Approaches to Advanced Use of Sedimentation Lake for Aqua-Cultivation and Fertilizer Production in Cheung Ek Lake, Cambodia

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Tokyo University of Agriculture

Doctoral Dissertation

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SUMMARY

Chapter 1 Background and Objectives

The fastest-growing economies in Cambodia are leading to significant environmental pollution. Wastewater management has become a concern for the Royal Government of Cambodia since the population in Phnom Penh has grown from 1.4 million in 2008 to 2.1 million in 2018. Until now, the city still does not have a proper wastewater treatment facility, while its population continues to grow as well as the expansion of the city. Wastewater from this city is directly discharged using a combined sewer system, then pumped and stored in three wetlands, namely Tumpon Lake, Trabek Lake, and Cheung Ek Lake before its discharge to the Bassac and Tonle Sab Rivers. Cheung Ek Lake is well known as a sedimentation lake for natural wastewater treatment and aqua-cultivation. Recently, the lake's area has declined due to urbanization, and agricultural activities have changed, for example, farmers started to use more chemical fertilizers. Thus, a concern has been raised about the water quality degradation in the lake.

The objectives of this study are to evaluate the impact of urbanization on the lake's remediation capacity and propose approaches to improve water quality and fertilizer production in Cheung Ek Lake, Cambodia.

Chapter 2 Changes in Remediation Capacity of Cheung Ek Lake Due to Urbanization

As the area of Cheung Ek Lake has declined, a great concern about the water quality degradation has risen. Therefore, this chapter deals with changes in the nutrient removal rate of Cheung Ek Lake from 2019 to 2022. The water samples were collected

at various locations with different depths in the lake and analyzed for their physical and chemical properties, i.e., water discharge, pH, EC, Fe, NO_3^-, NH_4^+, PO_4^{3-}, DO, Cr, and Cu.

The results revealed a reduction in nutrient loads (28% to 84% for NO_3^-, 29% to 91% for PO_4^{3-}, and 96% for NH_4^+) between the inlet and the outlet points from 2019 to the dry season in 2022. Unfortunately, an increase (36% for PO_4^{3-}, 46% for NH_4^+ and 28% for Cu) was observed in the rainy season, 2022. Even though the lake area declined, the nutrient removal in the lake was confirmed. However, the declining lake areas led farmers to use many chemical fertilizers for their aqua-cultivation. This contributes to the higher load of nutrients at the inlet compared with the inlet. Apparently, Cheung Ek Lake lost its capacity for nutrient removal in the rainy season of 2022.

Chapter 3 Assessment of Economic and Analysis of Water Morning Glory Produced

Aqua-cultivation stands as a crucial economic asset for farmers in Cheung Ek Lake. Previous studies reported that vegetables cultivated in the lake were contaminated by heavy metals. Therefore, the objective of this chapter is to evaluate the economic benefits of aqua-cultivation and identify the causes of heavy metal contamination in water morning glory in Cheung Ek Lake. In 2019, a survey involving 35 farmers was carried out to assess the profitability of production. Water morning glory plants were collected from the lake for analyzing heavy metal concentrations, such as Cr, Cu, Cd, Pb, and As. Additionally, fertilizers and lake sediment and water were collected for analyzing heavy metal and chemical properties.

The results from the economic analysis indicated the profit from water morning glory production was 8,712.55 USD/year/ha. Compared to the previous research in 2017 (13,656.40 USD/year/ha), the profit from production in 2019 reduced by 36%.

Similar to previous studies, water morning glory cultivated in the lake was contaminated by heavy metals, i.e., Cr = 4 mg/kg and Cu = 3 mg/kg. The fertilizer applied in the field contained a high concentration of Cu (1.68 mg/L). The concentrations of Cr and Cu were high in the sediment at the inlet point and low in the sediment at the middle point. The results suggest that most heavy metals are derived from wastewater deposits near the inlet point, and chemical fertilizer serves as the primary cause of Cu contamination in water morning glory. The Cr derived from wastewater may contribute to Cr contamination in water morning glory. From this chapter, water morning glory production provides economic benefits to farmers; however, excess use of chemical fertilizers for higher production causes heavy metal contamination in water morning glory.

Chapter 4 Development of Calcium Silicate Hydrate (CSH) for Fertilizer Reproduction

The findings in Chapter 2 recommended that the nutrient removal rate of the lake should be improved. From Chapter 3, the amounts of chemical fertilizers should be reduced to prevent the contamination of water morning glory. Therefore, this chapter deals with the development of CSH and evaluates its capacity for nutrient removal from wastewater. CSH is an absorbent that can absorb nutrients, and the absorbed nutrients can be released from used CSH (nutrient absorbed CSH). In other words, CSH can be used as a fertilizer. The application of CSH into the lake made it possible to improve the nutrient removal rate along with fertilizer production in the lake. To make CSH, the first calcium hydroxide ($Ca(OH)_2$) was mixed with rice husk charcoal powder. Then, a small amount of water was added to the mixture and vibrated for 1 to 3 min using a vibrator. Absorption tests were conducted to examine the capacity of developed CSH in removing NH_4^+ and PO_4^{3-}.

In the absorption test for PO_4^{3-}, the removal efficiency increased from 44% on Day 1 to 98% on Day 7, remaining stable until Day 14. As for NH_4^+, the removal efficiency was 29% on Day 1, reaching 97% on Day 7. The absorption quantity was 0.11 mg-PO_4^{3-}/g-CSH and 0.065 mg-NH_4^+/g-CSH on Day 7. It can be concluded that CSH is effective in the removal of nutrients, specifically NH_4^+ and PO_4^{3-}, which can be used to increase the remediation capacity of Cheung Ek Lake.

Chapter 5 Used CSH as a Fertilizer for Agricultural Productions

In this chapter, elution experiments were carried out to investigate the release of absorbed nutrients from used CSH. This, in turn, contributes to the determination to use CSH as a fertilizer for aqua-cultivation. Other experiments were conducted to assess the growth rate of spinach in soils with 5% CHS, 5% used CSH, and without CSH. The growth rates, for example, weight, height root, leaf length, and leaf width, were measured. Soil fertility (N, P, K) was also measured to assess nutrient improvement in the soils.

From the elution experiments, CSH released nutrients back into the water in the concentration of 0.995 mg/kg for NH_4^+ and 1.35 mg/kg for PO_4^{3-}, indicating that the used CSH can be used as a fertilizer in aqua-cultivation. The addition of used CSH provided better growth rates, in which plant weight, height, root, leaf length, and leaf width increased. Additionally, the soil NPK levels indicated a notable three-fold increase, suggesting an improvement in soil fertility. From this chapter, it is suggested that CSH can be used as a viable replacement for chemical fertilizers in both farmland and aqua-cultivation.

Chapter 6 Conclusions and Recommendations

From this research, it was found that rapid urbanization of Phnom Penh caused a decline in the lake area, leading to changes in agricultural activities (excess use of chemical fertilizers) for higher production in the lake. This, in turn, increased the nutrient loads at the outlet point of the lake and contaminated water morning glory, which provided economic benefits to farmers. Therefore, a new method is required to increase the removal rate of nutrients in the lake.

It is recommended to use CSH, which is made from calcium hydroxide and rice husk charcoal because the raw materials for making CSH are available in Cambodia. The approach involved a simple and easily adaptable manufacturing process, specifically designed for implementation by farmers. The experimental results showed that the developed CSH could absorb nutrients with high efficiency, and the used CSH could be used as a fertilizer in both farmland and aqua-cultivation. This ensures that CHS can be used for wastewater treatment and national fertilizer production in Cambodia. Additionally, the research strives for indirect outcomes, including the reduction of agricultural waste input, i.e., rice husk, and an associated increase in income for farmers.

