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DYNAMIC SOIL PROPERTIES AFFECT THE ACIDITY OF ARTIFICIAL WETLANDS: A CASE STUDY IN THUNG YIEW PAK PHLI OF NAKHON NAYOK PROVINCE, THAILAND

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Abstract: This study examined the soil elements and properties of an area becoming an artificial wetland and compared them with those of an agricultural area. The study site is an artificial wetland in Nakhon Nayok Province, Thailand. Its soil properties and element content were compared with a nearby agricultural area using a one-way analysis of variance (ANOVA). The results of the study found this artificial wetland to be within the soil acidity zone of central Thailand, with an average soil pH above 3.99 ± 0.49 and a topsoil organic matter average of 17090 ± 2685 mg kg^{-1}, with aluminium (Al) and iron (Fe) as the major soil minerals. Compared to the agricultural area, the soil properties of the artificial wetland had slightly lower topsoil pH but significantly lower pH in the soil layer 100 cm deep in the agricultural area, and the EC in the artificial wetland was higher than in the agricultural area. However, there are three distinct patterns in the elemental composition of the artificial wetland: (1) A lower-quantity soil surface that improves with depth, (2) a high-quantity of topsoil that worsens with depth, and (3) highly variable soil quality below 50-100 cm. In the soil, the organic carbon in artificial wetlands has a ratio of 1:0.17:0.51 to reference area 1 and reference area 2, indicating that wetlands can store carbon in the soil. The element content of the topsoil and 50 cm soil layer is potentially influenced by land use and beneficial microbial activity, and the soil 100-150 cm layer has an element quantity shared with its parent soil. In this study, we sought to understand the physics and chemical composition of soil in an area transitioning to an artificial wetland over approximately 30 years.

Keywords: Artificial wetland, dynamic soil properties, soil properties, soil acidity, Nakhon Nayok province.

Introduction

Ecosystems are vulnerable to change depending on the relationship and functional components of the environment, including land use along its boundary (Lange *et al.,* 2010), the economic importance of the region (Zorrilla-Miras *et al.,* 2014), and the dynamic relationship of ecological components with nonlinear effects in the analysis of their cycles or wider correlations (Coskun, 2019). However, wetlands are ecosystems in which the relationship between water resources and living organisms is temporal, and their ecology benefits humans by sustaining (McInnes, 2013) and preserving plant and animal biodiversity.

Wetlands are reservoirs or swampy forests that occur due to natural or man-made processes that influence water flow through an area, including water levels below six metres with low tides (Ramsar, 1971; FAO. & SAFR., 1998) and are associated with nutrient recycling, flood mitigation, and wildlife habitat. However, the benefits of wetlands can be categorised based on their immediate use: Direct, such as fish and wildlife habitat, food production, and local economic benefits from wetland products, and indirect, such as natural improvements in water quality and flood control (U.S. Environmental Protection Agency, 2006). Artificial wetlands can be the outcome of human land development or construction, such as catchment areas or lagoons and new roads, or the grading of a piece of land for building construction. However, artificial wetlands can also be deliberately created to improve water quality (Shutes, 2001; Vymazal, 2012) or collect water to support irrigation.

Wetland soil characteristics essential for its drainage, such as clay and silt (Craft, 2016), and low pH compared with nearby areas can prevent the release of methanogens (Megonigal *et al.,* 2014). Most man-made wetlands occur accidentally through road construction or land grading, whereby the ecological structure of the area changes and affects the makeup (Janicke *et al.,*1993), including the soil properties, of the area. Therefore, in these situations, it is reasonable to study soil elements and properties as they transform into artificial wetlands and compare them with nearby agricultural areas to understand the soil condition with dynamic soil elements for future soil conservation planning.

Material and Method

History and Status of Nakhon Nayok Artificial Wetlands

The artificial wetland in Nakhon Nayok province is named locally, ʻThung' (field or paddy field), ʻPak Phli' (the name of a district in Nakhon Nayok province) or 'Thung Yiew (kite) Pak Phli' in the Area Base Approaches Annually Management in Wetland of Nakhon Nayok Province, for Responding to Sustainable Eco-tourism Business in Dong Yiew Dam, Pak Phli District, Nakhon Nayok province project (Kroeksakul *et al.,* 2020), which describes the history of the Thung Yiew Pak Phli artificial wetland (Table 1).

In this timeline, the area possibly changed after the local government set up a project to limit the public area zone in 1990, after which the field developed an ecology system conforming to an artificial wetland based on the following criteria:

1. It has experienced long-lasting flooding, lasting 4-6 months annually since 1990.
2. The water level during flooding is not deep, approximately 0.5-1 m.
3. The flooding of the field is artificial.
4. Some aquatic plant species are found in the field.

Additionally, these are the components of Thung Yiew Pak Phli that confirm that it has the properties of an artificial wetland based on its flooding.

Study Location

The location selected was an artificial wetland zone in Nakhon Nayok Province, Thailand. In the study, the general land use in this zone was compared to two agricultural reference areas to assess the condition of the artificial wetland

Table 1: The timeline of Thung Yiew Pak Phli (artificial wetland) in Nakhon Nayok Province

Year	Situation
Before 1990	Thung Yiew Pak Phli is a public area, and some villagers use it as a paddy field.
1990	The local government develops a project to dig a canal and construct a bund to delimit the public zone.
1991	The field floods for a long period, approximately 2-3 months.
1996	The local government and a village planted *Eucalyptus radiata* to honour Her Royal Highness Princess Maha Chakri Sirindhorn.
2000	The first fire burned in the field.
2004	The second fire burned on the ground.
2007	The third shot on the battlefield.
2009	This year, a kite (*Milvus migrans*) came to live in the region.

at six sampling locations to three sampling locations in each reference area (red spots in Figure 1). The soil samples were collected with a soil augur or metal mattock at four soil layer depths: (1) Topsoil no deeper than 5 cm, (2) 50 cm soil depth, (3) 100 cm soil depth, and (4) 150 cm soil depth. The soil collected from soil core layers (0-50 cm) and deep layers by spade (100-150 cm) were stored in plastic bags and kept in an ice box before transfer to the laboratory, where they were kept at –4°C in freezers before extraction and analysis. According to the landowners, reference area 1 is used for rice production once a year before the remnants are burned in preparation for the next planting, and reference area 2 is used for rice production once a year, and the remnants are burned before being used to grow watermelons or other crops.

pH and EC Analysis

Soil pH and electrical conductivity (EC) were tested using a solution technique (Nadler & Frenkel, 1980; Carmo *et al.,* 2016). The soil sample was dissolved in the water in a 1:2 ratio, 5 g of soil in 10 ml of deionised water and shaken for 30 minutes. Samples were allowed to settle for 30 minutes before pH was measured using a Hach HQ40D portable multimeter, and the EC was checked with a solution technique using the Eutech CON700 electrochemistry instrument.

