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Role of *Colocasia esculenta L. schott* in arsenic removal by a pilot-scale constructed wetland filled with laterite soil

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Abstract

The role of plant *Colocasia esculenta L. schott* (*C. esculenta*) in arsenic removal was investigated in a pilot-scale constructed wetland (PCW), which was filled with laterite soil (19.90−28.25% iron by weight). This PCW consists of 2 sets of flow systems in parallel, with *C. esculenta* planted at a density of 20 plants/m^2 in one system and the other without any plants. The synthetic water containing arsenic concentration of 0.50 mg/l, with its pH controlled at 7.0 and influent flow at 1.5 m^3/day. With *C. esculenta*, the arsenic in water decreased from 0.485 mg/l to 0.054 mg/l (89% removal), whereas, without *C. esculenta*, the arsenic decreased from 0.485 mg/l to 0.233 mg/l (52% removal). As for the fate of the influent arsenic, the *C. esculenta* was responsible for 65% of arsenic

accumulation. Note that the arsenic was found mostly within the root zone depth (20−40 cm). It appears that such a high capacity of arsenic removal was enhanced both by the plants through rhizostabilization and by the iron-adsorbed process within the laterite soil bed. In addition, the arsenic removal was observed to increase along with the time from 30 to 90 days, and it reached to a maximum removal around 90 days, and then decreased after 122 days. Thus, the arsenic removal efficiency including mechanisms founded can then be applied in designing of constructed wetland for arsenic treatment from gold mine drainage with similar site/soil characteristic.

Keyword: Environmental science

1. Introduction

Constructed wetland is known as providing a complex biological and physical environment, which can change the chemical nature of contaminants (Shi et al., 2018). According to the literature, the arsenic can be removed in a wetland system by transforming arsenite (As (III)) to less soluble form, arsenate (As (V)). Besides, the arsenic may accumulate in the wetland sediment through precipitation, co-precipitation, and sorption (Lizama et al., 2011). These mechanisms demonstrate removing arsenic from the aqueous phase by direct formation of insoluble arsenic complex or by incorporation of trace amounts of arsenic into the newly formed insoluble compounds (Henke and Hutchison, 2009).

Arsenic in the nature is coexistent in the mineral vein with other elements such as copper, manganese, lead, tin, silver, and gold. Mining of these minerals may cause arsenic releasing into the surrounding area. Inappropriate management of mining that causes arsenic contamination was reported in many areas around the world. For example, the Wangsaphung district of Loei province in the northeast of Thailand is an area of naturally occurring with the arsenic-rich material. According to the report, the arsenic concentrations were 0.003−0.107 mg/l in the surface water, 0.001−0.130 mg/l in the groundwater and water supply well, and 28.32−429 mg/kg in the sediment and soil (PCD, 2012). Interestingly, in this district, there exists a gold mining site, and a small natural wetland is nearby, namely Phu Lek Creek, which receives potential arsenic-contaminated runoff from the mining site. As a result of long-term monitoring, it was reported that reduction of arsenic has taken place after passing through this natural wetland (PCD, 2006−2010). Based on the survey of this study, the soil properties in this area belong to mostly laterite soil or red clay ranged from 0.2 to 0.4 m bed depth, which contains high amount of iron. The laterite soil originating from hematite (Fe_2O_3) and goethite ($FeO(OH)$) is capable of removing arsenic from water via chemical adsorption and precipitation because of its high content of iron (Ramaswami et al., 2001; Maiti et al., 2007).

Besides, the dominating plant species in this wetland is *C. escolenta* (taro) at a density of approximately 20 plants/m^2. In 2011, a preliminary study was performed and the results show that the arsenic in water was reduced through precipitation in soil and takeup by plants in this natural wetland. This seems in agreement with some reports, which describe the arsenite and arsenate possibly removed through their co-precipitation with iron oxyhydroxides ($Fe(OH)_3(s)$) and iron oxidizing bacteria (IOB) (Hedin et al., 1994; Emerson et al., 2010; Lizama et al., 2011). Specifically, in the low iron content environment, especially under acidic conditions, As(III) may precipitate as arsenopyrite (FeAsS) (Wilkin and Ford, 2006). In addition, the aquatic plants can retain arsenic in the wetland through sorption onto the roots and submerged shoots, as well as translocation to emergent shoots and tips (An et al., 2011; Blute et al., 2004; Sundberg-Jones and Hassan, 2007). Furthermore, the plant roots can alter the chemical conditions of the surrounding sediment, thus enhancing the rate of transformation and fixation of metals (Wang and Peverly, 1999). Many aquatic plants in the wetland, including *Typha latifolia* (broadleafcattail) translocate oxygen from the atmosphere to the rhizosphere via radical oxygen loss from roots (Doyle and Otte, 1997).

Therefore, in this study, it was attempted to elucidate the role of *C. esculenta* in the arsenic removal by a pilot-scale constructed wetland (PCW), which was filled with the local laterite soil. The operation of this PCW was designed to last for 122 days, and the arsenic contents were monitored in the phases of water, soil, and the plants. Consequently, the role of selected plant species was identified and the relationship between arsenic in the laterite soil and in the plants was illustrated.

2. Materials and methods

2.1. Laterite soil

The laterite soil filled in this PCW was taken from the surrounded area of the Phu Lek creek within the 1 km radius of the gold mine area. The soil sample was collected at the bed depth of 15−30 cm and then air-dried for 7 days and further used for installation in this PCW by removing the debris in it. The soil sample was characterized by both physical and chemical properties namely, particle size, Eh, pH, organic matter, and chemical compositions.

