chl b} = 20.31 \times A_{646.6} - 4.91 \times A_{663.6},$$

$$\text{Chl a} + \text{b} = 17.76 \times A_{646.6} + 7.34 \times A_{663.6},$$

where Chl a and Chl b are chlorophyll a and chlorophyll b, respectively.

The WC was quantified and represented as a percentage using the following formula (Slawinski et al., 2021):

$$WC (\%) = \frac{\text{Fresh weight} - \text{Dry weight} \times 100}{\text{Fresh weight}} \quad (4)$$

### 3.5 Statistical Analysis

The mean and standard error of five replicates were calculated, and data were analyzed using SPSS v21.0. A two-way factorial ANOVA was performed with metal treatment (control, Cd, and Zn) and soil moisture (100%, 60%, and 40% PC) as fixed factors, including the metal  $\times$  moisture interaction. When significant effects were detected ( $p < 0.05$ ), Duncan's multiple range test was used to compare mean differences among treatments.

## 4. Results

### 4.1 Combined Effect of Metal and Drought on Plant Growth

Table 1 presents the growth responses of *C. esculenta* under different drought and metal stress conditions. In control treatments (C1–C3), RGR and root length did not differ significantly ( $p > 0.05$ ). However, exposure to Cd and Zn (T1–T6) significantly reduced dry biomass and stem height ( $p < 0.05$ ), indicating that heavy metals acted as stressors affecting plant growth. Among treatments, dry biomass after 30 days ranged from 10.2 to 14.5 g/plant. A minor reduction in root

length was observed, varying between 13.1 and 14.3 cm in plants exposed to each heavy metal as soil moisture levels decreased from 100% to 60% and 40% PC. The well-watered control (C1; 100% PC) demonstrated the greatest stem height at  $35.9 \pm 2.13$  cm, whereas plants exposed to either reduced moisture or metal treatments showed reduced stem heights, ranging from approximately 28.2 to 32.5 cm. The RGR values varied between 0.040 and 0.059 g/g/d, with the combination of Zn + 100% PC exhibiting the highest mean RGR at  $0.059 \pm 0.02$  g/g/d, whereas the combination of Cd + 40% PC recorded the lowest at  $0.040 \pm 0.02$  g/g/d.

#### 4.2 Combined Effect of Metal and Drought on Photochemical Responses

Table 2 summarizes the photochemical responses of *C. esculenta* to combined stress. No significant differences ( $p > 0.05$ ) were observed in

terms of chlorophyll content (total, Chl a+b), PI values, or the maximum quantum yield of PSII photochemistry (Fv/Fm) among treatments. This suggests that the degree of drought and heavy metal did not substantially influence fluctuations in Chl contents after 30 days of exposure. The fluorescence parameters from this study indicated that photosystem II maintained its functional integrity under drought stress. In contrast, WC exhibited significant differences among treatments ( $p < 0.05$ ), with higher values in controls (C1–C3: 60.8%–73.8%) and markedly lower values under combined stress (T1 – T6: 20.8% – 51.2%). The pronounced reduction in WC of T2, T3, T5, and T6 co-treatments suggested that water limitation, rather than Cd/Zn toxicity, was the primary factor affecting tissue hydration during early stress exposure. This may reflect a more rapid and stronger physiological response to osmotic imbalance than to metal detoxification.

**Table 1** Dry biomass, root length, stem height, and RGR of *C. esculenta* measured under various drought conditions with and without heavy metal contamination after 30 days of exposure