Soil Extraction and Element Analysis

The soil sample was dried in a 105°C hot air oven for 72 hours and then ground using a mortar and pestle. A net of 10 mm of sifted soil samples was selected and maintained in a refrigerator at a temperature of 4°C. The soil extracted for analysing the Al, Fe, K, Cd, Cu, Mn, Ni, Pb, and Zn were used in an inductively coupled plasma–optical emission spectrometry (ICP–OES) analysis of 2 g soil samples in concentrated hydrofluoric acid (HF), perchloric acid ($HClO_4$), and nitric acid (HNO_3) at a ratio of 1:1:1 and volume of 20 ml. It was extracted at ~500°C in a SpeedDigester K-425 until it was dry. Each residue was rinsed with 1% HNO_3 and then sieved through filter paper, and the supernatant was transferred to a 50 ml volumetric flask, and 1% HNO_3 was added for continued inductively coupled plasma (ICP) technique in a PlasmaQuant 9100 series ICP–OES, and the element content from the analysis will show the overall value of the elements in the samples.

Available nitrogen (N) and carbon (C) were calculated from total nitrogen (TN) and total

Figure 1: Study site and plots where soil samples were collected

carbon (TC) in samples analysed by the CHN-628 analyser. Available phosphorus (P) was calculated using the Bray II method (Bray & Kurtz,1945) and measured by absorbance at 882 nm with a spectrophotometer.

Soil Organic Carbon (SOC) and Soil Organic Matter (SOM)

After collection, the percentage of carbon in the soil was calculated as SOM using the following formula:

$$\%SOM = 100(\%C/c) \quad [1]$$

where SOM = percentage of soil organic matter, C = value from CHN analyser processing, and c = 52 is used to represent the weight proportion of organic carbon in the soil (Soil Lecture Team, 2006). The %SOM will be used to calculate the weight of the SOM content in the soil according to the formula:

$$SOM\ (mg\ kg^{-1}) = [\%SOM \times (W_1/100)] \times 10^6 \quad [2]$$

where SOM = soil organic matter (mg kg^{-1}), %SOM = rate from the first equation, and W1 = dry weight of the sample (mg) in the experiment using 2 mg per sample. However, the SOC content in the soil was calculated using the following formula:

$$SOC\ (mg\ kg^{-1}) = \%SOM \times 0.58 \times 100 \quad [3]$$

where SOC = soil organic carbon (mg kg^{-1}), %SOM = rate from the first equation, and 0.58 is the van Bemmelen conversion factor of 58% of carbon in soil organic matter (Liao *et al.,* 2015; Han *et al.*, 2018).

Statistical Analysis

The data were analysed using a one-way analysis of variance (ANOVA) and compared using Tukey's honest significance test (HSD) between a soil component and the soil layer of the study site. Correlations between soil components were assessed using Spearman's correlation coefficient (*r*). All analyses were performed using the SPSS v.22, and SigmaPlot v.12.0 software. Results with $p < 0.05$ were considered statistically significant.

Results and Discussion

Influence of Soil Depth in the Acidic Soil Zone: Soil Properties in the Study Site

The artificial wetland formed from an agricultural area similar to those surrounding it. The area has an average topsoil pH of 3.99 ± 0.49 which differs significantly between the topsoil and deeper soil layers ($p < 0.05$), decreasing with depth (Table 2). The average EC of the topsoil was 379 ± 246 µm/cm, which did not change significantly across soil layers. The average percentage of moisture in the topsoil was 17.4 ± 2.28%, significantly lower than that of the 50 (23.9 ± 1.99) and 100 cm (31.5 ± 4.79) soil layers ($p < 0.05$) but not the 150 cm soil layer. The bulk density (BD) of the topsoil was significantly higher than that of the other soil layers ($p < 0.05$). However, the average weight of soil organic matter (SOM) in the topsoil was 17090 ± 2685 mg kg^{-1} and did not differ significantly from those of the other soil deep layers. Similarly, the average weight of soil organic carbon (SOC) in the topsoil was 495 ± 77.8 mg kg^{-1}, higher than those of the other layers but not significantly. The soil properties are presented in Table 2.

The Element Composition in the Soil Acidic Soil Zone

The concentrations of each element in the soil are shown in Table 3. Among the elements present in the topsoil, aluminium (Al) was the most common (80.60 ± 19.46 mg kg^{-1}), followed by iron (Fe; 37.89 ± 5.88 mg kg^{-1}), and potassium (K; 4.64 ± 1.82 mg kg^{-1}). However, the concentrations of phosphorus (P), N, cadmium (Cd), copper (Cu), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn) were < 1 mg kg^{-1} (Table 3). The concentration of Al in the topsoil was significantly higher than that in the 100 and 150 cm soil layers ($p < 0.05$). Similarly, the concentration of Fe in the topsoil was significantly lower than that in the 100 and 150 cm soil layers ($p < 0.05$). However, the concentration of K was significantly higher in the 100 cm soil layer (13.66 ± 7.12 mg kg^{-1}) than in the topsoil and 50 and 150 cm soil layers ($p <$

Table 2: Soil properties in the study site by soil layer

Soil Properties	0 cm	50 cm	100 cm	150 cm
pH	3.99 ± 0.495^{a}	3.45 ± 0.340^{b}	3.36 ± 0.302^{b}	3.32 ± 0.319^{b}
EC (µm/cm)	379 ± 246	481 ± 331	389 ± 220	546 ± 403
Soil moisture (%)	17.7 ± 2.28^{a}	23.9 ± 1.91^{b}	31.5 ± 4.79^{c}	36.3 ± 9.27^{c}
Bulk density (g cm^{-3})	2.88 ± 0.892^{a}	4.29 ± 0.399^{b}	5.74 ± 1.31^{c}	7.38 ± 2.51^{d}
SOM (mg kg^{-1})	17090 ± 2685	4455 ± 3192	2530 ± 1280	10247 ± 147
SOC (mg kg^{-1})	495 ± 77.8	129 ± 92.5	73.3 ± 37.1	297 ± 42.8

Note: ^{abcd} The mean difference across soil layers is significant at $p < 0.05$ (HDS) and the value without no letter indicates a non-significant difference across the area ($p > 0.05$); EC = electrical conductivity; SOM = soil organic matter; SOC = soil organic carbon