2.2. Plant material

C. esculenta seedlings were collected at a height of 10 cm from Phu Lek creek. After that, seedlings were moved and cultured in the greenhouse for 15 days. The seedlings (size approximately 15 cm) that grew in the greenhouse were then transported into the PWC experimental plot.

Note that, the rootlet was removed from the seedling and the stalk was cut into the size approximately 10 cm in order to break the new rootlet and new leaf, respectively. The 10 cm *C. esculenta* stalks without rootlet were planted in 3 PWC experimental sets at 22 plants/unit (density of 20 plants/m^2) for other 15 days. After 15 days, all of experiments can be carried out by pumping the arsenic contaminated water to the PWC systems.

2.3. Pilot-scale constructed wetland

The pilot-scale constructed wetland setup consists of 2 sets with triplicated units each (PCW 3 units and control 3 units), with the dimension of each unit 1.80 × 0.50 × 0.60 m as illustrated in Fig. 1. To determine the effect of laterite soil on arsenic removal, the first set of the PCW was filled with 0.4 m bed height of laterite
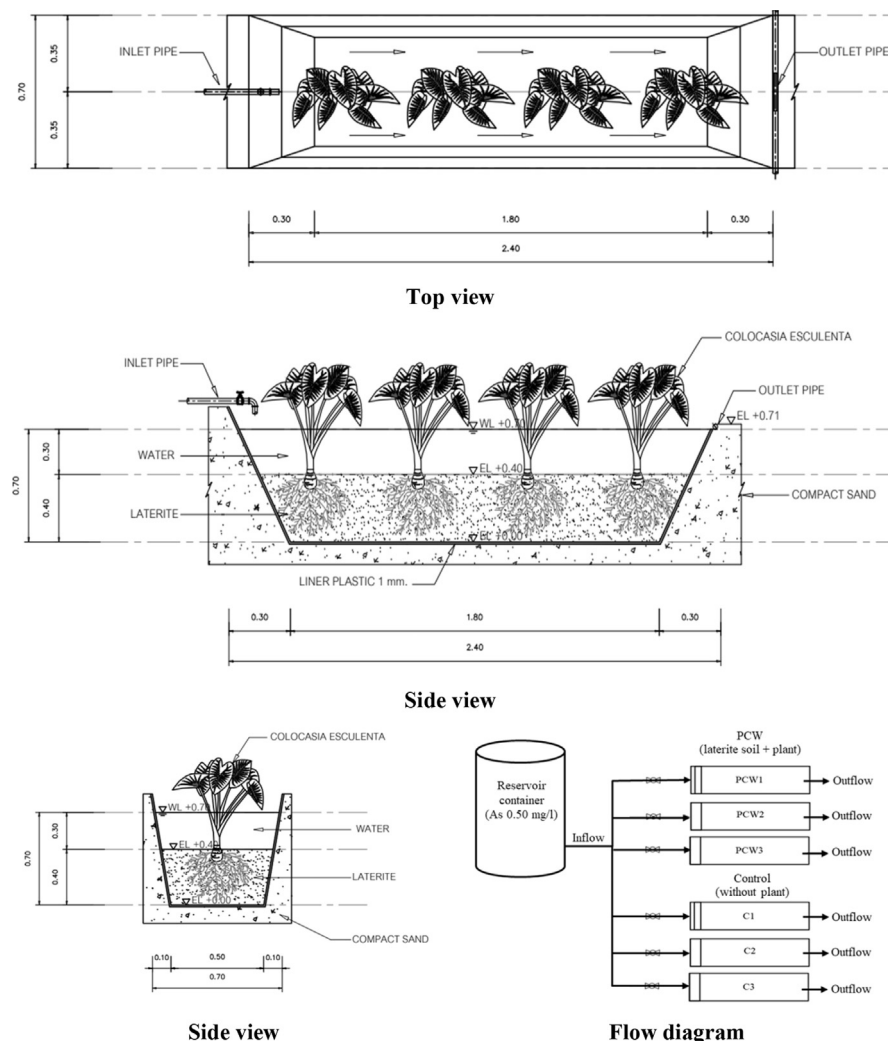

Fig. 1. Schematic diagram of the basic unit installation for the pilot-scale constructed wetland.

soil without any aquatic plants planted in it. The second set of the PCW was constructed with plants at a density of 20 plants/m^2 and laterite at 0.4 m of bed height (from the result of preliminary study in Phu Lek creek). The 2 sets of PCW were placed in the greenhouse in order to minimize the impact of rainfall. The dimension of each basic unit was so designed to allow adequate contact time and sufficient space for plants growth (Yeh et al., 2009; Aksorn and Visoottiviseth, 2004).