要旨

カンボジア国プノンペン市における 2008 年の人口は 140 万人に過ぎなかったが、2018 年には 210 万人にも達している。しかし、生活雑排水や産業排水等の都市域からの排水に対する処理機能は未整備のままである。そのため都市域からの排水はプノンペン市に位置する 3 つの沈砂湖（タンポン湖、トラベック湖、チュンエク湖）に排出され、自然浄化されている。人口増加に伴う都市化によって沈砂湖の面積が減少し、湖内で水耕栽培を行なっている農家は生産量を維持させるために化学肥料の施肥量を増やしている。そこで本研究では、都市化がチュンエク湖の自然浄化能力に与える影響を評価し、湖内の水耕栽培と肥料生産のための適切なアプローズについて論議し、沈砂湖の高度利用を目指している。

先ず、2019 年から 2022 年までの 4 年間におけるチュンエク湖の流況と水質特性から差し引き負荷を求めた。その結果、2019 年度から 2022 年乾季まで、流出地点における栄養塩類の流出負荷は流入負荷を大きく下回り（NO_3^-は 28％から 84％、PO_4^{3-}は 29％から 91％、NH_4^+は 96％）、チュンエク湖の自然浄化機能を高く評価できた。しかし、2022 年雨季には流出負荷が流入負荷より大きくなった。湖内水耕栽培への過施肥がチュンエク湖の水質に影響を及ぼし、見かけ上沈砂湖が有する浄化機能が失っていることが明らかになった。

従来、チュンエク湖は空心菜（*Ipomoea aquatica*）を生産する現地農家にとって重要な経済基盤であり、2019 年の調査では平均で 8,712.55 USD/year/ha の利益を上げていることが明らかとなった。しかし、空心菜の生育には Cu（1.68 g/kg）と NH_4^+（266.50 g/kg）が高濃度に含まれる液肥が施用されており、生産される空心菜にも Cr（4 mg/kg）と Cu（3 mg/kg）が高濃度に含まれている。各地点の湖水と底泥の重金属の分析結果により、空心菜の Cr 汚染は下水、Cu 汚染は化学肥料から由来している可能性が高いと推定された。

そこで本研究では、湖内の栄養除去率の向上と化学肥料の使用量の削減(湖内で肥料生産)を実現するためのアプローズを考案した。カンボジア農家に利用しやすい水酸化カルシウム（$Ca(OH)_2$）と籾殻灰で構成されるケイ酸カルシウム水和物 CSH の製造法を開発し、NH_4^+とPO_4^{3-}等の吸着能力を評価した。吸着に要する時間は異なるものの、PO_4^{3-}の吸着能力は 0.11 mg-PO_4^{3-}/g-CSH、NH_4^+では 0.065 mg-NH_4^+/g-CSH であり、一定の養分吸着能を確認できた。更に養分吸着に使用した（使用済）CSH は農地や水耕栽培に肥料としての利用可能性について検討を進めた。具体的には、使用済 CSH からの栄養塩類の溶出特性に加えて、施用による土壌肥沃度の変化と小松菜（*Brassica rapa var. perviridis*）の生長を調べ、施用区における優位性を明らかにすることができた。これらの結果より、使用済 CSH が農地施用のみならず、水耕栽培においても重金属を含む液肥の代替品として使用できる可能性を示すことができ、CSH の適用による肥料生産の一事例を明示することができた。

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Chapter 1

Background and objective

1.1 Background

1.1.1 General information of Cambodia

Cambodia is located in Southeast Asia with a total land area of 181,035 km^2 and it has 443 km of coastline along the Gulf of Thailand. Cambodia shares its international boundary with Thailand in the northwest, Laos in the northeast, Vietnam in the east (Figure 1-1). The country's population is 15.3 million (NIS, 2019). Cambodia is classified into four geographical regions: Central Plain, Tonle Sap, Coastal and Sea, and Plateau and Mountain. The country's GDP was composed of contributions of 23.36% from agriculture, 30.85% from industry, and 39.72% from services (NIS, 2017). Concurrently, the labor engaged in agriculture constituted 37% of the total workforce.

Figure 1-1 Map of Cambodia

Cambodia is comprised of 24 provinces and one special administrative unit for the Phnom Penh Capital City. The area of Phnom Penh Capital City is approximately 679 square kilometers, divided into 14 districts. Within these districts, there are 105 communes, and each Sangkat is further divided into villages. Administrative boundaries have been revised periodically by dividing existing districts/communes.

The climate of the country is governed by the monsoon winds, which define two major seasons: dry (October to April) and rainy (May to September). January is the coldest month, and April is the warmest. Average annual rainfall is between 1,000 and 1,500 millimeters, with the heaviest fall in the southeast. The relative humidity is high at night throughout the year. During the daytime in the dry season, humidity averages 50% or slightly lower, but it may remain at about 60% in the rainy season. Given a starting population of about 2.19 million in 2019 and an annual growth rate of 3.2%, the population of Phnom Penh is forecasted to increase to about 2.62 million by the year 2035. (NIS, 2019).

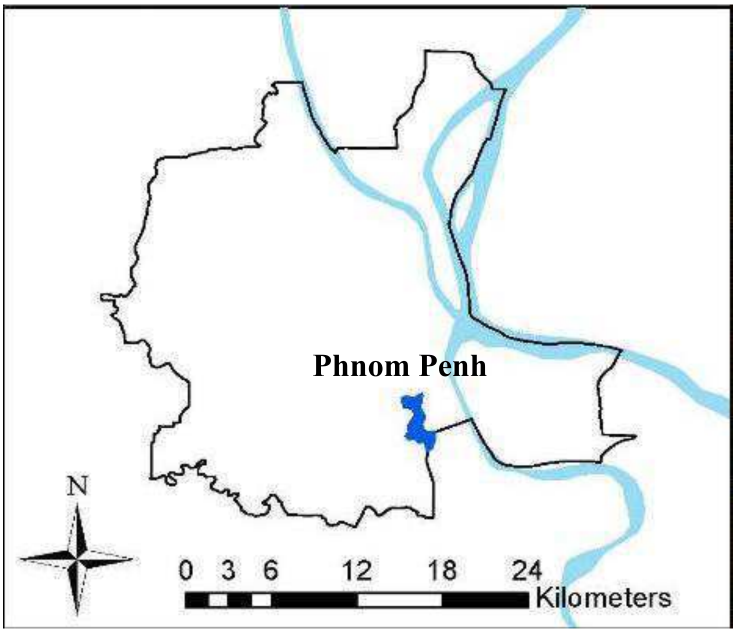

Figure 1-2 Map of Phnom Penh city

1.1.2 Urbanization in Cambodia

The economy of Cambodia experienced rapid growth, achieving an average annual rate of 7.7% from 1998 to 2019, positioning it among the most rapidly expanding economies globally during that period (World bank, 2023). As Cambodia's gateway to the global economy, it has attracted an increasing flow of foreign investment in trade, production for export and service sectors, including the real estate and construction sectors, in the past decade (World bank, 2017).

In 2014, Phnom Penh had a total of 97,200 established enterprises, an increase of 1.4 percent from 2011 (NIS, 2015), and provided 552,625 jobs, an increase from 17,625 jobs in 2011 (NIS, 2013). This expansion has created thousands of jobs every year resulting in increasing demand for basic public services including water security an adequate supply of clean water and a proper waste management system. In the city of Phnom Penh, the economic growth also triggered an expansion of its total area, with the size increasing from 290 km^2 in 1998 to 679 km^2 in 2019.

The general population census in Cambodia has been conducted in 1998, 2008, and 2019. The most recent census was conducted in 2019, with the final report published in October 2020. Additionally, an inter-censual population survey was conducted in 2013, sampling households to be surveyed, with accuracy achieved at the province level.

Over the decades, the population in Cambodia has shown steady growth, increasing from 11.4 million in 1998 to 15.6 million in 2019, as illustrated in Table 1-1.

The population of Phnom Penh is increasing significantly due to large-scale urban development, which attracts more citizens from other provinces. The city's economic importance, abundant employment opportunities, and educational institutions are key factors driving this migration.

Phnom Penh now occupies the highest share of the country's population at the provincial level, accounting for 14.7% of the total population, which amounts to 2,281,915 people. This represents a significant increase from 8.7% (999,804 people) in 1998 (NIS, 2008 and NIS, 2019)

As a result of this population growth, the population density in Phnom Penh is the highest in the country, with 3,361 persons per km^2, compared to the national average of 87 persons per km^2. This high population density reflects the city's status as a major urban center and underscores the challenges and opportunities associated with managing urban growth and development in Phnom Penh.

Table 1-1 Annual growth rate by area and capital Cambodia, 1998-2019

Area/Capital	Total Population			Annual Growth Rate	
	2019	2008	1998	1998-2008	2008-2019
Total	15,552,211	13,395,682	11,437,656	1.5	1.4
Urban area	6,135,194	2,614,207	1,795,575	2.0	7.8
Rural area	9,417,017	10,781,655	9,642,081	1.3	-1.2
Phnom Penh	2,281,951	1,327,615	999,804	2.8	4.9

(Source: National Institute of Statistics, Ministry of Planning, 2019)

The population in Phnom Penh has doubled between 1998 and 2019, the development of infrastructure has struggled to keep pace with urbanization. The rapid growth of urban populations across the country has created several challenges, including a lack of infrastructure and urban services, traffic congestion and lack of parking, increased urban flooding, shrinking public spaces, negative environmental impacts, and a lack of inclusive urbanization and planning. Furthermore, water consumption in the city has almost doubled its capacity to supply clean water over the decades (Figure 1-3), reaching 580,000 m^3 per day. This has led to a significant consequence related to the degradation of water quality due to increased pollution. Urban areas often witness heightened industrial activities, extensive use of chemicals, and improper disposal of waste, leading to the release of harmful pollutants into water bodies.