Table 3: Soil element content of each soil layer in the study site

Element	0 cm	50 cm	100 cm	150 cm
Al (mg kg^{-1})	80.60 ± 19.4^{6}a	72.66 ± 12.61^{ab}	65.22 ± 11.08^{b}	58.73 ± 20.73^{cb}
Fe (mg kg^{-1})	37.89 ± 5.8^{8}a	40.53 ± 3.80^{ab}	41.44 ± 0.197^{b}	40.17 ± 3.88^{ab}
K (mg kg^{-1})	4.64 ± 1.8^{2}a	4.56 ± 1.48^{a}	13.66 ± 7.1^{2}b	5.34 ± 2.75^{a}
Available P (mg kg^{-1})	0.030 ± 0.017^{a}	0.020 ± 0.007^{b}	0.016 ± 0.001^{ab}	0.024 ± 0.015^{ab}
N (mg kg^{-1})	0.445 ± 0.205	0.433 ± 0.118	0.411 ± 0.160	0.320 ± 0.193
Cd (mg kg^{-1})	0.155 ± 0.000^{a}	0.156 ± 0.000^{a}	0.156 ± 0.00^{0}b	0.156 ± 0.000^{a}
Cu (mg kg^{-1})	0.277 ± 0.027^{a}	0.292 ± 0.022^{a}	0.305 ± 0.035^{a}	0.424 ± 0.23^{6}b
Mn (mg kg^{-1})	0.350 ± 0.090^{a}	0.236 ± 0.043^{b}	0.237 ± 0.035^{b}	0.250 ± 0.068^{b}
Ni (mg kg^{-1})	0.232 ± 0.02^{2}a	0.208 ± 0.018^{b}	0.200 ± 0.012^{b}	0.203 ± 0.018^{b}
Pb (mg kg^{-1})	0.300 ± 0.028^{a}	0.335 ± 0.042^{a}	0.401 ± 0.10^{0}b	0.313 ± 0.037^{a}
Zn (mg kg^{-1})	0.342 ± 0.045^{a}	0.299 ± 0.030^{b}	0.282 ± 0.027^{b}	0.263 ± 0.036^{c}

Note: ^{abcd} The mean difference across soil layers is significant at $p < 0.05$ (HDS) and the value without no letter indicates non-significant difference across area ($p > 0.05$); Al = Aluminium; Fe = Iron; K = Potassium; P = Available phosphorus; N = Total nitrogen; Cd = Cadmium; Cu = Copper; Mn = Manganese; Ni = Nickle; Pb = Lead; Zn = Zinc

0.05). In addition, the concentration of Cd in the 100 cm soil layer (0.1563 ± .000 mg kg^{-1}) was significantly higher than that in the topsoil and 50 and 150 cm soil layers ($p < 0.05$). Moreover, the concentration of Cu in the 150 cm soil layer (0.424 ± 0.236 mg kg^{-1}) was significantly higher than that in the topsoil and 50 and 100 cm soil layers ($p < 0.05$). Furthermore, the concentration of Mn in the topsoil (0.350 ± 0.090 mg kg^{-1}) was significantly higher than that in the 50, 100, and 150 cm soil layers ($p < 0.05$). Additionally, the concentration of Ni in the topsoil (0.232 ± 0.022 mg kg^{-1}) was significantly higher than that in the 50, 100, and 150 cm soil layers ($p < 0.05$). The concentration of Pb in the 100 cm soil layer (0.401 ± 0.100 mg kg^{-1}) was significantly higher than that in the 0, 50, and 150 cm soil layers ($p < 0.05$). Finally, the concentration of Zn in the topsoil (0.342 ± 0.045 mg kg^{-1}) was significantly higher than that in the 50, 100, and 150 cm soil layers ($p < 0.05$).

Correlation of Depth and Soil Components in the Acidic Soil Zone

We explored the correlation among 17 soil properties using Spearman's r (Table 4): Soil layer, Al, Cd, Cu, Fe, K, Mn, Ni, Pb, Zn, P, N, soil moisture, bulk density, pH, SOM, and SOC. We found a positive correlation between soil layer and Cd quantity ($r = 0.298$, $p < 0.05$), Cu quantity ($r = 0.326$, $p < 0.01$), and bulk density (r

= 0.789, $p < 0.01$) but negative correlations with Al quantity ($r = –0.442$, $p < 0.01$), Mn quantity ($r = –0.396$, $p < 0.01$), Ni quantity ($r = –0.481$, $p < 0.01$), Zn quantity ($r = –0.603$, $p < 0.01$), and pH ($r = –0.469$, $p < 0.01$). However, soil pH was positively correlated with Mn quantity ($r = 0.327$, $p < 0.01$), Zn quantity ($r = 0.352$, $p < 0.01$), and P ($r = 0.467$, $p < 0.01$), but negatively correlated with soil layer ($r = –0.469$, $p < 0.01$), Cd quantity ($r = –0.352$, $p < 0.05$), K quantity ($r = –0.364$, $p < 0.05$).

Influence of Soil Depth in the Acidic Soil Zone: Factor Analysis of Acidic Soil Components

We performed a factor analysis of the 16 soil components affecting soil acidity with principal components analysis (PCA; Figure 2). We identified 5 principal components (PCs) with an eigenvalue > 1 that explained 76% of the total variance in the dataset (Table 5). Three PCs each explained > 10% of the total variance of > 10%: PC1 (31.4%), PC2 (16.2%), and PC3 (12.6%). In PC1, Zn was the major contributor with a loading factor of 0.838, which was selected first, followed by Ni (0.833), Mn (0.787), and soil layer (–0.701), consistent with the correlations between the soil layer and Ni ($r = 0.793$) and Zn ($r = –0.631$) quantity (Table 4). In PC2, N was the major contributor with a loading factor of –0.637, followed by K (0.634), consistent with the correlation of N with bulk density ($r = –0.390$), SOM ($r = –0.307$), SOC ($r = –0.307$), and Fe ($r = –0.303$), and K with Cd ($r = 0.742$) and Pb ($r = 0.634$). In PC3, Cu was the major contributor with a loading factor of –0.601, followed by the soil layer (–0.530), consistent with the correlation of Cu with soil layer ($r = 0.392$) and bulk density ($r = 0.422$), and soil layer with bulk density ($r = 0.758$), Zn ($r = –0.631$), and pH ($r = –0.531$; Table 4).