The wetland bed was installed with a liner of polyethylene plastic in order to prevent both water infiltration and adsorption of arsenic onto the surface of the water flow system (Stottmeister et al., 2006). The experimental period in this study was set for 4 months to ensure that the *C. esculenta* grows long enough to provide the best performance of arsenic removal. The greenhouse was installed in the open area with proper airflow. The roof of the greenhouse was constructed by using a 6 mm clear durable polyethylene plastic sheet to allow enough light similar to the outside environment. The main functions in greenhouse are to prevent only rainwater entering to the experiment plots and to protect the contamination of the outside soil. Other conditions in the greenhouse are similar to the outside environments namely airflow, sunlight, humidity, etc. The experiments were carried out during rainy season (May−Oct., 2017). In the operation of the PCW, it was fed with arsenic-contained water continuously, with the arsenic concentration prepared at 0.50 mg/l, the solution pH adjusted at 7, and a constant flow rate controlled at 1.5 m^3/day. Note that these conditions were reproduced from those of the nearby natural wetland system. The influent water was prepared and stored in a 3,000 L of fiberglass container for the use throughout the experiment. This container was installed at an elevated level to provide a desired gravity flow of the influent by adjusting the control valve.

2.4. Sampling and analyses

Water samples were collected daily at the inflow and outflow. Water samples 1,000 mL of water was collected by grab sampling method at the location shown in Fig. 1. Samples were acidified with HNO$_3$ to pH < 2, and stored at 4 ± 0.5 °C until being analyzed for metal concentrations with ICP Optima 2100 DV, Perkin Elmer, U.S.A. (APHA, 1998).

The bed soil samples were collected at 4 different depths at the center of each unit (0−10, 10−20, 20−30 and 30−40 cm). Soil collected by core sampling at surface of sediment (0−20 cm). Samples were air dried, sieved, and then dried in oven at 105 °C for 24 h to weighted and digested to solution. Digestion was performed with 1:3, HNO$_3$: HClO$_4$) (v/v). Samples of plant and soil were taken monthly. Plants were collected at the center of each unit. Plant samples were washed to remove clay and sand particles, and then dried in oven at 105 °c for 24 h to a constant weight. The dry weight was measured. Dried samples were ground to a fine powder with ceramic

mortar. Digestion method and chemical used are the same as sediment digestion mentioned above.

All samples were prepared and analyzed at the Science Center Laboratory, Loei Rajabhat University. After being digested, arsenic and iron solution were analyzed using Inductive Coupled Plasma Optical Emission Spectrometry (ICP-OES), Perkin Elmer, Optima 8000, located in the laboratory of the center for Scientific and Technological Equipment, Suranaree University of Technology. The details of methods for sampling and analysis are depicted in Table 1.

2.5. Data analysis

Aqueous arsenic removal efficiency (RE) was determined using Eq. (1) (Lizama et al., 2011; Vanlop T., 2018).

$$\text{RE (\%)} = \frac{\text{As}_{(inflow)} - \text{As}_{(outflow)}}{\text{As}_{(inflow)}} \times 100 \tag{1}$$

where $\text{As}_{(outflow)}$ is arsenic outflow concentration (mg/l) and $\text{As}_{(inflow)}$ is arsenic inflow concentration (mg/l).

The translocation factor (TF) reflects the ability of plants to translocate arsenic concentration in plant's aerial parts (stems and leaves) (Marchiol et al., 2004; Wang and Peverly, 1999; Vanlop T., 2018). TF is the ratio of arsenic concentration in above

Table 1. Methods for sampling and analysis.

Samples/duration	Sampling method	Analytical method	
		Parameters	**Methods/reference**
Water: daily, (n = 122*6 cells)	Grab sampling at the inflow and the outflow	pH	pH meter, APHA (2012)
		Eh	EC meter, APHA (2012)
		EC	EC meter, APHA (2012)
		DO	DO meter, APHA (2012)
		TDS	TDS meter, APHA (2012)
		TSS	TSS meter, APHA (2012)
		DOC	UV254, APHA (2012)
		Sulfates	Turbid metric method APHA (2012)
		Iron	ICP-OES, APHA (2012)
		Arsenic	ICP-OES, APHA (2012)
Plants: monthly, (n = 192*3 cells)	Sampling with quadrats (1 set/plant) 4 parts; foliage, leaf stalk, rootlet and rhizome.	Arsenic	Digestion with 1:3 (1000 mg dw), HNO_3:$HClO_4$) (v/v), Italmar OPR. ICP-OES, Perkin Elmer, Optima 8000, U.S.A. APHA (2012)
Sediment: monthly, (n = 128*6 cells)	Core sampling (0−10, 10−20, 20−30, 30−40 cm depth)	Arsenic, Fe, S	Digestion with 1:3(HNO_3: $HClO_4$) (v/v), ICP-OES, Perkin Elmer, Optima 8000, U.S.A. APHA (1998)

ground plant tissues (foliage and leaf stalk) to arsenic concentration in plant part rootlets was calculated using Eq. (2).

$$TF = \frac{As_{above \text{ (foliage and leaf stalk)}}}{As_{rootlets}} \times 100 \qquad (2)$$

where As_{above} is arsenic concentration in above ground plant tissues (sum of concentrations in foliage and leaf stalk; mg/kg, plant dry weight) and $As_{rootlets}$ is arsenic concentration in the rootlets (mg/kg, plant dry weight).

The bioconcentration factor (BCF) reflects the ability of plants to accumulate arsenic. It is the ratio of arsenic concentration in plant parts (foliage, leaf stake, rootlets and rhizome) to arsenic concentration in the soil (Liu et al., 2014; Mac Farlane et al., 2007; Wu et al., 2015; Vanlop T., 2018), was calculated using Eq. (3).

$$BCF = \frac{As_{plant \text{(foliage, leaf stalk, rootlet and rhizome)}}}{As_{soil}} \times 100 \qquad (3)$$

where As_{plant} is arsenic concentration in plant tissue (sum of arsenic concentrations in foliage, lefts stake, rootlets and rhizome; mg/kg, plant dry weight) and As_{soil} is arsenic concentration in sediment (mg/kg).