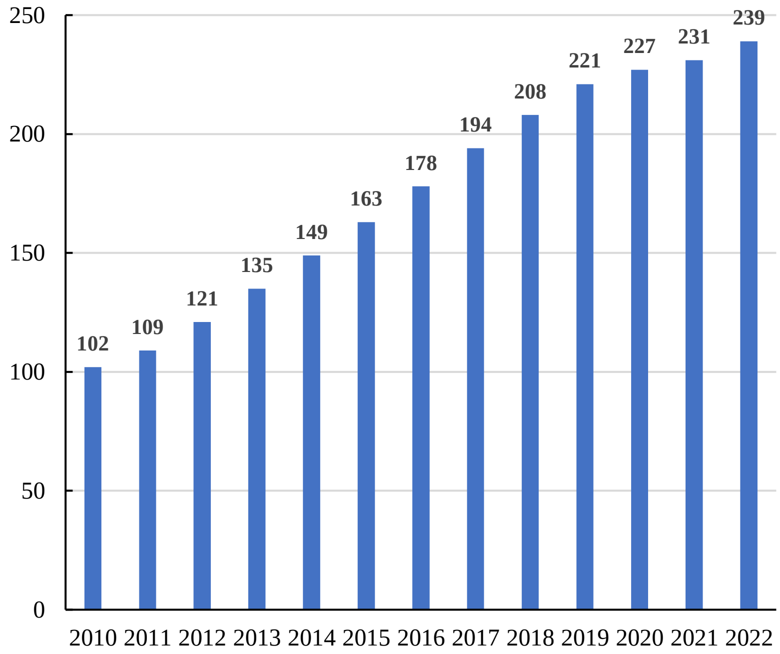

Figure 1-3 Quantity of clean water supply in Phnom Penh (million m^3 /year)

(Source: Phnom Penh Water Supply Authority, 2023)

Currently, wastewater released from households contains 234 tons of feces, 2,335 m^3 of urine and 8,154 m^3 of grey water per day. Moreover, wastewater discharged from 3000 small enterprises amounts to more than 1 million m^3 daily (WEPA, 2018). Phnom Penh's 732-kilometer drainage system comprises 14 pumping stations, with 44,807 converted-holds dedicated to wastewater management within the city. Primarily constructed during the colonial period, this sewer system is characterized by narrow passages and retains many of its original settings. (Ty et al., 2018). The proportion of well-functioning sewers increased from 7% of the total in 2011 to 11% in 2015, indicating a gradual improvement. However, the majority of the sewer system still requires further enhancement to meet desired standards (WEPA, 2018). As a result, only 9% of discharged water in Cambodia undergoes proper treatment before being released into the main water bodies, representing the second lowest capacity in Southeast Asia, trailing only behind Lao PDR (Figure 1-4). Phnom Penh, specifically, frequently faces flooding during the rainy season (Heng et al., 2017), primarily attributed to its vulnerable sewage and drainage infrastructure (Figure 1-5).

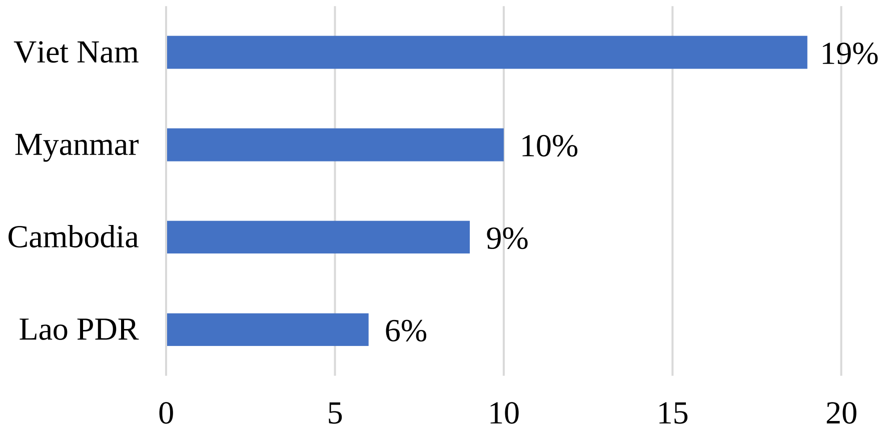

Figure 1-4 Wastewater treatment by countries in Southeast Asia in 2017

(Source: Buth et al, 2019)

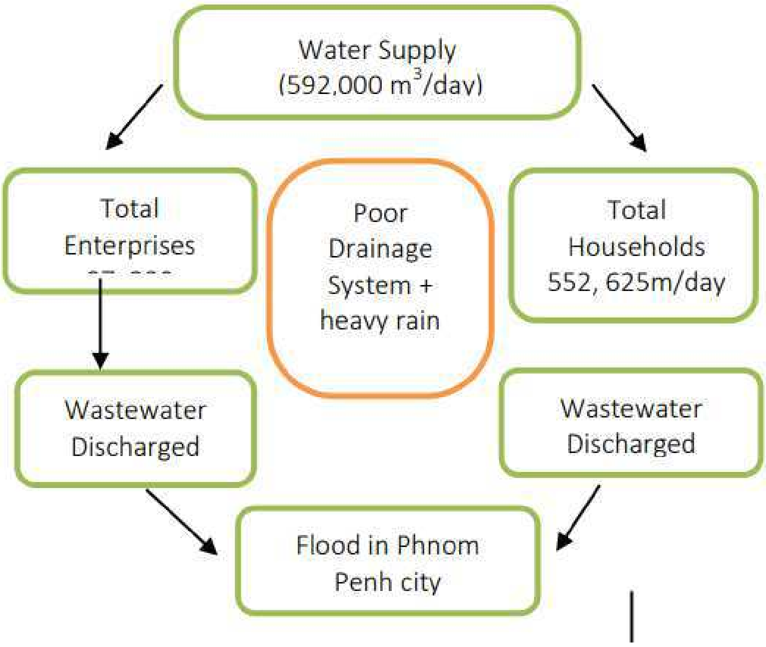

Figure 1-5 Cause of seasonal flood in Phnom Penh

(Source: Buth et al., 2019)

1.1.2.1 Land use change in Phnom Penh

In the last two decades, Cambodia has been implementing national policies to facilitate internal migration and ensure good basic services for the newly settled migrants, but coherence and proper implementation of policies are still lacking (Diepart and Ngin, 2020; Hing and Ly, 2014). As urbanization generates a lot of manual and blue-collar jobs, rural citizens are moving to towns and the capital city to seek a better life.

Due to the effect of natural population growth and rural-urban migration, Cambodia has experienced rapid urbanization over the last decade when the urban population grew from 19.5% in 2008 to 39.5% in 2019 (NIS, 2019). Phnom Penh, the capital city of Cambodia, is surrounded by natural wetlands which play a significant role in the storage of wastewater, sewage and stormwater.

Cambodia's mostly unplanned and unregulated process of urbanization has resulted in several major problems such as lack of infrastructure and urban services, traffic congestion, increased urban flooding and more importantly the neglect of the urban poor and the environment and the lack of pro-poor, inclusive urbanization processes.

Since 2003, developers of satellite city and gated housing communities have poured sand into the wetlands and lakes, completely in-filling over 60% of Phnom Penh's lakes and more than 40% of Phnom Penh's major wetland areas (STT, 2019). This satellite city project has greatly impacted Cheung Ek Lake, threatening the livelihoods and homes of more than a thousand families, devastating the wetlands ecosystem, placing more than a million people at increased risk of flooding, worsening food insecurity, and polluting the Mekong and Bassac rivers with untreated sewage and harmful pollutants.