Soil Condition in the Artificial Wetland of Nakhon Nayok Province

The pH of the soil is a crucial indicator of the acidity or alkalinity of the environment since it is connected to plant growth and the existence of local microorganisms. The study site has a pH of between 4.4-3.5 and is extremely acidic (The U. S. Department of Agriculture, 1998), with an average topsoil pH in the artificial wetland of 3.23 ± 0.234, in reference area 1 of 3.76 ± 0.442, and reference area 2 of 3.56 ± 0.080. Interestingly, the pH in the topsoil was higher than that in the layers at 50, 100, and 150 cm [Figure 3 (A)], with the pH in the deepest 100 cm layer in the artificial wetland significantly lower than those in reference areas 1 and 2 ($p < 0.05$). The soil bulk density in the topsoil of reference area 1 (0.200 ± 0.040 g cm^{-3}) was significantly lower than reference area 1 and the artificial wetland ($p < 0.05$). In contrast, SOM and SOC in the topsoil and 50 cm soil layer differed significantly from the 100 and 150 cm soil lathers ($p < 0.05$). The physical properties of the soil by layer in the artificial wetland and reference areas 1 and 2 are shown in Table 6 and Figure 3.

Elements in the Soil of the Artificial Wetland Compared with Agricultural Areas

The soil elements considered in this study were Al, Fe, K, P, N, Cd, Cu, Mn, Ni, Pb, and Zn. The quantity of Al, Fe, and K are high at the study site. So, Al and Fe are the major elements contributing to soil acidity in this area (von UexkÜll, 1986; Gazey & Davies, 2009).

Al quantities were highest in the topsoil and progressively decreased with increasing soil depth, indicating that the quantity of aluminium in soil layers varies with soil pH and land-use practices, particularly on the probability of an increase in aluminium in the soil from precipitates of organic materials combined (Gruba & Mulder, 2008; Bojórquez-Quintal *et al.,* 2017). The Fe concentration in the topsoil of the artificial wetland and reference area 2 was not significantly different from reference area 1 but did not change with increased soil depth. However, K quantity did not significantly differ between reference areas 1 and 2 in all soil layers but not significantly. The concentration of P in the 100 cm soil layer in the artificial wetland was significantly lower than that in reference areas 2 ($p < 0.05$), and it decreased from the topsoil

Table 4: Correlation between soil layer and soil components in the study site

	Layer	Al	Cd	Cu	Fe	K	Mn	Ni	Pb
Layer	1	–.442**	.298*	.326*			–.396**	–.481**	
Al	–.442**	1					.633**	.634**	
Cd	.298*	0.067	1	.446**	–.550**	.653**			
Cu	.326*	0.137	.446**	1	–.304*	0.264			.339*
Fe			–.550**	–.304*	1				
K			.653**			1			.392**
Mn	–.396**	.633**					1	.791**	
Ni	–.481**	.634**					.791**	1	
Pb				.339*		.392**			1
Zn	–.603**	.712**					.821**	.750**	
P				.360*			.484**		
N	–.375**			–.483**					–.351*
Moisture			.330*	.301*		.304*			.619**
BD	.789**		.339*	.436**				–.291*	
pH	–.469**		–.352*			–.364*	.327*		
SOM	–.377**	.328*					.438**	.374**	
SOC	–.377**	.328*					.438**	.374**	

	Zn	P	N	Moisture	Bulk	pH	SOM	SOC
Layer	–.603**		–.375**		.789**	–.469**	–.377**	–.377**
Al	.712**						.328*	.328*
Cd				.330*	.339*	–.352*		
Cu		.360*	–.483**	.301*	.436**			
Fe								
K				.304*		–.364*		
Mn	.821**	.484**				.327*	.438**	.438**
Ni	.750**				–.291*		.374**	.374**
Pb			–.351*	.619**				
Zn	1	.402**		–0.155	–.434**	.352*	.455**	.455**
P	.402**	1		–.286*		.467**		
N			1		–.394**			
Moisture		–.286*		1	.396**		–.384**	–.384**
BD	–.434**		–.394**	.396**	1		–.396**	–.396**
pH	.352*	.467**				1	.370**	.370**
SOM	.455**			–.384**	–.396**	.370**	1	1.000**
SOC	.455**			–.384**	–.396**	.370**	1.000**	1

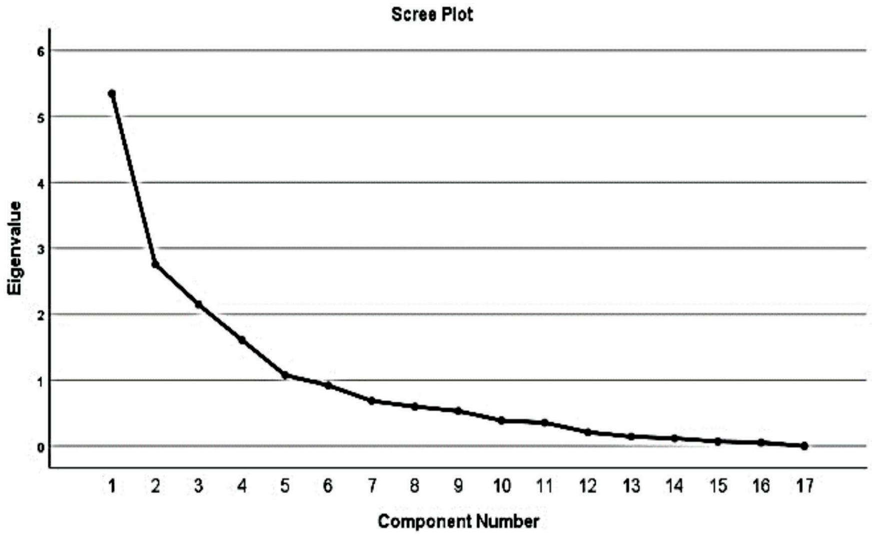
Note: *, two-tailed $p < 0.05$; **, two-tailed $p < 0.01$; Layer = 0, 50, 100, and 150 cm soil layers; Al = aluminium; Cd = cadmium; Cu = copper; Fe = iron; K = potassium; Mn = manganese; Ni = nickel; Pb = lead; Zn = zinc; P = available phosphorus; N = total nitrogen; BD = Bulk density; SOM = soil organic matter; SOC = soil organic carbon