Concerning the ability of arsenic accumulation (AC), it is defined as the ratio of arsenic concentration in the laterite soil with plants installation to that without plants installation (Vanlop T., 2018), as is expressed in Eq. (4).

$$AC\,(\%) = \frac{As_{(wp)} - As_{(wo)}}{As_{(wp)}} \times 100 \qquad (4)$$

where the $As_{(wp)}$ is the arsenic concentration in the laterite soil with plants (mg/kg) and the $As_{(wo)}$ the arsenic concentration in laterite soil without plants (mg/kg).

2.6. Statistical analysis

All statistical data analysis was performed by using SPSS v.17.0 (IBM Corp., Armonk, NY, USA). The measured data are expressed as means ± standard deviation (SD). Comparisons between groups were performed with t-test and analysis of variance (One way-ANOVA), where a value of $P < 0.05$ was considered statistically significant. Quality assurance (QA) and quality control (QC) were used in planning, sampling, analysis and reporting of data in all process throughout this study.

3. Results and discussion

3.1. Soil and water characterization

In this study, the characteristics of the PCW bed soil is depicted in Table 2. The composition of the installed soil was mostly coarse sand and clay, with a particle

Table 2. Physicochemical properties of laterite soil used in the PCW system.

Properties	Quantitative value	Analytical method
Particle size (mm)	0.025−2.20	Sieve analysis, Sampling, S., 2006
Bulk density (g/cm^3)	1.24−2.55	Core method, Sampling, S., 2006
Surface area (m^2/g)	16.01−18.66	Multi-point BET, Scanning electron microscrope (SEM), Sampling, S., 2006
Pore volume (ml/g)	0.022−0.056	Core method, Sampling, S., 2006
pH$_{ZPC}$ (1:5, laterite:water mixture)	4.80−6.23	1:5, laterite:water mixture, EC meter, APHA, 2012
Conductivity (1:5, laterite:water mixture) (µS/cm)	150.25−172.42	1:5, laterite:water mixture, EC meter, APHA, 2012
Organic Matter (%)	1.26−1.98	UV254, APHA, 2012
Inorganic composition (as metal: wt%)		
- Magnesium (Mg) (%)	0.25−0.28	SEM-EDX, model: ESM-5800, GEOL, Japan
- Aluminum (Al) (%)	23.50−24.13	
- Silicon (Si) (%)	43.68−44.80	
- Sulfur (S) (%)	<0.10	
- Arsenic (As) (%)	<0.10	
- Potassium (K) (%)	2.66−2.85	
- Titanium (Ti) (%)	1.41−1.45	
- Iron (Fe) (%)	19.90−28.25	

size range of 0.025−2.20 mm. It was slightly acidic since the pH$_{zpc}$ (defined as the pH with zero point charge of the soil) fell within the range of 4.80−6.23. According to this study, the soil was characterized as laterite soil or red clay containing a relatively high content of iron (19.90−28.25%). As reported, the major forms of iron in laterite soil are hematite (Fe$_2$O$_3$), magnetite (Fe$_3$O$_4$) and pyrite (FeS$_2$) (Mutembei, 2013). Besides, high content of aluminum (∼24%) was also measured for the soil applied in this PCW.

The results of water sample analyses are shown in Table 3, which summarizes the water quality variables monitored at the inflow and outflow of each unit in this PCW, depending on the presence and absence of plants. With the plants, the pH was 6.68−7.05 at the inflow and 6.75−7.32 at the outflow. This indicates that the water in the PCW system was in a neutral condition. Also, the data for both Eh (236.10−422.20 mV) and DO (4.21−5.42 mg/l) implied an oxidation condition of the water. The decreases of both EC and TDS at the outflow indicate that inorganic ions in water have been adsorbed by the bed soil. In addition, the DOC increased from 1.85 to 2.34 mg/l at the inflow to 4.50−6.41 mg/l at the outflow. The reason might be due to its release from the bed soil (organic matter content

Table 3. Water qualities in the PCW system.

Variables	With plants (n = 366)				Without plants (n = 366)			
	Inflow		Outflow		Inflow		Outflow	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Temperature (°C)	27.52	25.14−28.26	27.03	25.52−27.64	27.10	26.5−27.32	27.00	26.00−27.14
pH	6.84	6.68−7.05	7.12	6.75−7.32	6.85	6.53−7.07	7.06	6.88−7.05
Eh (mV)	352.55	326.15−422.20	267.65	236.10−401.25	341.51	316.15−352.60	275.87	223.78−351.45
DO (mg/l)	4.34	4.21−4.40	5.24	4.65−5.42	4.37	4.11−4.50	4.52	4.05−4.80
EC (μmhos/cm)	632.50	625.87−685.61	326.23	284.69−584.77	638.50	621.5−666.51	345.61	311.56−414.70
TDS (mg/l)	465.21	455.12−473.68	312.14	250.70−390.50	468.33	425.78−485.01	352.05	275.20−381.51
TSS (mg/l)	19.67	19.20−20.90	14.62	12.11−15.69	21.08	19.01−23.91	15.74	14.70−18.10
DOC (mg/l)	2.05	1.85−2.34	5.46	4.50−6.41	2.00	1.70−2.01	<0.01	<0.01
Sulfates (mg/l)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Iron (mg/l)	<0.01	<0.01	0.21	0.07−0.24	<0.01	<0.01	0.35	0.15−0.40
Arsenic (mg/l)	0.485	0.481−0.495	0.054	0.087−0.139	0.485	0.481−0.495	0.233	0.137−0.317
Arsenic removal (%)	-	-	88.77	71.32−98.38	-	-	52.06	34.50−71.83