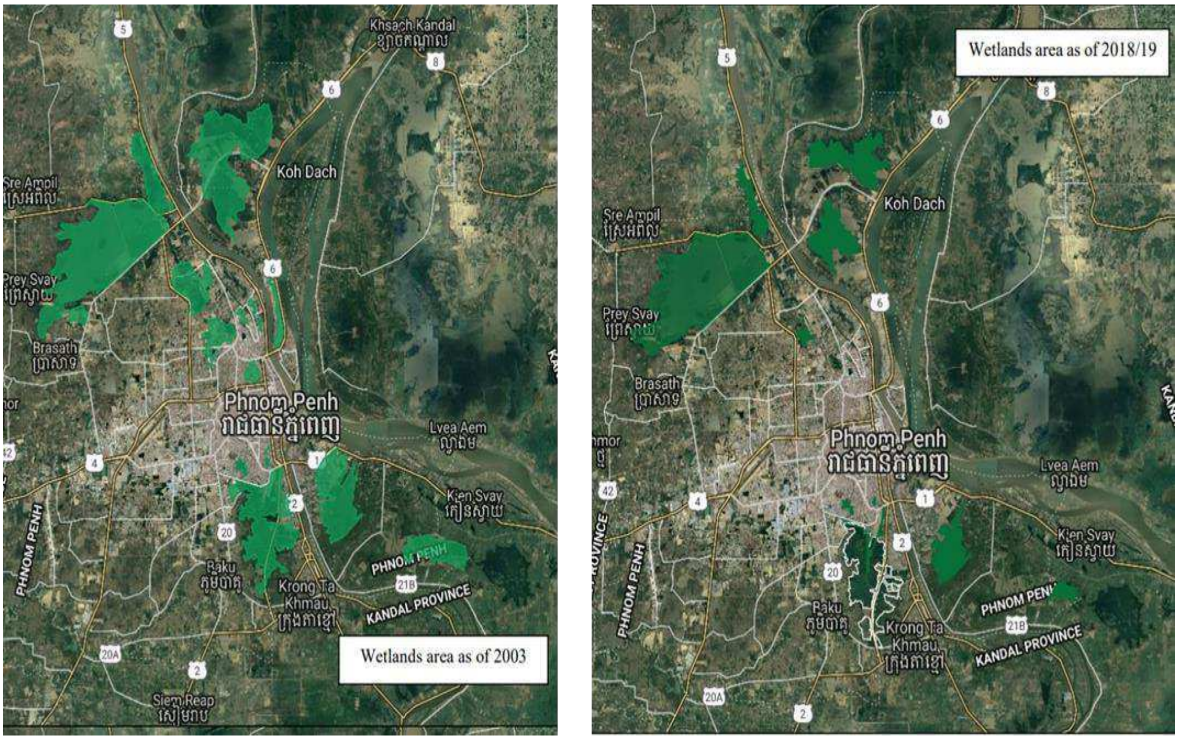

Figure 1-6 Land use change of wetland area in Phnom Penh

(Source: STT, 2019)

This Cheung Ek Lake (Figure 1-6) is a vital flood protection area for Phnom Penh, as well as the city's only wastewater treatment system. This natural wetland has received untreated city sewage discharges, and takes a heavy load from two wastewater pumping stations for wastewater treatment.

According to the time frame in Figure 1-7, in 1980 the lake area in Cheung Ek Lake was 14 km^2 and can expand to 30 km^2 in the rainy season (Irvine et al., 2008). In 2008, the government decreed only 5.2 km^2 of the lake and about 25 km^2 to be kept as state-public land. The surface area has been revised to approximately 15 km^2. Out of this total, only 1.07 km^2 was estimated to remain untouched by development in 2020. More recent data from STT (2019) indicates that only 1.56 km^2 of the 15 km^2 has not yet been privatized or allocated. Despite only 1.56 km^2 being officially given to the private sector, the surface area of the lake available for aquaculture was approximately 7 km^2 in 2020, as some investors had not initiated construction at that time (Figure 1-8).

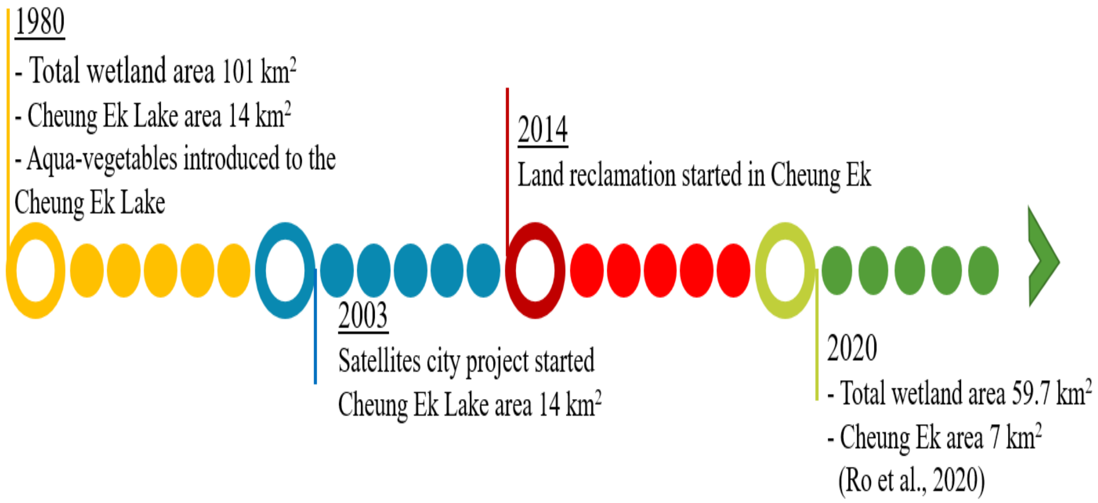

Figure 1-7 Time frame of land use change in Cheung Ek Lake

Figure 1-8 Activities of aqua-cultivation and land fill in Cheung Ek Lake

(Source: Gerald Flynn and Vutha Srey, 2022)

1.1.3 Aqua-cultivation in wastewater lake

Peri-urban environments and communities share many facets with those defined as urban (or intra-urban). Usually the transition or interface from rural to peri-urban to urban is regarded as a continuum. Due to changes in the factors that determine aquatic production systems, namely the availability of land, in general one can state that in the urban setting relatively smaller and more intensively managed aquatic production systems are more common. The peri-urban areas are in a state of constant change and are often characterized by having only a basic infrastructure (roads, schools, medical centers) and poor service provision. There are often conflicts over land and water use, and urban industries often move into these areas to escape restrictions and regulations. Peri-urban communities are often heterogeneous with respect to ethnicity, income levels, language and social norms and are characterized by increasing population density through migration, caused not just by rural people coming in from outside the cities, but also by the movement of urban people radiating outwards from the urban core.

The classification of aquaculture systems by William (2005), which is based on production intensity and management demands, indicates the degree of control and surveillance operators are able to exercise, both practically and in terms of the assets upon which they have to draw. This might be particularly helpful in discussing the peri-urban situation. In the case of peri-urban aquaculture production, the transition from extensive to semi-intensive aquatic production systems may be attributed to various factors. However, greater demand from markets combined with improved marketing channels often constitutes a particularly important driver for intensification. Control of resources and more access to production-enhancing inputs such as waste resources, food processing byproducts and credit to purchase additional seed, feed and labor can also stimulate intensification. This transition from semi-intensive to intensive production appears to be driven largely by financial considerations and increased competition for resources, in particular land, but also solid organic and wastewater resources, labour, credit and markets. Intensification also appears to offer producers greater control, enabling them to better safeguard and enhance the quality of products, and also address concerns expressed by consumers regarding possible health hazards. Despite the competitive advantage associated with intensification, several barriers to such a transition and thus the sustainability of the production systems can be identified: transaction costs may be high, whilst limited access to knowledge, training, credit, markets and institutional support limit the options and opportunities available to producers.

The cultivation of fish and aquatic vegetables in wastewater and non-wastewater is widespread throughout many cities in Southeast Asia, Africa and Latin America (Stuart et al., 2004). In many Asian developing countries, the production systems involve dare frequently semi-intensive utilizing wastewater directly from the city as a source of nutrients to increase production (Stuart et al., 2006). Urban aquatic production is often intrinsically linked with the livelihoods of many poor people (Stuart et al., 2006). Wastewater use in agriculture and aquaculture has a long history in China (Zhiwan et al., 1999) as well as in Cambodia and Vietnam, where wastewater is often used to culture fish and aquatic plants in peri-urban lakes (Kuoung et al., 2005; Leschen et al., 2005; Lan et al., 2007).

In Vietnam, the reuse of wastewater has shown potential for aquaculture during the year 2000s. According to Phuong et al., 2005, wastewater-fed fish production increased by 35% compared to non-wastewater use. In Hanoi city, untreated urban wastewater was also used for water morning glory and water mimosa cultivation (Marcussen et al., 2004). Furthermore, in Ho Chi Minh City, some households combined the fish culture with water morning glory cultivation (Hung et al., 2005).

In Thailand, aquatic production systems, including the farming of edible aquatic vegetables and fish, also played an essential role in the livelihoods of many urban farmers and vendors (Yoonpundh et al., 2006).

In Cambodia, peri-urban lakes are important sources of edible aquatic vegetables and fish farming to supply the city's food demand as well as other areas of Cambodia. (Khuong et al., 2005). In Southeast Asia, the peri-urban lake is widely used as a vital source for food production. However, the decrease in wastewater lake use for cultivation can be seen as more study has shown the negative effect of the wastewater lake quality on food production.