Table 5: PCA results on the acidic soil components in the study site

PC	Component				
	PC1	**PC2**	**PC3**	**PC4**	**PC5**
Variance %	31.423	16.219	12.624	9.465	6.328
Cumulative %	31.423	47.643	60.266	69.731	76.060
Eigenvalue	5.342	2.757	2.146	1.609	1.076
Soil layer	–0.701	0.245	–0.530	0.043	–0.068
Al	0.605	0.324	0.362	0.239	0.017
Cd	–0.421	0.614	0.250	0.215	–0.279
Cu	–0.078	0.253	–0.601	0.435	0.089
Fe	–0.432	0.091	0.153	–0.638	0.273
K	–0.440	0.627	0.447	–0.053	–0.255
Mn	0.787	0.300	0.051	0.105	0.174
Ni	0.833	0.188	0.019	0.250	–0.214
Pb	–0.386	0.546	0.409	–0.031	0.249
Zn	0.838	0.264	0.294	0.103	–0.036
P	0.540	0.299	–0.370	0.249	0.106
N	0.036	–0.637	0.300	0.277	–0.456
BD	–0.499	0.428	–0.470	0.333	0.103
pH	0.552	–0.131	0.157	0.073	0.603
SOM	0.575	0.447	–0.286	–0.505	–0.213
SOC	0.575	0.447	–0.286	–0.505	–0.213

Note: PC, principal component. Underlined factor loading is weighted higher when within 10% of the variance of the absolute value of the highest factor loading in each PC.; Soil layer = 0, 50, 100, and 150 cm soil layers; Al = aluminium; Cd = cadmium; Cu = copper; Fe = iron; K = potassium; Mn = manganese; Ni = nickel; Pb = lead; Zn = zinc; P = available phosphorus; N = total nitrogen; BD = Bulk density; SOM = soil organic matter; SOC = soil organic carbon

(a)



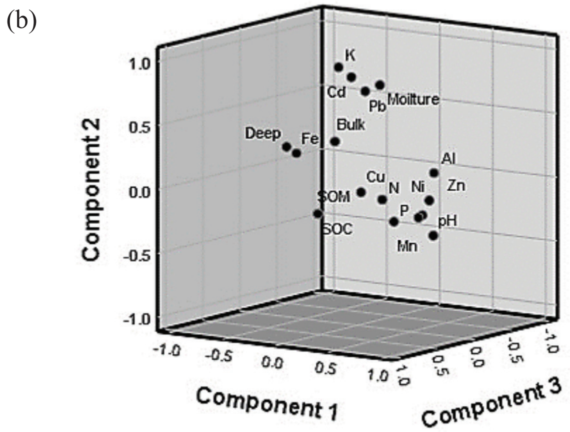
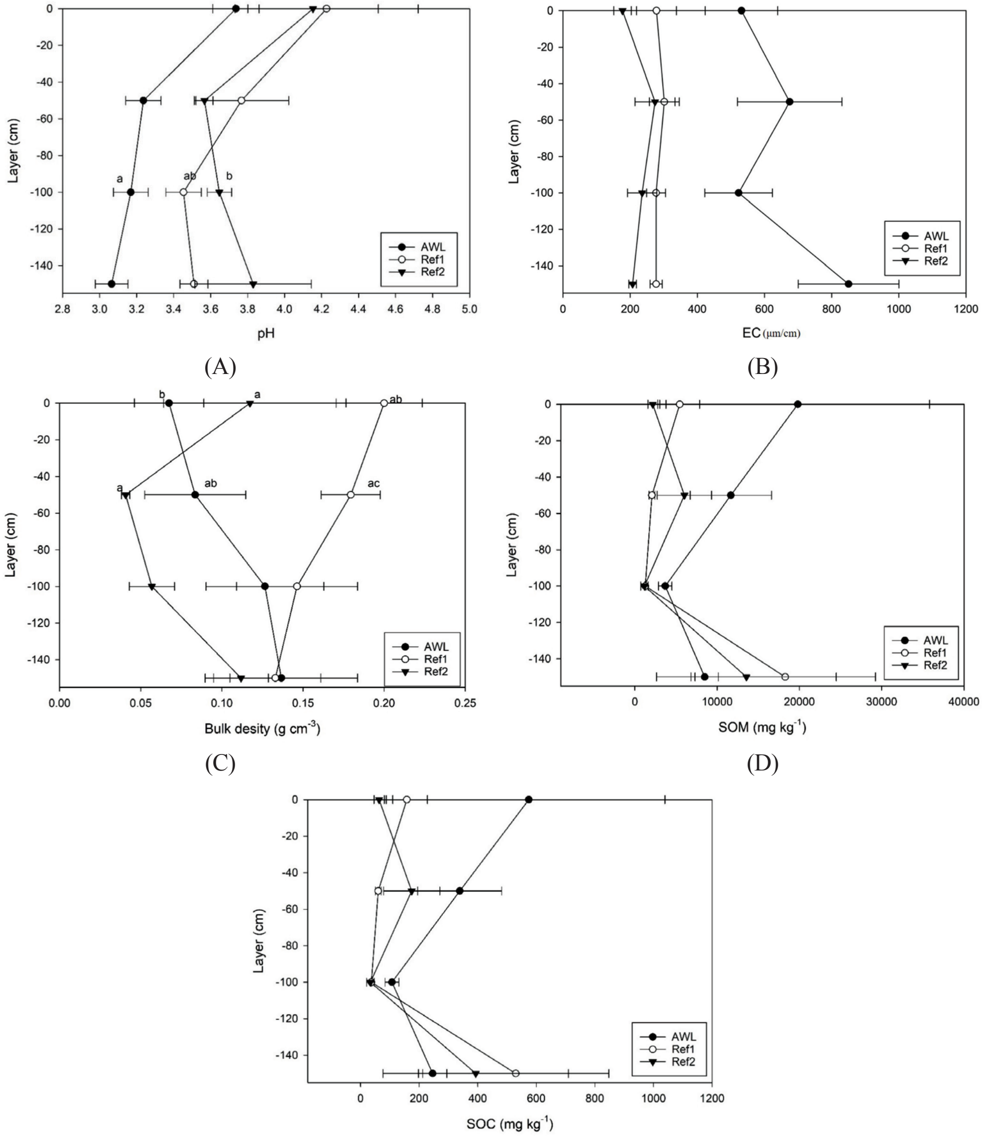


Figure 2: PCA of acidic soil components. (a) The eigenvalue of PCA components, (b) the component loading onto PCs, where PC1 is Zn > Ni > Mn > Soil layer > Al > SOM > SOC > P > pH, and PC2 is N > K > Cd > Pb, and PC3 is Deep > Fe

Table 6: Soil physical properties in the artificial wetland and reference areas for each soil layer