of 1.26−1.98%), and the plants. Furthermore, the sulfate concentrations at the inflow and outflow were less than 0.01 mg/l, whereas, the iron concentration was less than 0.01 mg/l at the inflow and 0.07−1.24 mg/l at the outflow. This demonstrates that partial iron content has been desorbed from the bed soil into water stream. Interestingly, the arsenic content in water decreased from 0.485 mg/l at the inflow to 0.087−0.139 mg/l at the outflow. In other words, the arsenic was removed by 71−98% over the detention time period of 3.44 hrs in each unit.

Without the plants, similar to the case with the plants, a neutral condition of water was observed at both the inflow (pH = 6.85−7.07) and outflow (pH = 6.88−7.05) and the oxidation condition was monitored based on the Eh of 223.78−352.60 mV and the DO of 4.05−4.80 mg/l. Besides, both EC and TDS dropped between the inflow and outflow, implying that inorganic ions in water were adsorbed onto the bed soil. As for the DOC, it decreased from 1.70 to 2.01 mg/l at the inflow to < 0.01 mg/l at the outflow. The sulfates in water were found to be less than 0.01 mg/l at both the inflow and outflow. On the other hand, the iron content increased from less than 0.01 mg/l at the inflow to 0.15−0.40 mg/l at the outflow. In contrast to the case with the plants, the arsenic in water decreased from 0.485 at the inflow to 0.137−0.317 at the outflow. This is to say that, without the plants, the arsenic was removed by 35−72% over the detention time period of 5.45 hrs in each unit, which is significantly lower than the case with the plants, in terms of arsenic removal efficiency.

3.2. Arsenic distribution within the bed soil

According to this study, the arsenic content in the bed soil (laterite) was 0.06−100.12 mg/kg in the presence of the plants and, without the plants, it was 0.06−54.53 mg/kg. It appears that the arsenic accumulation within the bed soil was significantly different, with and without the plants. As understood, the removal of arsenic was due to the co-precipitation and sorption onto the iron oxides. As mentioned earlier on the soil characterization (see Table 2), the iron content in the laterite soil was as high as 19.90−28.25%. In addition, the PCW condition was in the oxidation state, with Eh = 223.78−352.60 mV, DO = 4.05−4.80 mg/l, and DOC = 4.70−6.45 mg/l. Hence, it was very possible that the arsenic in the form of H_2AsO_4 tends to precipitate with iron to form the product of $FeAsO_{4(s)}$ under the oxidation state of water (Bang et al., 2005; Kadlec and Wallace, 2009). On the other hand, as presented in Table 4, the arsenic content in the bed soil was time-dependent ($p < 0.05$). With the plants, the average arsenic content increased with time until it reached to its maximum (111.98 mg/kg) at Day 90, and then decreased to 100.12 mg/kg at Day 122. A similar pattern was observed in the absence of the plants, the average arsenic content increased to a maximum (56.67 mg/kg) at Day 90, and then dropped down to 54.53 mg/kg at Day 122.

Table 4. Average arsenic content in the PCW bed soil.

Depth (m)	Average arsenic in the bed soil (mg/kg)				
	0 day	**30 day**	**60 day**	**90 day**	**122 day**
With the plants					
0−10	0.07	61.04	78.64	127.32	101.87
10−20	0.06	68.20	95.45	134.62	111.30
20−30	0.06	53.60	84.90	95.88	88.74
30−40	0.06	46.80	70.11	90.11	98.57
Mean	0.06 ± 0.01	57.41 ± 9.25	82.28 ± 10.67	111.98 ± 22.25	100.12 ± 9.31
Without the plants					
0−10	0.07	33.08	43.10	57.10	59.80
10−20	0.06	38.22	44.63	63.09	51.25
20−30	0.06	40.90	43.75	55.35	54.46
30−40	0.06	36.32	41.89	51.13	52.60
Mean	0.06 ± 0.01	37.13 ± 3.29	43.34 ± 1.15	56.67 ± 4.96	54.53 ± 3.75