| Treatments     | Dry biomass (g/plant) |                   | Root length (cm) | Stem height (cm)      | RGR (g/g/d)      |
|----------------|-----------------------|-------------------|------------------|-----------------------|------------------|
|                | Initial               | Final             |                  |                       |                  |
| C1: 100% PC    | $3.6 \pm 0.62$        | $14.5 \pm 2.18$   | $15.8 \pm 1.45$  | $35.9 \pm 2.13^{b,B}$ | $0.046 \pm 0.03$ |
| C2: 60% PC     | $2.9 \pm 1.85$        | $14.1 \pm 1.21^B$ | $16.2 \pm 2.50$  | $30.2 \pm 4.18^a$     | $0.053 \pm 0.01$ |
| C3: 40% PC     | $3.4 \pm 0.19$        | $13.3 \pm 0.27^B$ | $14.9 \pm 1.37$  | $32.5 \pm 1.15^B$     | $0.045 \pm 0.02$ |
| T1: Cd+100% PC | $2.7 \pm 0.11$        | $13.7 \pm 4.12$   | $16.3 \pm 0.44$  | $31.6 \pm 0.31^A$     | $0.054 \pm 0.01$ |
| T2: Cd+60% PC  | $2.8 \pm 0.12$        | $13.4 \pm 5.39^A$ | $13.8 \pm 1.33$  | $30.1 \pm 2.94$       | $0.052 \pm 0.01$ |
| T3: Cd+40% PC  | $3.3 \pm 0.18$        | $11.1 \pm 1.24^A$ | $14.3 \pm 0.60$  | $29.7 \pm 5.63$       | $0.040 \pm 0.02$ |
| T4: Zn+100% PC | $2.5 \pm 0.64$        | $14.3 \pm 1.09$   | $15.8 \pm 0.83$  | $30.2 \pm 0.73^{b,A}$ | $0.059 \pm 0.02$ |
| T5: Zn+60% PC  | $3.1 \pm 0.29$        | $11.4 \pm 4.43^A$ | $14.0 \pm 1.50$  | $29.7 \pm 1.88$       | $0.043 \pm 0.01$ |
| T6: Zn+40% PC  | $2.8 \pm 1.17$        | $10.2 \pm 2.23^A$ | $13.1 \pm 1.27$  | $28.2 \pm 0.58^{a,A}$ | $0.043 \pm 0.01$ |

Values are presented as mean  $\pm$  SE (n=5), with lowercase letters indicating differences between treatments with and without heavy metal contamination, and uppercase letters indicating significant differences among control, Cd, and Zn treatments ( $p < 0.05$ ).

**Table 2** Chlorophyll content, fluorescence parameters, and WC of *C. esculenta* grown under various drought conditions with and without heavy metal contamination after 30 days of exposure

| Treatments     | Chlorophyll content (mg/g FW) |                  |                 | PI               | Fv/Fm            | WC (%)                |
|----------------|-------------------------------|------------------|-----------------|------------------|------------------|-----------------------|
|                | Total                         | a                | b               |                  |                  |                       |
| C1: 100% PC    | $19.85 \pm 2.11$              | $11.69 \pm 2.12$ | $7.96 \pm 0.98$ | $5.87 \pm 0.002$ | $0.78 \pm 0.001$ | $73.8 \pm 0.93^{c,B}$ |
| C2: 60% PC     | $21.77 \pm 0.79$              | $13.65 \pm 2.08$ | $8.22 \pm 1.74$ | $5.33 \pm 0.004$ | $0.83 \pm 0.007$ | $69.7 \pm 0.51^{b,C}$ |
| C3: 40% PC     | $18.31 \pm 1.48$              | $12.19 \pm 1.66$ | $8.12 \pm 1.56$ | $4.97 \pm 0.003$ | $0.82 \pm 0.005$ | $60.8 \pm 0.45^{a,C}$ |
| T1: Cd+100% PC | $21.35 \pm 1.72$              | $13.01 \pm 0.81$ | $8.24 \pm 1.28$ | $5.89 \pm 0.001$ | $0.77 \pm 0.008$ | $49.1 \pm 0.93^{b,A}$ |
| T2: Cd+60% PC  | $22.16 \pm 2.04$              | $13.68 \pm 1.91$ | $8.39 \pm 1.58$ | $4.68 \pm 0.007$ | $0.73 \pm 0.004$ | $24.2 \pm 0.57^{a,A}$ |
| T3: Cd+40% PC  | $19.44 \pm 0.68$              | $12.19 \pm 0.82$ | $7.25 \pm 1.47$ | $5.60 \pm 0.004$ | $0.81 \pm 0.003$ | $20.8 \pm 0.34^{a,A}$ |
| T4: Zn+100% PC | $20.81 \pm 0.71$              | $12.63 \pm 2.07$ | $8.65 \pm 3.22$ | $6.09 \pm 0.007$ | $0.75 \pm 0.001$ | $51.2 \pm 0.37^{b,A}$ |
| T5: Zn+60% PC  | $19.79 \pm 1.24$              | $12.38 \pm 1.08$ | $7.68 \pm 0.96$ | $5.41 \pm 0.002$ | $0.79 \pm 0.002$ | $31.8 \pm 0.67^{a,B}$ |
| T6: Zn+40% PC  | $18.66 \pm 1.47$              | $12.40 \pm 0.91$ | $7.35 \pm 1.04$ | $5.24 \pm 0.004$ | $0.76 \pm 0.002$ | $37.6 \pm 0.25^{a,B}$ |

Values are presented as mean  $\pm$  SE; columns followed by the same letter are not significantly different according to the Duncan test ( $p < 0.05$ )