Cheung Ek Lake is known as the area where aquatic plants such as water morning glory (*Ipomoea aquatica*) and water mimosa (*Neptunia oleracea*). The characteristic of these aquatic plants that can be grown all year round becomes one of the benefits of phytoremediation. In 2003, the aquatic plants, especially water morning glory occupied about half of the total surface of the lake. It represented a source of income for more than 400 households living around the lake (Khov et al., 2007). The vegetables cultivated on the lake are used for human needs and also for animal feed. The farmers usually sell their products just in front of their houses or sell them to wholesalers or collectors. A marketing appraisal of the aquatic plants from Cheung Ek Lake has been partially conducted. The exact markets where the wholesalers will sell the products are not identified yet. The activities on the surface of Cheung Ek Lake represented an important source of income for many households living around the lake and affected their socio-economic status (Sar et al., 2009).

Water morning glory, a semi-aquatic tropical plant native to Southeast Asia, is cultivated as a vegetable. Nearly all parts of the young plant tissue are edible, with a preference for the tender shoot tips and younger leaves. Notably, water morning glory requires significantly more water compared to most other vegetable crops due to its semi-aquatic nature. Increased irrigation can lead to the leaching out of readily available nutrients. Hence, it is advisable to utilize slow-release forms of fertility to mitigate nutrient loss. In the production cycle, harvesting of the entire plant can typically be done 50 to 60 days after planting. The plants are harvested by cutting the stem close to the ground, and nitrogen is subsequently applied to stimulate re-growth.

Table 1-2 Nutrient facts of water morning glory

Calories 19	
	% Daily Value*
Total Fat 0.2 g	0%
Cholesterol 0 mg	0%
Sodium 113 mg	4%
Potassium 312 mg	8%
Total Carbohydrate 3.1 g	1%
Dietary fiber 2.1 g	8%
Protein 2.6 g	5%

Vitamin C	91%	Calcium	7%
Iron	9%	Vitamin D	0%
Vitamin B6	5%	Cobalamin	0%
Magnesium	17%		

(Source: USDA)

Water morning glory serves as the primary crop cultivated in Cheung Ek Lake, and its cultivation takes place throughout the year. The water morning glory plants are floating on the surface of the water and arranged in line strings that are 1 m to 1.5 m wide and 20 m to 30 m long. In one hectare area, there are typically consist of 30-40 lines. During harvest, water morning glory plants are manually pulled out, leaving the root part in the water. Without the application of additional fertilizer, the crop has a natural cycle of 4 to 5 weeks (Figure 1-9).

As urbanization progresses, the cultivation area of water morning glory in Cheung Ek Lake has significantly decreased, thereby impacting the income of local farmers. With limited available space due to urbanization and the need to sustain income, farmers resort to applying fertilizer to accelerate the harvest cycle, reducing it to just 2 weeks. This expedited cycle allows farmers to maintain their income despite the shrinking cultivation area caused by urban development.

The rise in chemical fertilizer usage in water morning glory production has raised concerns about its potential impact on both the quality and safety of consumption. Given that water morning glory grows in wastewater lakes, there is a heightened worry about the accumulation of chemical residues from fertilizers in the plants. This situation prompts questions about the potential health risks associated with consuming water morning glory grown in such environments. Therefore, there is a need for thorough monitoring and assessment of the quality and safety standards of water morning glory cultivated in these wastewater lakes to ensure consumer health and well-being.

Figure 1-9 Water morning glory loaded for market in Cheung Ek Lake

1.1.4 Fertilizer use in agriculture in Cambodia

The agricultural sector holds a pivotal role in Cambodia's economy, contributing approximately 23.36% to the GDP. However, crop cultivation across Cambodia's 4 million hectares of agricultural land has become progressively challenging due to low soil fertility (White et al., 1997). Fertilizer application is essential for replenishing nutrients, enhancing crop yields, and boosting crop biomass, crucial for moisture retention and nutrient efficiency (Bumb, 1996). Cambodia anticipates a significant portion of improved crop production to stem from increased crop yields, with fertilizers expected to play a vital role in meeting future demands for crop intensification and bolstering food security (RGC, 2010).

Considered an indispensable input for production, fertilizers have been imported and utilized by Cambodian farmers for numerous years. According to FAO estimates, there has been a notable overall increase in the consumption of Nitrogen (N), Phosphorus (P), and Potassium (K) - commonly referred to as NPK fertilizers.

According to a report from the Ministry of Agriculture, Forestry and Fisheries, Cambodia imported over 1.2 million tonnes of fertilizers and pesticides in 2019, representing a year-on-year increase of 9% of this total, fertilizer imports amounted to 1.14 million tonnes, while pesticide imports reached 810,000 tonnes.

Until now, Cambodia lacks a domestic fertilizer production facility, relying heavily on imports from neighboring countries. The primary sources of fertilizer imports for Cambodia include Thailand, Vietnam, and China. Construction of a fertilizer blending plant commenced in 2009 in Kandal province, and operations commenced in early 2013. In its first phase of operation, the plant has an annual blending capacity of around 350,000 tonnes of NPK fertilizers. Upon reaching full capacity, which is estimated to be around 500,000 tonnes per annum, the plant aims to meet the growing demand for fertilizers in Cambodia. However, despite this significant step towards local fertilizer production, it is estimated that Cambodia still requires approximately 617,000 tonnes per annum to adequately fertilize about 4.1 million hectares of farmland.

Furthermore, several challenges hinder investment in this sector, including the high cost of electricity and the absence of certain key raw materials required for fertilizer production, which must be imported. These challenges create barriers for investors looking to establish fertilizer production facilities in Cambodia. Additionally, the uncertain market conditions and the need for significant capital investment further deter potential investors from entering the market. As a result, Cambodia continues to rely heavily on imported fertilizers to meet the needs of its agricultural sector.

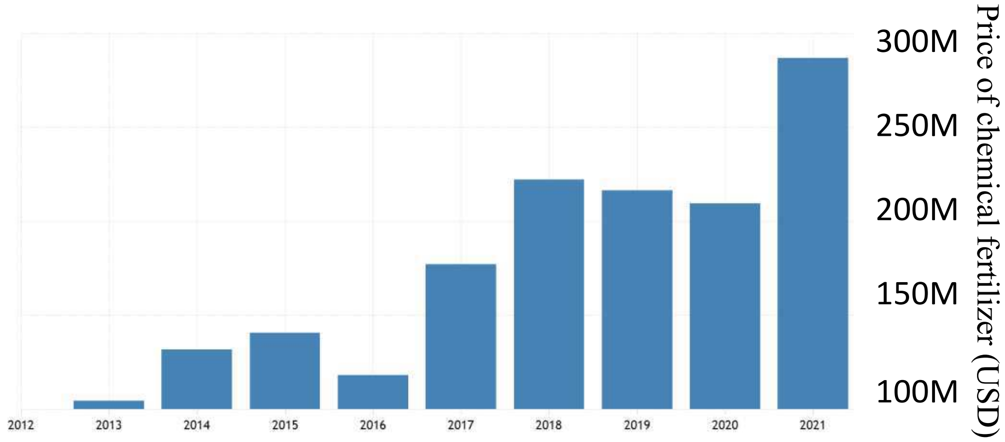

Figure 1-10 Prices of chemical fertilizer import in Cambodia (USD)

(Source: Trading economics, 2021)

However, with prices steadily increasing, imported fertilizer prices increase from 210 million USD in 2020 to 287 million USD in 2022 (Figure 1-10), many farmers are finding it challenging to afford these essential agricultural inputs (Figure 1-11). Consequently, a significant number of farmers are forced to abandon their land and seek job opportunities in other countries as a means of livelihood. This migration of farmers due to economic pressures exacerbates challenges within the agricultural sector and poses broader socio-economic implications for Cambodia. Addressing these challenges will be crucial for stimulating local investment in fertilizer production and reducing the country's dependence on imports in the future.