It's also interesting to point out that the arsenic content at different depths was time-dependent. Fig. 2 shows the arsenic content profiles at different depths. With the plants, it appears that there's no significant change of arsenic content at Day 0 in all different depths (0.06−0.07 mg/l). Yet, over the time, the arsenic started to move and accumulate within the lower depth of the bed soil Mostly, the arsenic accumulated at the depth of 10−20 cm (root zone). Lin et al. (2015) reported that the vertical distribution of arsenic content in the wetland bed soil was controlled by the distribution of adsorbents, arsenic deposition and biogeochemical processes. The emergent plant rootlet and rhizome can stabilize heavy metals around its tissue via rhizostabilization in the presence of rhizospheric microbes (Kumar et al., 2017).
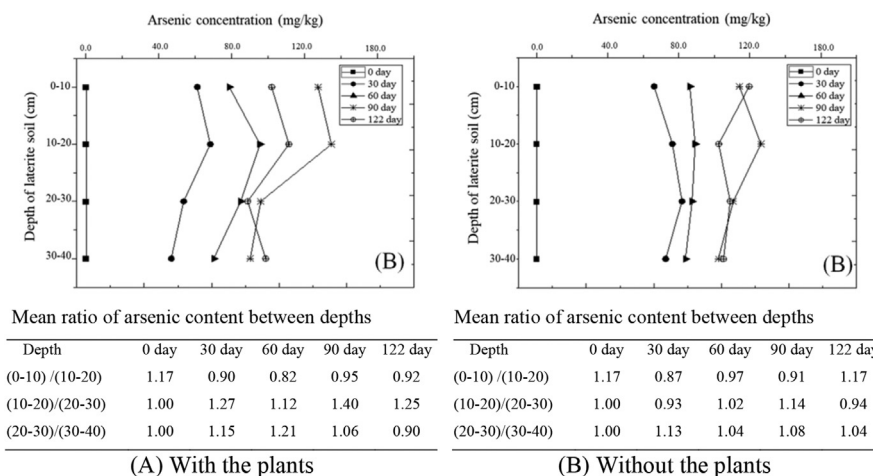

Depth	0 day	30 day	60 day	90 day	122 day
(0-10) /(10-20)	1.17	0.90	0.82	0.95	0.92
(10-20)/(20-30)	1.00	1.27	1.12	1.40	1.25
(20-30)/(30-40)	1.00	1.15	1.21	1.06	0.90

(A) With the plants

Depth	0 day	30 day	60 day	90 day	122 day
(0-10) /(10-20)	1.17	0.87	0.97	0.91	1.17
(10-20)/(20-30)	1.00	0.93	1.02	1.14	0.94
(20-30)/(30-40)	1.00	1.13	1.04	1.08	1.04

(B) Without the plants

Fig. 2. Vertical distribution of arsenic at different times in the PCW bed depth.

Without the plants, in the beginning of experiment (Day 0), the arsenic concentration in water showed no significant difference in all depths. Over the time, the arsenic transport to a lower depth of the bed soil. Consequently, the Arsenic accumulated mostly at the depth of 0−10 cm. Note that the arsenic accumulated in the lower depth might also occur through its transport with water and remain within the soil pores.

3.3. Arsenic distribution within the plants

To understand the arsenic distribution within the plants, the plants were harvested monthly and analyzed for the arsenic contents in various parts of the plants, including foliage, leaf stalk, rootlet and rhizome. As shown in Fig. 3, it can be seen clearly that the arsenic content was significantly high in rootlet for all samples. The arsenic content was in the order as follows: rootlet > rhizome > foliage > leaf stalk. The arsenic contents of the four different parts were found to increase with time up to 90 days, and it then started to decrease. The plants *C. esculenta* used belong to emergent biennial ones. According to this study, the plants reached to its maximum growth after two months, and they started to lose theirs leaves after 3 months. The visual changes of the above-ground mass were observed. This might be due to toxicity of heavy metals. Such results agreed with the report by Bindu et al. (2010). They described that the *C. esculenta* exposed to lead and chromium decreased its ability of metals accumulation and started to lose its above-ground mass, depending on the increasing metals content.

In view of bioconcentration factor (BCF), high BCF was found in the rootlet (0.28−0.80), foliage (0.17−0.38) and rhizome (0.15−0.21), whereas low BCF
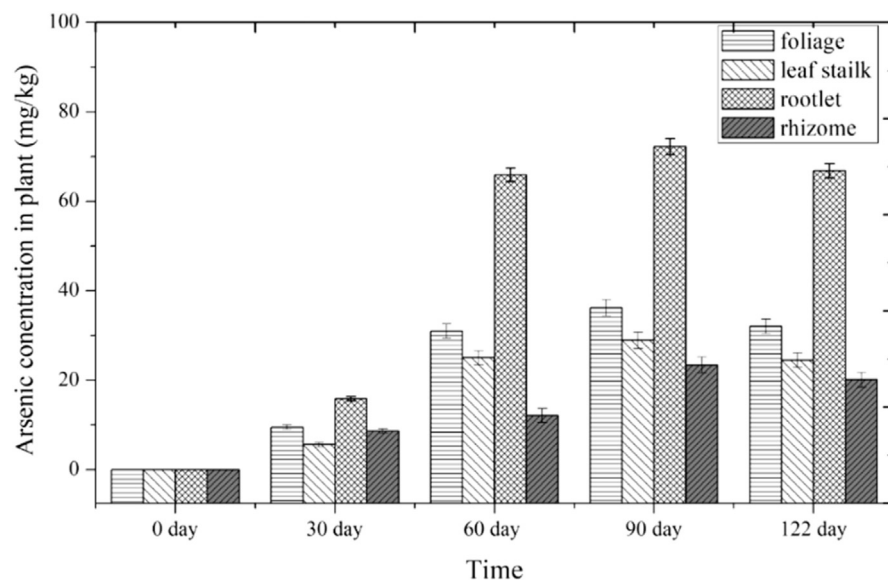

Fig. 3. Arsenic contents in foliage, leaf stalk, rhizome and rootlet of *C. escolenta* at different times.

occurred in the leaf stalk (0.00−0.26). As for the translocation factor (TF), low TF was observed in the foliage/rootlet (0.00−0.60) and leaf stalk/rootlet (0.00−0.40). Furthermore, both BCF and TF increased with time and started to decrease after 90 days, as depicted in Table 5. Such a result was in agreement with the reports by Ye et al. (2003) and Singhakant et al. (2009), who conluded the arsenic uptake more by the plant root than by its shoot.