Soil Properties	**Layer (cm)**	**Area**		
		Artificial Wetland	**Reference 1**	**Reference 2**
pH	0	3.73 ± 0.307	4.22 ± 0.857	4.15 ± 0.610
	50	3.23 ± 0.234	3.76 ± 0.442	3.56 ± 0.080
	100	3.16 ± 0.229^{a}	3.45 ± 0.166^{ab}	3.64 ± 0.113^{b}
	150	3.07 ± 0.227	3.51 ± 0.136	3.83 ± 0.173
EC (µm/cm)	0	531 ± 246	278 ± 102	177 ± 44.8
	50	675 ± 381	301 ± 77.1	273 ± 103
	100	522 ± 246	277 ± 49.0	235 ± 75.8
	150	850 ± 366	277 ± 28.3	207 ± 21.2
Bulk density (g cm^{-3})	0	0.067 ± 0.052^{b}	0.200 ± 0.040^{ab}	0.117 ± 0.0^{92a}
	50	0.083 ± 0.076^{ab}	0.179 ± 0.031^{ac}	0.040 ± 0.004^{a}
	100	0.126 ± 0.088	0.146 ± 0.064	0.056 ± 0.024
	150	0.136 ± 0.115	0.132 ± 0.048	0.111 ± 0.029
SOM (mg kg^{-1})	0	19805 ± 3729	5448 ± 306	2181 ± 651
	50	11667 ± 3761	2081 ± 1167	6017 ± 3313
	100	3691 ± 1057^{ab}	1270 ± 504^{a}	1165 ± 1574^{b}
	150	8485 ± 4068^{a}	18275 ± 10964^{a}	13558 ± 8913^{b}
SOC (mg kg^{-1})	0	874 ± 108	158 ± 87.1	63 ± 18.8
	50	338 ± 109	60.3 ± 33.8	174 ± 96.1
	100	107 ± 57.4^{a}	36.8 ± 14.6^{a}	33.8 ± 22.7^{b}
	150	529 ± 230^{a}	529 ± 308^{a}	393 ± 315^{b}

Note: ^{abc} The mean difference across all rows is significant at $p < 0.05$ (HDS). and the value without no letter indicates a non-significant difference across the area ($p > 0.05$); SOM = Soil organic matter; SOC = Soil organic carbon.



(A) (B)

(C) (D)

(E)

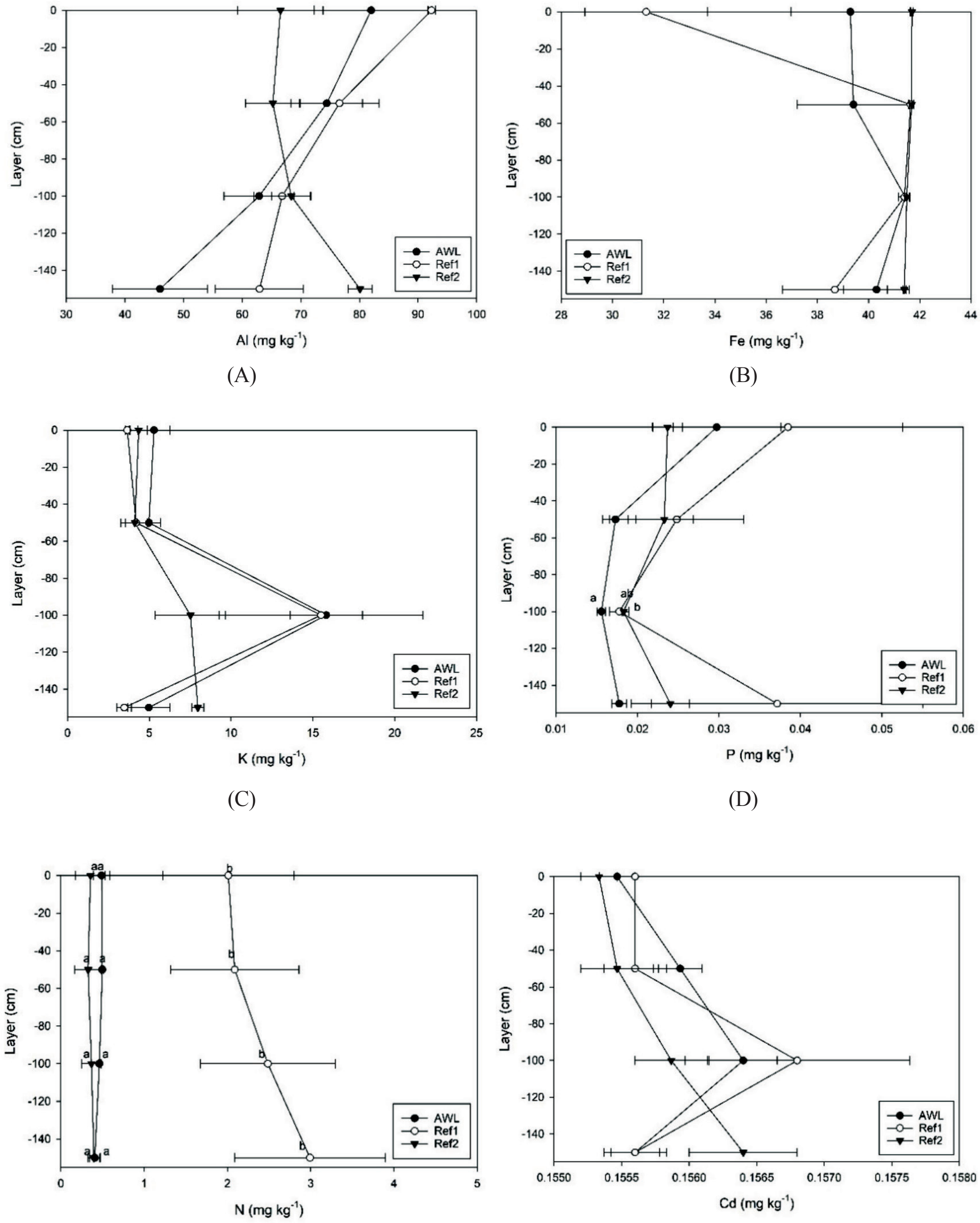
Figure 3: The properties of indicators between the artificial wetland and reference areas in different soil layers. (A) soil pH. (B) Water-soluble EC. (C) Bulk density. (D) Soil organic matter (SOM), and (E) Soil organic carbon (SOC)

Table 7: Element content in the soil of the artificial wetland and reference areas for each soil layer

Elements	Layer (cm)	Artificial wetland	Reference 1	Reference 2
Al (mg kg^{-1})	0	81.8 ± 23.8	92.3 ± 1.20	66.5 ± 12.6
	50	74.4 ± 14.9	76.6 ± 11.7	65.2 ± 8.03
	100	62.8 ± 14.6	66.8 ± 8.45	68.3 ± 5.76
	150	45.9 ± 19.8	62.9 ± 13.0	80 ± 3.56