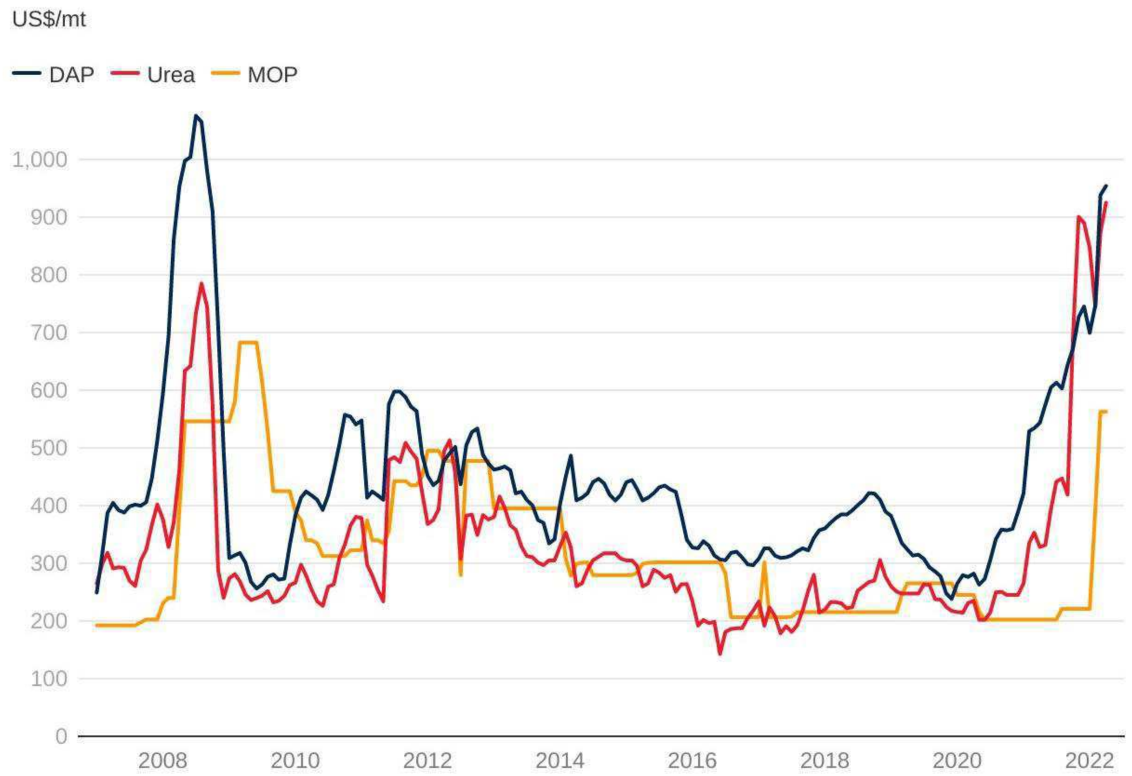

Figure 1-11 Global fertilizer price

(Source: World Bank, 2022)

1.1.5 Law and regulation on wastewater discharge

The royal government of Cambodia established the Sub-Decree on water pollution control on 6 April 1999 by the council of ministers. The sub-decree aims to minimize and phase out the various activities that cause pollution in public water areas in order to sustain good water quality that is suitable for human usage by improving wastewater management. Another key point of the sub-decree is to mention the responsibilities and obligations of the owner of pollution sources in water environment management. The standards (Table 1-3) for effluent discharge from any sources of pollution shall be specified in annex 2 of the sub-decree.

Table 1.3 Standard for pollution sources discharging wastewater to public water areas and sewer

N	Parameters	Unit	Allowable limits for pollutant substance discharge to	
			Protected public water area	Public water area and sewer
1	Temperature	^0C	<45	< 45
2	pH		6-9	5-9
3	Nitrate ($N0_3$)	mg/L	<10	<20
4	Phosphate($P0_4$)	mg/L	<3.0	<6.0
5	Iron (Fe)	mg/L	<l.0	<20
6	DO	mg/L	>2.0	>l.0

(Source: Sub-decree of RGC, 1999)

Moreover, in April 2004 the royal government of Cambodia has passed new environmental regulations stipulating that dischargers of wastewater, such as small and medium enterprises and housing estates, will be held responsible for wastewater pollution. Therefore, these entities should treat wastewater adequately on-site before it is discharged or released into the environment. Wastewater is advised or ordered to be treated to abide by the environmental legal instruments before discharging into receiving water, otherwise, a penalty will be done in according to the law.

This new sub-decree on water pollution control aims to minimize and phase out various pollution activities in public water areas, including improving wastewater management for sustaining good water quality suitable to human desires. The standard for discharging effluent into public water areas and the standard for water quality at public water areas for biodiversity conservation were included.

Sub-Decree includes the standards for:

(i) effluent standard for pollution sources discharging wastewater to public water areas or sewer

(ii) type of pollution sources required having permission from the Ministry of Environment before discharging or transporting their wastewater

(iii) Water Quality Standard in public water areas for bio-diversity conservation

(iv) Water Quality Standard in public water areas for public health protection.

In Chapter 2 article 7 also states that to ensure human health and bio-diversity conservation all the pollution load contained in liquid waste has to be released in the designed place to protect the public water area.

1.2 Study Area

Phnom Penh is located on the Mekong River floodplain and lies at the confluence of the Mekong, Tonle Sap, and Bassac Rivers in south-central Cambodia. The center of the capital is surrounded by natural wetlands and lakes such as Cheung Ek Lake, Boeng Kok Lake, and Poung Peay Lake. However, with the expansion of Phnom Penh, most lakes/wetlands have been reclaimed and are under high pressure due to anthropogenic activities. Natural wetland resources are also facing threats such as intensive agriculture, infrastructure development, pollution and nutrient inputs, decreasing biodiversity, and a compromise in their natural filtering capabilities.

The water supply of Phnom Penh city relies heavily on three main natural water bodies: the Mekong River, Tonle Sap, and Tonle Bassac. However, there was no central wastewater treatment plant until 2021. In 2022, the Cheung Ek Sewage Treatment Plant was built, and its construction was finished in January 2024. Normally, natural lakes or wetlands are used as a natural treatment process, and without proper treatment for municipal waste, natural degradation of contaminants in untreated water would take a long time.

Nonetheless, the ability of natural degradation is decreasing as the wetlands are being filled in, and, as of 2021, most of the wetlands have been developed and urbanized. Poor wastewater management results in water quality degradation, which increases human exposure to harmful substances and impacts ecosystem health.

Cheung Ek Lake (Figure 1-12) is a peri-urban lake in Phnom Penh City, which serves multiple purposes including acting as a natural wastewater treatment facility, supporting aquaculture, and contributing to flood control from the city center. This lake is a large wetland that receives untreated combined sewage effluent from 1.093 million inhabitants via a network of sewer lines 160 km long (Sothea et al., 2010; Yim et al., 2008). The main inflow is through two pumping stations, Tumpun in the west with a capacity of 15 m^3/s and Trabek in the east with a capacity of 8 m^3/s, pump effluent into the wetland from storage reservoirs over dike roads 371 and 271, respectively (JICA, 2016; Sovann et al., 2015). The total dry weather inflow to Cheung Ek Lake from these stations is approximately 52,704 m^3/d (Sovann et al., 2015).

The wetland cycles seasonally in a flooded surface area between 13-20 km^2 (Sovann et al., 2015). It has been estimated that 90% of municipal wastewater produced by the city is loaded to natural wetlands with the remaining 10% flowing directly into the Mekong River (Yim et al., 2008).

A portion of wastewater also enters Cheung Ek Lake via gravity, without requiring pumps, through a wastewater canal running along Street 371. The estimated discharge rate from this canal was recorded at 1.0 m3/s in February 2007 (Visoth et al., 2010). Water exits Cheung Ek Lake through two outlet streams: the north outlet stream and the south outlet stream. Both of these streams feed into the Prek Thnout River, which ultimately flows into the Bassac River (Figure 1-13).

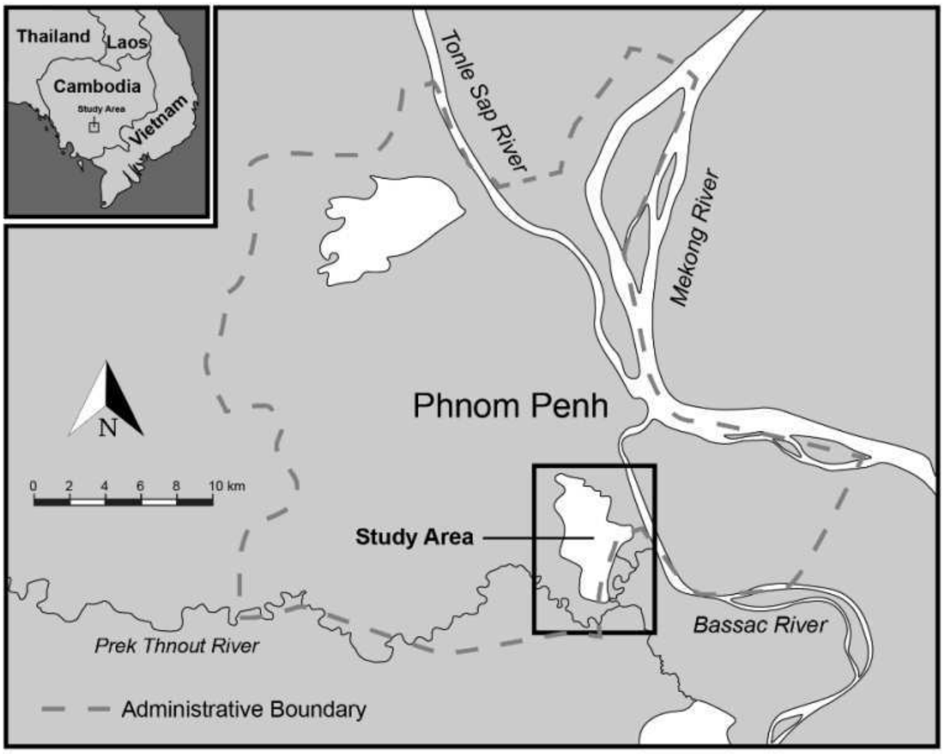

Figure 1-12 Map of the Cheung Ek Lake

(Source: Samuel et al., 2019)