3.4. Role of laterite soil and plant

Based on the outcomes of this study, possible roles of the laterite bed soil and the plants played in absorbing arsenic were further elaborated in the following, in addition to the factor of time of duration in the system.

3.4.1. Role of laterite soil

As presented in Table 3, the arsenic removal by laterite soil alone was 35−72% in the absence of the plants. This demonstrates that the laterite soil was effective in arsenic removal via co-precipitation and sorption onto the iron oxides (Jahan et al., 2010; Maiti et al., 2007; Maji et al., 2008; Canales et al., 2012). Dominant species of arsenic under such experimental conditions as pH = 6.75−7.32 and Eh = 223.78−401.25 will be arsenate ($HAsO_4^{-2}$). With such an oxidation condition, the arsenate could be precipitated with iron to form $FeAsO_{4(s)}$ (Bang et al., 2005; Kadlec and Wallace, 2009). In addition, the surface of laterite soil particles was positively charged ($pH_{ZPC} = 4.80−6.23$). According to Maji et al. (2007), under the condition of the positively charged environment, the arsenic adsorbed onto laterite soil is mostly due to coulombic and van der Waals forces between the solute and the laterite soil surface.

Table 5. Bioconcentration factor (BCF) and translocation factor (TF) of arsenic in *C. esculenta* at different times.

Time	0 day	30 day	60 day	90 day	122 day
Mean bioconcentration factor (BCF)					
Foliage	0.00	0.17	0.38	0.32	0.32
Leaf stalk	0.00	0.10	0.30	0.26	0.24
Rootlet	0.48	0.28	0.80	0.64	0.67
Rhizome	0.16	0.15	0.15	0.21	0.20
Mean translocation factor (TF)					
Foliage/rootlet	0.00	0.60	0.47	0.50	0.48
Leaf stalk/rootlet	0.00	0.35	0.38	0.40	0.37

3.4.2. Role of the plants

As shown in Fig. 4, the capacity of arsenic accumulation was 54.62–97.61% as the duration of time increased from 30 – 90 days, and it started to decrease after 90 days. On the average, the capacity of arsenic accumulation by the plants was 65.13%. The maximum arsenic content in the plants at day 90 was 54.33 mg/kg in the foliage, 81.21 mg/kg in the leaf stalk, 71.83 mg/kg in the rhizome and 24.98 mg/kg in the rootlet. Both bioconcentration factor and translocation factor indicate the arsenic uptake more by plant roots than by its shoots. As reported, plants could retain arsenic in the wetland through sorption to roots and the submerged shoots, and through translocation to emergent shoots (An et al., 2011; Blute et al., 2004; Sundberg-Jones and Hassan, 2007). Since the *C. esculenta* is a non-hyper accumulator, sorption onto such plants plays a minor role.

The comparison of arsenic removal in the presence and absence of the plant is shown in Fig. 5. Obviously, higher arsenic removal was observed in the presence of the plants. It appears that the capacity of arsenic accumulation (AC) depends greatly on the plants, arsenic content and time of duration.

Notably, it was indicated that the plants enhancing transformation and fixation of arsenic in soil. Mechanisms of *C. esculenta* enhancing arsenic accumulation in can be explained in 3 aspects. Firstly, the enhancement may be through physical
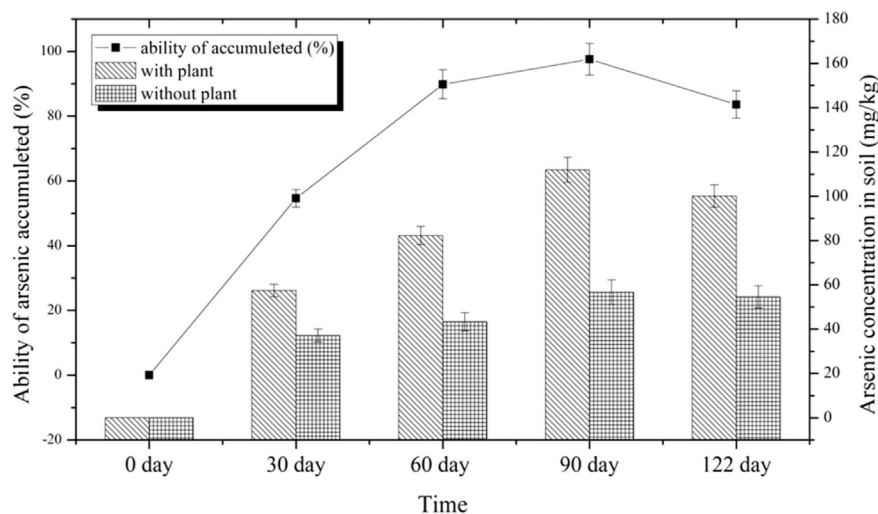
Unit of the PCW	0 day	30 days	60 days	90 days	122 days	mean
with the plants	0.06	57.41	82.28	111.98	100.12	70.37±44.36
without the plants	0.06	37.13	43.34	56.67	54.53	38.35±22.86
Capacity of arsenic accumulation (%)	0.00	54.62	89.83	97.61	83.61	65.13±39.87