Fe (mg kg^{-1})	0	39.3 ± 5.68	31.3 ± 4.14	41.7 ± 0.09
	50	39.4 ± 5.37	41.6 ± 0.14	41.7 ± 0.14
	100	41.4 ± 0.12	41.4 ± 0.39	41.9 ± 0.15
	150	40.3 ± 3.15	38.6 ± 3.53	41.4 ± 0.11
K (mg kg^{-1})	0	5.28 ± 2.41	3.65 ± 0.20	4.35 ± 0.92
	50	4.97 ± 1.74	4.19 ± 1.16	4.11 ± 1.45
	100	15.8 ± 5.41	15.5 ± 10.7	7.51 ± 3.71
	150	4.96 ± 3.14	3.47 ± 0.75	7.96 ± 0.63
Available P (mg kg^{-1})	0	0.029 ± 0.017	0.038 ± 0.009	0.023 ± 0.003
	50	0.017 ± 0.003	0.024 ± 0.014	0.023 ± 0.006
	100	0.015 ± 0.001^{a}	0.017 ± 0.002^{ab}	0.018 ± 0.000^{b}
	150	0.017 ± 0.002	0.037 ± 0.031	0.024 ± 0.004
N (mg kg^{-1})	0	0.480 ± 0.030^{a}	2.01 ± 0.105^{b}	0.350 ± 0.178^{a}
	50	0.497 ± 0.030^{a}	2.08 ± 0.079^{b}	0.298 ± 0.170^{a}
	100	0.462 ± 0.020^{a}	2.48 ± 0.235^{b}	0.371 ± 0.262^{a}
	150	0.407 ± 0.162^{a}	2.99 ± 0.194^{b}	0.109 ± 0.102^{a}
Cd (mg kg^{-1})	0	0.1554 ± 0.0003	0.1556 ± 0.0000	0.1553 ± 0.0002
	50	0.1559 ± 0.0004	0.1556 ± 0.0004	0.1554 ± 0.0004
	100	0.1564 ± 0.0006	0.1568 ± 0.0014	0.1558 ± 0.0004
	150	0.1556 ± 0.0004	0.1546 ± 0.0004	0.1564 ± 0.0006
Cu (mg kg^{-1})	0	0.272 ± 0.029	0.282 ± 0.030	0.281 ± 0.031
	50	0.291 ± 0.023	0.292 ± 0.033	0.293 ± 0.019
	100	0.293 ± 0.020	0.303 ± 0.034	0.331 ± 0.058
	150	0.344 ± 0.186	0.641 ± 0.350	0.366 ± 0.055
Mn (mg kg^{-1})	0	0.324 ± 0.093	0.396 ± 0.130	0.358 ± 0.025
	50	0.250 ± 0.057	0.214 ± 0.004	0.230 ± 0.024
	100	0.238 ± 0.045	0.212 ± 0.016	0.254 ± 0.017
	150	0.218 ± 0.056	0.278 ± 0.095	0.284 ± 0.053
Ni (mg kg^{-1})	0	0.239 ± 0.029	0.238 ± 0.003	0.214 ± 0.005
	50	0.216 ± 0.022	0.205 ± 0.003	0.195 ± 0.001
	100	0.206 ± 0.015	0.194 ± 0.004	0.195 ± 0.002
	150	0.200 ± 0.014	0.216 ± 0.030	0.197 ± 0.005
Pb (mg kg^{-1})	0	0.298 ± 0.032	0.284 ± 0.011	0.320 ± 0.025
	50	0.323 ± 0.042	0.326 ± 0.019	0.366 ± 0.056
	100	0.394 ± 0.113	0.446 ± 0.128	0.373 ± 0.041
	150	0.300 ± 0.023	0.320 ± 0.044	0.332 ± 0.058
Zn (mg kg^{-1})	0	0.345 ± 0.064	0.348 ± 0.017	0.330 ± 0.008
	50	0.315 ± 0.036	0.288 ± 0.006	0.278 ± 0.009
	100	0.274 ± 0.032	0.273 ± 0.014	0.307 ± 0.015
	150	0.244 ± 0.031	0.277 ± 0.042	0.288 ± 0.025

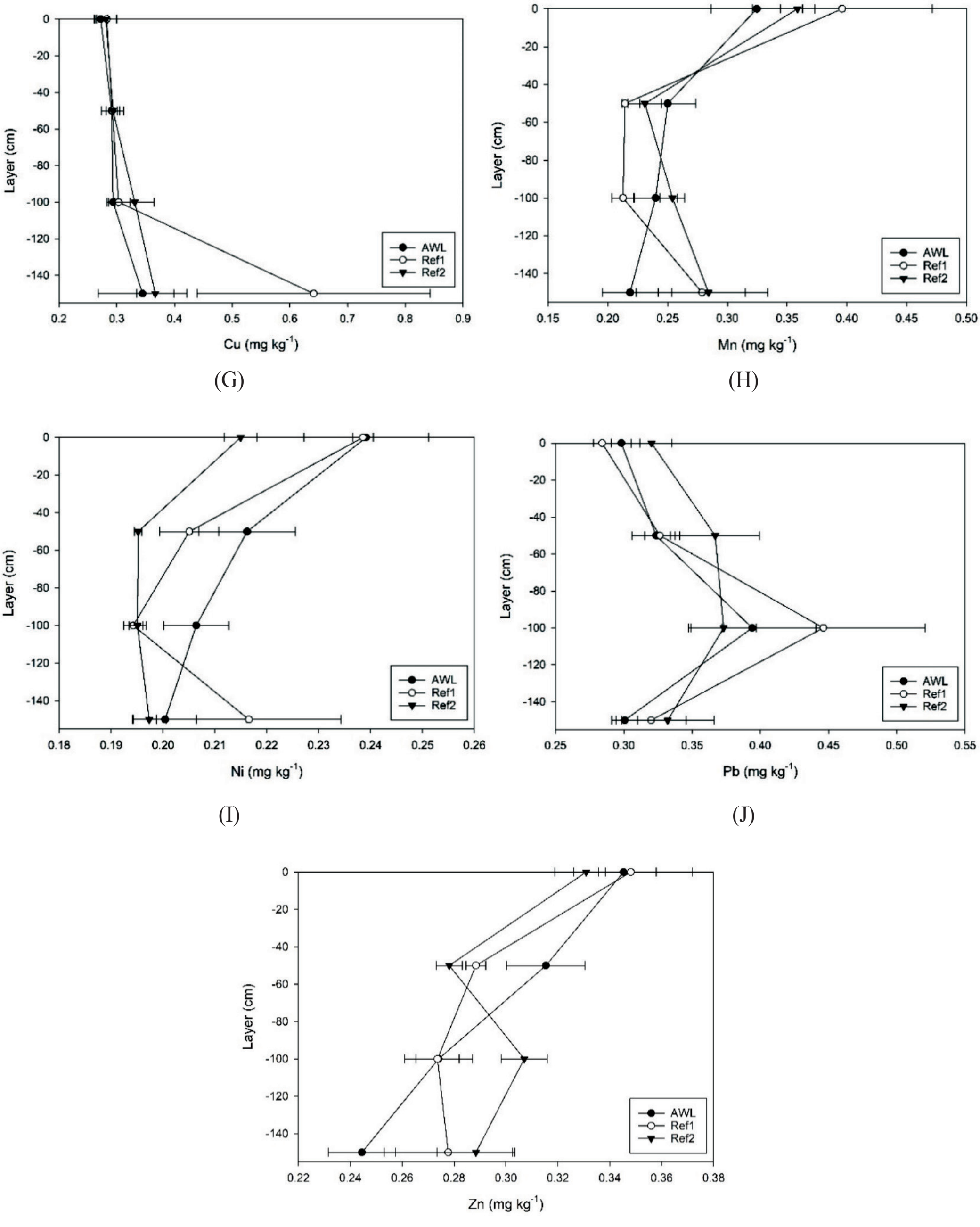
Note: ^{abc} The mean difference across rows is significant at $p < 0.05$ (HDS) and the value without no letter indicates a non-significant difference across the area ($p > 0.05$); Layer = 0, 50, 100, and 150 cm soil layers; Al = aluminium; Cd = cadmium; Cu = copper; Fe = iron; K = potassium; Mn = manganese; Ni = nickel; Pb = lead; Zn = zinc; P = available phosphorus; N = total nitrogen