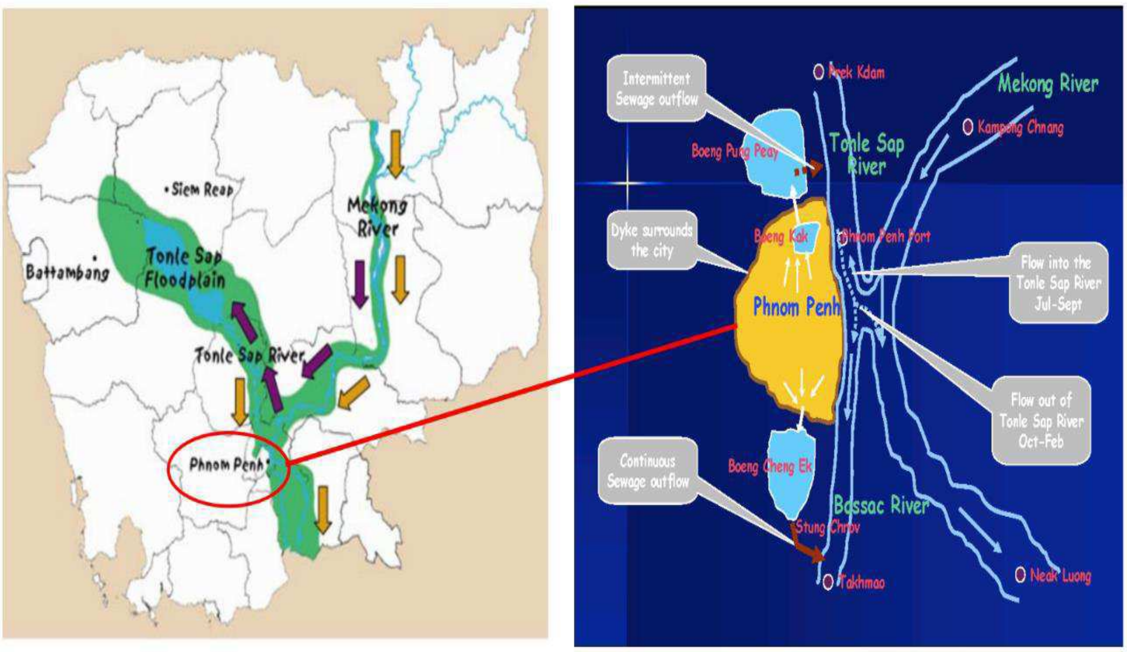

Figure 1-13 Direction of water flow in Cheung Ek Lake

(Source: Meng et al., 2016)

The vegetation of the wetland is primarily comprised of soft-tissue emergent and floating plants. Among these, water hyacinth (*Eichhornia crassipes*) stands out as one of the most extensively studied species utilized in constructed wetlands, and it is notably abundant in Cheung Ek Lake (JICA, 1999; Kivaisi et al., 2001). Agricultural crops cultivated within the wetland area include water spinach (Ipomoea aquatica), water mimosa (*Neptunia oleracea*), and water parsley (*Oenanthe javanica*). Additionally, fish farms are dispersed throughout the wetland, while naturally occurring snails are harvested and marketed within the city for human consumption.

1.3 Overall objective of this study

Cheung Ek Lake holds significant importance for agricultural activities, providing income for numerous farmer households in Phnom Penh city. Originally lake's area spanning 14 km^2 in 1980, the lake faced significant changes with the onset of satellite projects in 2003. This led to the allocation of the Cheung Ek area to private investors, triggering intensive construction activities from 2014 onwards. Consequently, these activities caused a drastic 50% reduction in the lake area. As urbanization encroaches upon the lake, the population and water consumption continue to rise annually. This surge in water demand has resulted in increased wastewater discharge into the city's surroundings, adding to the environmental load. The escalating environmental pressure likely impacts the quality of Cheung Ek Lake's water. Therefore, there's an imperative need to determine the change in the lake's remediation capacity due to urbanization, highlighting the necessity for comprehensive studies to address the evolving environmental challenges faced by this crucial resource.

With the change, urbanization led to the land decrease, and water retention time could be changed there for its effect on the capacity of natural water treatment. Moreover, the change in fertilizer use in Cheung Ek Lake during the urbanization could affect to the quality of the product and increase the input of production. Therefore, fertilizer is needed for the nation.

With this problem, the objective of this study was to evaluate the impact of urbanization on the lake's remediation capacity and aquaculture and propose a suitable method to improve water quality and fertilizer production in Cheung Ek Lake in Cambodia.

1.4 Dissertation structure

For achieving the above overall objective, the following research structure as shown in Figure 1-14 were formulated and carried out.

In Chapter 1, background information on peri-urban aquatic food production in Phnom Penh. Moreover, the general information on how urbanization has affected the water environment, laws and regulations, and the objective of this research were summarized.

Chapter 2 of this research investigates water quality changes in the last 4-year period between 2019 to 2022 in different seasons. This chapter also determined the impact of urbanization on the remediation capacity of Cheung Ek Lake.

Chapter 3 objective was to assess the effect of increased wastewater load on the economy of the farmers and aquaculture (*Ipomoea aquatica*) quality.

Chapter 4 dealt with the development of the calcium silicate hydrate (CSH) as the new method for removal of the nutrients from wastewater and fertilizer production. In this chapter, the discussion on existing methods for wastewater treatment will be summarized, and the process of manufacturing CSH and the effectiveness of nutrient removal from wastewater by CSH will be evaluated.

Chapter 5 evaluated the calcium silicate hydrate (CSH) as the alternative fertilizer for aquaculture and farmland cultivation. In this chapter, an elusion test was carried out to see the release of the nutrient from the used CSH. Additionally, the plant-grown experiment was also tested to see the effect of used CSH on the plant growth in the soil.

In Chapter 6, according to the outcomes of each chapter, the overall conclusion on "Approaches to Advanced use of Sedimentation Lake for Aqua-cultivation and Fertilizer Production in Cheung Ek Lake, Cambodia" was summarized in this chapter.