**Table 3** Accumulation of Cd and Zn in the roots and shoots, translocation factor (TF), and bioaccumulation factor (BAF) of *C. esculenta* after 30 days of exposure

| Treatments       | Total metal accumulation<br>(mg/kg) | Metal accumulation<br>(mg/kg) |                             | TF  | BAF  |       |
|------------------|-------------------------------------|-------------------------------|-----------------------------|-----|------|-------|
|                  |                                     | Root                          | Shoot                       |     | Root | Shoot |
| T1: Cd + 100% PC | 286.2                               | 126.9 ± 8.55 <sup>b,B</sup>   | 159.3 ± 2.63 <sup>a,B</sup> | 1.3 | 1.27 | 1.59  |
| T2: Cd + 60% PC  | 398.4                               | 95.8 ± 2.32 <sup>a,A</sup>    | 302.6 ± 0.90 <sup>b,B</sup> | 3.2 | 0.96 | 3.03  |
| T3: Cd + 40% PC  | 424.1                               | 184.6 ± 8.42 <sup>a,C</sup>   | 239.5 ± 4.15 <sup>a,C</sup> | 1.3 | 1.85 | 2.40  |
| T4: Zn + 100% PC | 226.6                               | 73.8 ± 4.84 <sup>b,A</sup>    | 152.8 ± 1.59 <sup>a,A</sup> | 2.1 | 0.74 | 1.53  |
| T5: Zn + 60% PC  | 193.3                               | 54.3 ± 1.69 <sup>a,A</sup>    | 139.0 ± 3.22 <sup>b,B</sup> | 2.6 | 0.54 | 1.39  |
| T6: Zn + 40% PC  | 397.3                               | 99.8 ± 3.68 <sup>a,B</sup>    | 297.5 ± 7.40 <sup>b,D</sup> | 3.0 | 1.00 | 2.98  |

Values are expressed as mean ± SE; lowercase letters indicate differences between the same treatments with and without heavy metal contamination, while uppercase letters denote significant differences among the control, Cd, and Zn treatments based on the Duncan test ( $p < 0.05$ )

### 4.3 Heavy Metal Accumulation in Plants under Drought

Table 3 shows that Cd and Zn primarily accumulated in the shoots of *C. esculenta*, with the highest concentrations recorded in T2 and T6 (302.6 ± 0.90 and 297.5 ± 7.40 mg/kg, respectively). Cd exhibited markedly greater total accumulation than Zn ( $p < 0.05$ ), suggesting potentially greater phytoextraction capability for Cd than for Zn under the present experimental conditions. After 30 days, the total accumulation of Cd (286.2 – 424.1 mg/kg) was generally greater than that of Zn (193.3–397.3 mg/kg). The increasing Cd concentration during moderate drought (T2+T3; 398.4–424.1 mg/kg) indicates that water scarcity did not affect Cd absorption efficiency. Moreover, Cd translocation was highest under the 60% PC treatment (TF = 3.2), whereas Zn translocation was elevated under drought conditions, reaching its maximum at 40% PC (TF = 3.0). BAF values in shoots exceed 1 for both metals (Cd: 1.59–3.03; Zn: 1.39–2.98), with the highest BAF observed for Cd at 60% PC and for Zn at 40% PC. Moderate water deficit altered metal distribution and enhanced root-to-shoot translocation, suggesting the potential of *C. esculenta* for Cd/Zn phytoextraction in water-limited conditions.

### 5. Discussion

After 30 days of observation, the growth responses of *C. esculenta* demonstrated that metal contamination was the primary stressor impeding plant growth, particularly stem height, whereas drought alone did not significantly affect stem height in our experimental setup. This decrease aligns with the known phytotoxic effects of Cd, which disrupts cell elongation, and excessive Zn, which interferes with metabolic processes (Rashid et al., 2023).

However, no fertilizer was applied in this study. For this reason, growth inhibition under Cd/Zn treatments may be due to nutritional imbalances. For root growth and adaptation, wetlands often serve as sinks for heavy metals from natural runoff or mining discharges, exposing plants such as *C. esculenta* to both metal toxicity and water deficiency. A moderate water deficit may promote root proliferation and enhance water-use efficiency, thereby enhancing the plant's ability to withstand metal-induced stress (Gupta et al., 2020). Moreover, plants may activate detoxification mechanisms involving metal chelation and antioxidant production to mitigate oxidative damage (Islam et al., 2024). It was reported that *C. esculenta* is rich in phenolic and flavonoid compounds and exhibits high antioxidant capacity in phytochemical analyses (Nugroho et al., 2025). Thus, strong antioxidant capacity might facilitate *C. esculenta*'s tolerance of heavy metals as indicated by 100% survival after 30 days of exposure. Our findings demonstrate that Cd and Zn toxicity affected aboveground growth. However, the root system may be resilient to combined stress (Cd/Zn + drought), highlighting *C. esculenta*'s capacity to withstand both drought and metal pollution.