Fig. 4. Capacity of arsenic accumulation in the laterite soil at different times.
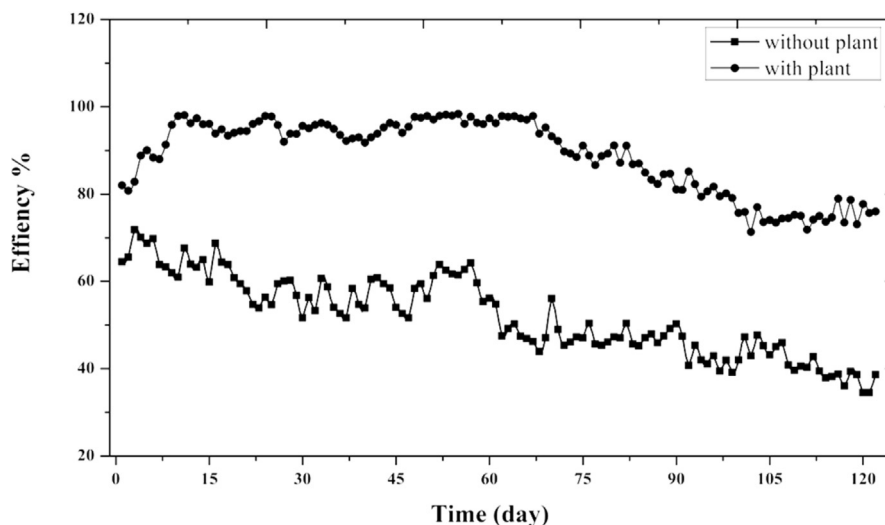
Fig. 5. Arsenic removal efficiency profiles with and without Plants.

effects of roots such as filtering, flow reduction, increasing sedimentation and decreasing resuspension (Stottmeister et al., 2006; Vymazal, 2011). Such effects could be evidenced in this study, where the hydraulic detention time of each unit reduced from 5.45 h in the presence of the plants to 3.44 h in the absence of the plants. Secondly, the enhancing effect may be observed with the rhizosphere acting as a base for microorganisms, where roots release oxygen that creates an aerobic

Table 6. Design criteria for constructed wetland for arsenic removal.

Design criteria	Values	Reference
Flow rate. (m³/day)	1.44	(Yeh et al., 2009)
Hydraulic loading rate. (cm./day)	8	
Depth(m)	0.5	
Width (m)	0.6	
Length(m)	1.8	
Volume (m³)/pond	$0.5 \times 0.6 \times 1.8 = 0.54$	
As concentration (mg/L)	0.5	concentration of As in Phu lek Creek
Plant: *C. esculenta*	20	This work
- *C. esculenta* of density (m²)	30	(Bindu et al., 2010)
- *C. esculenta* age (day)	Plant pilot scale experiment	
pH	6.75−7.32	This work
Laterite particle size	0.025−2.20	This work
Detention time (hr.)	5.45	This work
Time (day)	30−90	This work

condition for bacteria (Vymazal, 2011). Note that the wetland condition can enhance the development of iron-oxidizing bacteria by oxygen relocation into the rhizosphere. Such a condition also provides oxidizing environment in the precipitation process within the laterite soil bed (Niu et al., 2007; Shelef et al., 2013). In this study, with the plants, the highest arsenic accumulation in the unit occurred at the depth of 10−20 cm (root zone), whereas it was at the depth of 0−10 cm in the absence of the plants. Lastly, the promoting effect may be though the roots acting as surface precipitates and thus retaining the arsenic that co-precipitates with iron as $FeAsO_{4(s)}$ around the root zone (Wang and Peverly, 1999; Blute et al., 2004). In addition, the plant root system, as stated in the second and third, can stabilize heavy metals via rhizostabilization in the presence of rhizospheric microbes (Singhakant et al., 2009; Lizama et al., 2011; Vymazal, 2011; Kumar et al., 2017).

4. Conclusion

The study of the role of plant in arsenic removal was investigated in pilot scale constructed wetland. Results showed that arsenic in water decreased from 0.485 to 0.054 mg/L and decreased from 0.485 to 0.233 mg/L in cell with and without plant, respectively. Arsenic removal efficiency was significantly different between cells with plant (88.77%) and cells without plant (52.06%). The constructed wetland system with laterite soil and *C. esculenta* can effectively remove arsenic better than only laterite soil with ability of arsenic accumulated via *C. esculenta* was 65.13%. The high ability enhancement by plant might due to rhizostabilization and increment of oxidizing in precipitation process in laterite soil since arsenic was found mostly at depth 20−40 cm which is a root zone depth. Removal efficiency was increased with time from 30 to 90 days, reach optimum around 90 days, then decreasing after 122 days. Form plants analysis, the order of bioconcentration factor (BCF) was as follow: rootlet (0.28−0.80), rhizome (0.15−0.21), foliage (0.17−0.38), leaf stalk (0.00−0.26). The order of translocation factor (TF) was as follow: foliage/rootlet (0.00−0.60), leaf stalk/rootlet (0.00−0.40). Design criteria of constructed wetland were set according to our experimental pilot scale. Constructed wetlands pilot scale was effectively applied for arsenic removal using *C. esculenta* ($p < 0.05$). Design criteria can be summarized in Table 6.

Declarations

Author contribution statement

Vanlop Thathong, Netnapid Tantamsapya, Chatpet Yossapol, Chih-Hsiang Liao, Wanpen Wirojanagud, Surapol Padungthon: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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