Layer (cm)
0
-20
-40
-60
-80
-100
-120
-140
Al (mg kg-1)
30 40 50 60 70 80 90 100
Fe (mg kg-1)
28 30 32 34 36 38 40 42 44
K (mg kg-1)
0 5 10 15 20 25
P (mg kg-1)
0.01 0.02 0.03 0.04 0.05 0.06
N (mg kg-1)
0 1 2 3 4 5
Cd (mg kg-1)
0.1550 0.1555 0.1560 0.1565 0.1570 0.1575 0.1580
AWL
Ref1
Ref2
a
ab
b
aa

(A) (B)

(C) (D)

(E) (F)



(G) (H)

(I) (J)

(K)

Figure 4: The quantity of each element in the soil of the artificial wetland and reference areas in each soil layer. (A) Al. (B) Fe. (C) K. (D) Available P. (E) N. (F) Cd. (G) Cu. (H) Mn. (I) Ni. (J) Pb. (K) Zn

to the 100 cm soil layer, potentially reflecting the impact of P addition by long-term human activity and natural processes in the area (Smal *et al.,* 2019; Gluera *et al.,* 2020). The quantity of total N in the artificial wetland and reference areas 2 significantly in all soil layers ($p < 0.05$).

The soil element contents in each soil layer in the artificial wetland and reference areas are presented in Table 7, and the change in element quantity with increasing depth is shown in Figure 4. However, the impacts of land use (Zhiyanski *et al.,* 2016), soil parent, soil age, and microbial activity (Monhonval *et al*., 2021) on element quantities in each soil layer together.

Impact of Artificial Wetlands on Soil Conservation

By creating artificial wetlands in Nakhon Nayok (study site), the local government wanted to create a filtration zone to conserve the public area, but the site can store water for > 3-6 months. Consequently, this study found that the SOM (19805 ± 3729 mg kg^{-1}) and SOC (874 ± 108 mg kg^{-1}) in the topsoil of the artificial wetland were marginally higher than those in the reference areas. However, SOC in the artificial wetlands had a ratio of 1:0.17:0.51 compared with reference areas 1 and 2, indicating that the wetlands can store carbon in the soil (Uhran *et al.,* 2021). To enable microbial activity to continue in the topsoil, the quantity of SOC depends on SOM (Qingqing *et al.,* 2020). SOC quantity decreased with an increase in soil depth, consistent with Wang *et al.* (2016), who reported long-term increases in SOC in the deeper soil layers in the wetland.

Element Dynamics in the Artificial Wetland

The element dynamics and regional biodiversity levels of artificial wetlands are interrelated (Zhang *et al.,* 2011), as microorganisms are essential for biodegradation, the characteristics of man-made wetlands in nature are controlled by microbial diversity and general activity (Rajan *et al.,* 2019). The element dynamics in the wetland will be absorbed in the ground layer over time, particularly macronutrients by plants, such as N and P, even though the current concentration of N in the study site was significantly different [Figure 4 (E)] and decreased with increasing soil depth. P found in deeper soil layers influences the overall quantity, as it diffuses from the topsoil to the next soil layer (Vohla *et al.,* 2007). However, this study found that the 100-150 cm soil layers had high quantities of the elements K, Cu, Cd, P, and Pb affected by land use, SOM, microbial activity, and parent soil type (Dhaliwal *et al.,* 2019).

Conclusions

The artificial wetland in the Nakhon Nayok Province is located in central Thailand in a zone where soil acidity and soil layers influence element quantity, especially Fe. Among the soil properties in the artificial wetland, the topsoil pH was slightly lower than in the agriculture areas, but the pH of the 100 cm soil layer was significantly different in the artificial wetland compared with the agricultural area ($p < 0.05$), so human activity at the soil surface has an impact on soil properties in the soil sublayer. Among the soil properties in the artificial wetland, the topsoil pH was slightly lower than in the agriculture areas, but the pH of the 100 cm soil layer was significantly different in the artificial wetland compared to the agriculture area ($p < 0.05$), so human activity at the soil surface has an impact on soil properties in the soil sublayer.

However, the element composition in the artificial wetland could be classified into three patterns: (1) A lower quantity of topsoil that increases in K, Cd, Cu, and Pb content with depth; (2) a higher quantity of topsoil that decreases in Al, Fe, N, Ni, and Zn with depth; and (3) the quantity varies greatly in K, P, Cd, Mn, and Pb content at depths between 50-100 cm. Nevertheless, artificial wetlands in Nakhon Nayok have SOC at a ratio of 1:0.17:0.51 compared to agricultural areas, indicating that wetlands have potential carbon stocks in the soil, especially in the topsoil. An artificial wetland's topsoil has higher concentrations of K, N, and Ni than an agricultural area, indicating that the situation might have an effect on runoff in the region. However, this study provides data and evidence to advance the understanding of soil physical and chemical changes that accompany the transition of communal land into an artificial wetland over ~30 years and the influence of adjoining agricultural areas.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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