*Colocasia esculenta* maintained relatively stable chlorophyll levels when subjected to combined stress (Cd/Zn + drought), suggesting adaptive mechanisms that protect photosynthetic pigments, as observed in other stress-tolerant species (Nas & Ali, 2018). Even under combined stress, the Fv/Fm values remained essentially unchanged, indicating that PSII photochemistry was mostly maintained. This observation is consistent with the typical 0.75–0.85 range in healthy plants (Guidi et al., 2019). Meanwhile, WC was reduced due to highlighting osmotic imbalance as a critical factor limiting growth.

Heavy metals impact plant and soil water availability, thereby impairing water absorption. Soils saturated with metal have lower osmotic potential than root cell sap. Consequently, metal ions can accumulate to high levels, thereby restricting plant water intake and disrupting osmotic processes (Rucińska-Sobkowiak, 2016). Drought primarily affected the physiology of *C. esculenta*, whereas short-term exposure to Cd/Zn had a limited impact; nonetheless, prolonged heavy metal stress could interfere with water relations (Rucińska-Sobkowiak, 2016). Based on the stability of Fv/Fm and PI under combined Cd/Zn and drought stress, *C. esculenta* can maintain photochemical efficiency, probably through osmotic adjustment and the preservation of chloroplast integrity—mechanisms typical of stress-adapted wetland plants (Muhammad et al., 2024; Ozturk et al., 2021).

Based on our preliminary screening (data not shown), the drought treatment (40 – 60% PC) was chosen to maintain plant viability and biomass for heavy metal uptake and phytoremediation tests under a moderate water deficit. Similarly, in 2025, the TMD reported rainfall variability in northern Thailand, including below- and above-normal rainfall, particularly in Maesot, Tak province. In the present study, for heavy metal tolerance measurement, the accumulation of Cd and Zn was also higher in the shoots than in the roots, which might have resulted in reduced stem height and shoot biomass in *C. esculenta* compared to the control, as described above. It is possible that *C. esculenta* lowered the shoot elongation in its green stems to conserve water and mitigate combined stressor-induced photosynthesis losses. Thus, *C. esculenta* was a suitable candidate for Cd and Zn phytoremediation because it meets phytoremediation potential characteristics, including accumulation capacity, metal tolerance, and total metal uptake (Reeves & Baker, 2000). The notion that reduced soil moisture increases Cd bioavailability is further corroborated by the highest BAF in shoots recorded under moderate drought (T2; 3.03), which may be attributed to altered rhizosphere chemistry and decreased competition between phosphate and Cd ions (Zhao et al., 2025). The BAF values in shoots were greater than 1 across treatments, varying from 1.39 to 3.03, which contradicts previous findings related to shoot crops exposed to drought and metal stress (Saeng-ngam & Jampasri, 2022). The adaptation of wetland plants may depend on either the metal dose or the level and duration of drought stress. Moreover, even though wetland plants are generally non-hyperaccumulators, the present study

demonstrated that drought seemed to enhance Cd and Zn movement toward shoots, as evidenced by TF values > 1, indicating that moderate drought had no negative effect on metal translocation after 30 days of exposure, thereby supporting its potential purpose for phytoextraction.

Moreover, our previous study on the application of polyethylene glycol (PEG-6000) to induce drought stress in hydroponic tests for 30 days found that it did not affect the Cd/Zn content in the leaves and roots of siam weed (*Chromolaena odorata*) (Saeng-ngam & Jampasri, 2022). Unlike in *C. esculenta*, Zn accumulation was less pronounced, likely due to tighter homeostatic regulation compared with Cd. This suggests that drought-induced physiological mechanisms mobilize Cd > Zn and transport it to the shoot. However, these patterns should also be interpreted in the context of a growth medium. For example, Chayapan et al. (2015) reported higher Zn than Cd accumulation in *C. esculenta* grown hydroponically for 15 days under non-drought conditions. This may be due to medium-dependent metal chemistry because soil processes, such as sorption, precipitation, and complexation, dramatically alter Cd and Zn speciation and bioavailability compared to nutrient solutions. Nevertheless, evidence from *C. esculenta* and other Araceae species, such as elephant foot yam (*Amorphophallus paeoniifolius*), suggests that metal tolerance and sequestration traits may occur within this family, supporting further evaluation of Araceae candidates for phytoremediation under field-relevant soil and water regimes.

Although Zn and Cd may theoretically compete for root adsorption sites in phytoremediation-contaminated soils due to their analogous atomic characteristics and electrostatic interactions, this competitive behavior could not be explained in our investigation, which used a pot experiment that did not mix spiked Cd and Zn. The elevated Cd uptake can be ascribed to the plant's direct absorption potential. Additionally, *C. esculenta* is high in antioxidants and phenolic and flavonoid components (Nugroho et al., 2025). Under conditions of combined stress that lead to an increased accumulation of heavy metals, this phenomenon can be understood by recognizing that these metabolites likely play an integral role in the plant's tolerance and accumulation mechanisms under the combined stress of heavy metals and drought. Bhat et al. (2022) found that adaptive alterations in root absorption capacity and stress-responsive metabolism in particular

wetland plants increase phytoremediation capabilities during short-term drought and heavy metal exposure. Similarly, the present study found that 30 days of moderate drought or diminished soil moisture did not significantly reduce Cd and Zn uptake. This observation supports the ability of specific indigenous wetland flora to sustain phytoremediation during transient water deficits. This is because mild drought preserves membrane integrity and transporter function, which facilitates heavy metal translocation from the root to the shoot in tolerant species (Muhammad et al., 2024; Yan et al., 2020).

Therefore, our study explained the complex links between drought and heavy metal accumulation, as supported by previous research. Native wetland plants, such as *C. esculenta*, exposed to short-term moderate drought stress have various physiological responses that result in increased accumulation of heavy metals. The inclusion of drought-signaling molecules might enhance metal translocation and xylem loading through either increased chelation or vacuolar sequestration. Overall, *C. esculenta* may be a promising candidate for Cd/Zn phytoextraction under moderate water deficit due to its ability to store and translocate metals to aerial parts. However, practical application should be approached with long-term experiments, field-scale validation under varying rainfall conditions, and studies that include co-contamination scenarios; these are essential to verify the consistency, sustainability, and real-world efficacy of phytoextraction performance. In addition, harvested Cd/Zn-enriched biomass should be treated and prohibited from entering the food chain. Post-harvest management may include controlled incineration or thermal treatment, followed by stabilization and disposal of ash in regulated landfills or metal recovery from ash where applicable, in accordance with local environmental regulations (Mukherjee et al., 2025).

## 6. Conclusion

Based on the 30-day pot experiment, Cd and Zn stress reduced growth, whereas combined stress did not affect photosynthetic performance. *C. esculenta* can accumulate both Cd and Zn in the shoots under moderate drought stress (40%–60% PC), with a higher accumulation of Cd than Zn. Higher TF values revealed that the plant mobilizes heavy metals to aboveground tissues, which is suitable for phytoextraction. These results provide additional information on wetland plants, highlighting *C. esculenta* as a viable species for phytoremediation,

especially in drought-prone environments. However, a limitation of this study is that it was conducted as a short-term (30-day) pot experiment; therefore, longer-term experiments and field-scale trials are required to evaluate the sustainability of Cd–Zn phytoextraction and plant performance under prolonged drought and variable rainfall conditions. Furthermore, tissue nutrient profiling should be conducted to distinguish nutrient-deficiency effects from metal-specific toxicity mechanisms.

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## 8. CRediT Statement

**Sukhumaporn Saeng-ngam:** Investigation, data curation, writing—original draft, writing—review & editing.

**Panadda Larpkern:** Conceptualization, methodology, formal analysis, funding acquisition.

**Boontida Moungrimuangdee:** Data curation, methodology, validation, formal analysis.

**Kongkeat Jampasri:** Conceptualization, methodology, supervision, writing—review & editing, funding acquisition, and project administration.

## 9. Abbreviations

| Abbreviation | Full Term                                                                                                                  |
|--------------|----------------------------------------------------------------------------------------------------------------------------|
| BAF          | Bioaccumulation factor                                                                                                     |
| Cd           | Cadmium                                                                                                                    |
| Chl          | Chlorophyll                                                                                                                |
| FC           | Field capacity                                                                                                             |
| Fv/Fm        | Maximum quantum efficiency of PSII                                                                                         |
| PC           | Pot capacity (field capacity of the pot)                                                                                   |
| PI(PIABS)    | Performance index for energy conservation from photons absorbed by PSII to the reduction of intersystem electron acceptors |
| PSII         | Photosystem II                                                                                                             |
| RGR          | Relative growth rate                                                                                                       |
| TF           | Translocation factor                                                                                                       |
| WC           | Water content                                                                                                              |
| Zn           | Zinc                                                                                                                       |

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