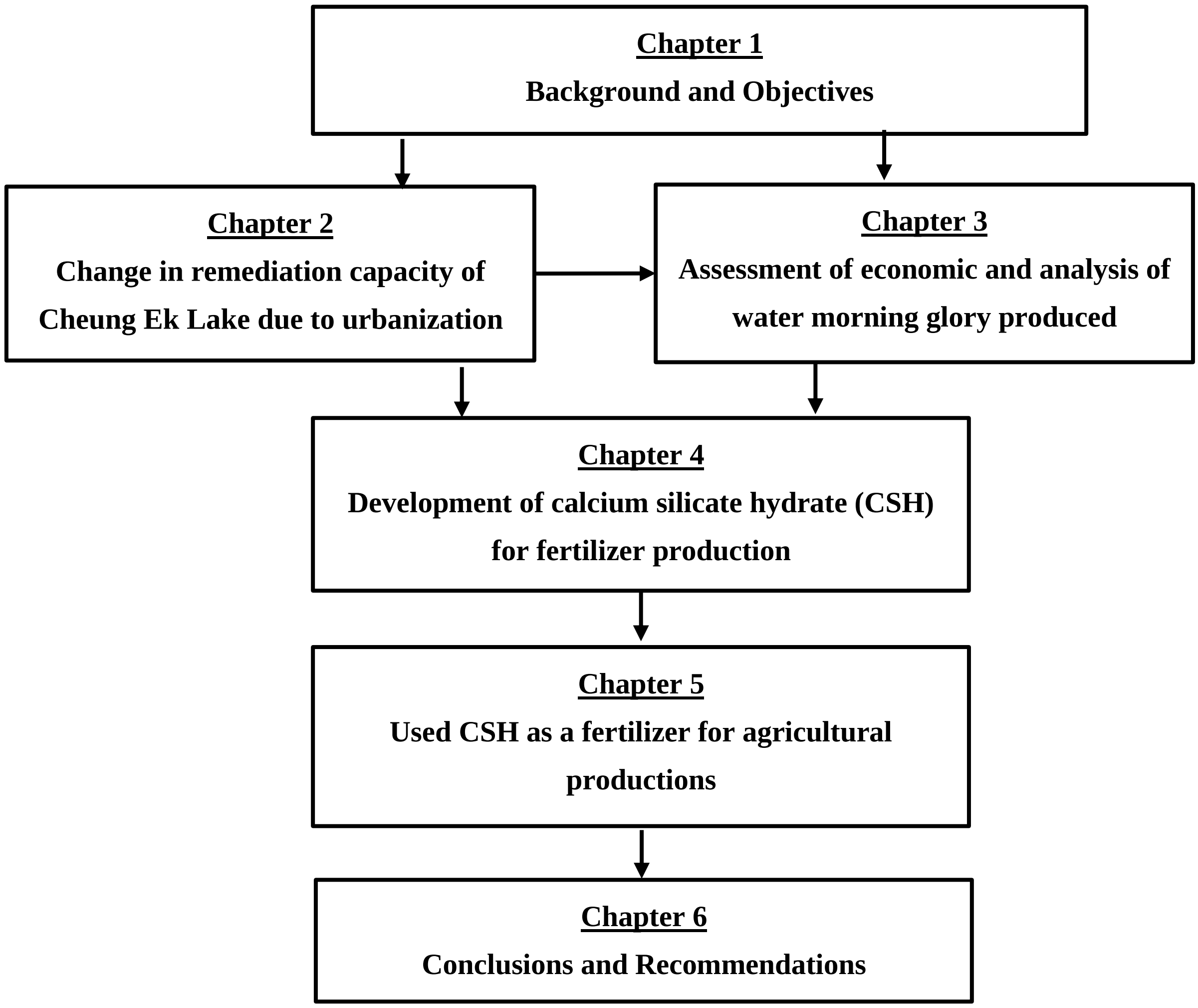

Figure 1-14 Dissertation structure

Reference of the chapter

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Chapter 2

Changes in remediation capacity of Cheung Ek Lake due to urbanization

2.1 Introduction of this chapter

2.1.1 Situation of wastewater treatment in Phnom Penh

Over the past two decades, Cambodia has experienced robust economic growth, rapid urbanization, and substantial development in agriculture and industry. Additionally, the emergence of a growing middle class has further contributed to these trends. As a result, there has been a significant increase in the amount of water consumed and wastewater generated across the country. This heightened demand for water resources, coupled with the increased discharge of wastewater, presents challenges for water management and environmental sustainability in Cambodia.

Water supply and wastewater treatment have emerged as significant concerns for Cambodian authorities. The primary reason for this concern is attributed to the low cost of water, which remains considerably cheaper than other utilities, such as electricity. Notably, water supply fees have remained unchanged for a decade. In the capital, the fee stands at 0.25 USD/m^3 for commercial customers and 0.175 USD/m^3 for domestic customers. Moreover, wastewater fees in larger cities are collected by the Phnom Penh Water Supply Authorities (PPWSA), representing 10% of the water bill.

Despite the environmental and health risks associated with discharging untreated and poorly treated wastewater, it remains a widespread practice in Cambodia due to the inadequate development of wastewater treatment systems. The country currently lacks a sewerage master plan and a comprehensive wastewater strategy.

During the dry season, the concentration of sewage and pollutants in sewerage systems and receiving water bodies in Phnom Penh becomes particularly high due to the lack of water for dilution. Separate sewerage systems for blackwater, greywater and rainwater do not exist in Phnom Penh city. As a result, sewage water flows via the existing sewerage systems (such as Boeng Trabek and Steoung Meanchey) into Cheung Ek Lake.

Figure 2-1 Wastewater discharge channel in Phnom Penh

(Source: Chea Vanyuth, 2021)

This Cheung Ek Lake plays a crucial role as a natural wastewater treatment area for Phnom Penh. It receives approximately 80% of the sewage water from the city, serving as an essential component of the city's wastewater management system. The lake's natural processes help to break down and remove pollutants from the sewage water before it continues its journey downstream into Bassac River.

In January 2024, Phnom Penh celebrated the completion of its first wastewater treatment plant, a significant milestone achieved under the JICA project. This plant, with a capacity of 5,000 cubic meters per day, represents a crucial step forward in the city's efforts to address its wastewater management challenges.

However, despite this achievement, the total amount of wastewater discharged in Phnom Penh city remains high, with approximately 370,000 m^3 (Van et al., 2020) of wastewater being discharged daily into the lake. Unfortunately, only a small portion, representing around 1.3%, is treated by the newly constructed wastewater treatment plant.

This disparity highlights the urgent need for additional treatment infrastructure to address the substantial volume of untreated wastewater entering the lake.

2.1.2 Literature review on water quality in Cheung Ek Lake

Research on the water quality of Cheung Ek Lake has been conducted by numerous researchers over the past decades. These studies have aimed to assess various aspects of water quality, including parameters such as pH, dissolved oxygen levels, nutrient concentrations, and pollutant levels.

According to Irvine et al. (2010), the reported study in Cheung Ek Lake that the concentrations of total phosphorus (TP) ranged from 9.2 to 10.6 mg/L, while total nitrogen (TN) concentrations ranged from 54 to 31 mg/L. Nara et al ., 2015 reported concentrations of total phosphorus (TP) ranged from 5.9 to 20.8 mg/L, while total nitrogen (TN) concentrations ranged from 5 to 11.6 mg/L. According to studies conducted by Marcussen (2009), potential toxic element concentrations were found to be minimal in water spinach and fish harvested from wastewater systems in Cheung Ek Lake. These findings suggest that the levels of these elements in food products pose minor food safety concerns.

Some more research also found this lake is efficacy in treating wastewater. Irvine et al. (2008) demonstrated that the majority of E. coli reduction (99.9%) takes place within a distance of 200-350 m from the Trabek pumping station. The geometric mean decreased to a range of 275-3,409 cfu/100 mL in the middle of the wetland. These levels meet or nearly meet the limit for unrestricted irrigation of crops eaten raw, as stipulated by the World Health Organization (WHO, 2006). However, they exceed the recreational or contact limit set by the United States Environmental Protection Agency, which is a geometric mean of 100 cfu/100 mL (EPA, 2012). There is only a slight increase in levels between the middle of the Cheung Ek Lake and the outlet point, possibly indicating contributions from local communities.

However, according to Chea et al. (2016), the water quality is significantly degraded, particularly at the point of water discharge from the city. This suggests that pollutants and contaminants from urban areas are having a notable impact on the water quality of Cheung Ek Lake, potentially posing risks to both aquatic ecosystems and human health.

The latest research on water quality in the lake, conducted by Samual et al. (2019), revealed concerning levels of pollutants in the inlet point into the lake. Specifically, the study found that the concentration of ammonium in the lake was measured at 50.6 mg/L, while phosphate levels were recorded at 8.2 mg/L indicating the pollution were from the urban household. However, a comparison between measurements taken at the inlet and outlet points of the lake revealed a significant decrease in the concentration of both ammonium and phosphate, ranging from 52% to 87% and 53% to 85%, respectively. Cheung Ek Lake is renowned for its high removal efficiency range when compared to wastewater treatment systems commonly employed in developing countries, such as conventional activated sludge systems.

Indeed, most studies on water quality and contamination in Cheung Ek Lake were conducted before the expansion of the lake area. Concerns arise regarding the potential impact of decreasing lake area on the capacity of natural purification functions within the lake. The reduction in lake area could lead to a decrease in the effectiveness of natural processes for purifying the water, such as sedimentation, nutrient uptake by aquatic plants, and microbial degradation of contaminants. This highlights the importance of ongoing monitoring and research to understand the effects of environmental changes on water quality and ecosystem health in Cheung Ek Lake.

2.2 Objective of this chapter

The objective of this chapter was to investigate the effects of urbanization remediation capacity in Cheung Ek Lake. To achieve the objective, the experiment on the water quality of the inlet, middle and outlet between 2019 to 2022 was conducted. Additionally, the inlet and outlet load were calculated to assess the lake's remediation capacity.

2.3 Methodology

2.3.1 Water Sampling and Analysis

To analyze changes in water quality parameters, water sampling was conducted during both the rainy and dry seasons from 2019 to 2022 (Figure 2-2). Sampling was performed at depths of 0.5 meters, 1 meter, and 1.5 meters using a Heyroth Water Sampler (Figure 2-4). The collected water samples were immediately transferred into plastic containers and kept at a temperature of 5°C. Within 3 hours of collection, the samples were transported to the laboratory for analysis. This method ensured that the integrity of the samples was maintained during transportation and allowed for accurate analysis of water quality parameters.

Water sampling was collected from three points: the inlet, middle, and outlet, to facilitate a comparative analysis of the concentration levels (Figure 2-2 and Figure 2-3).

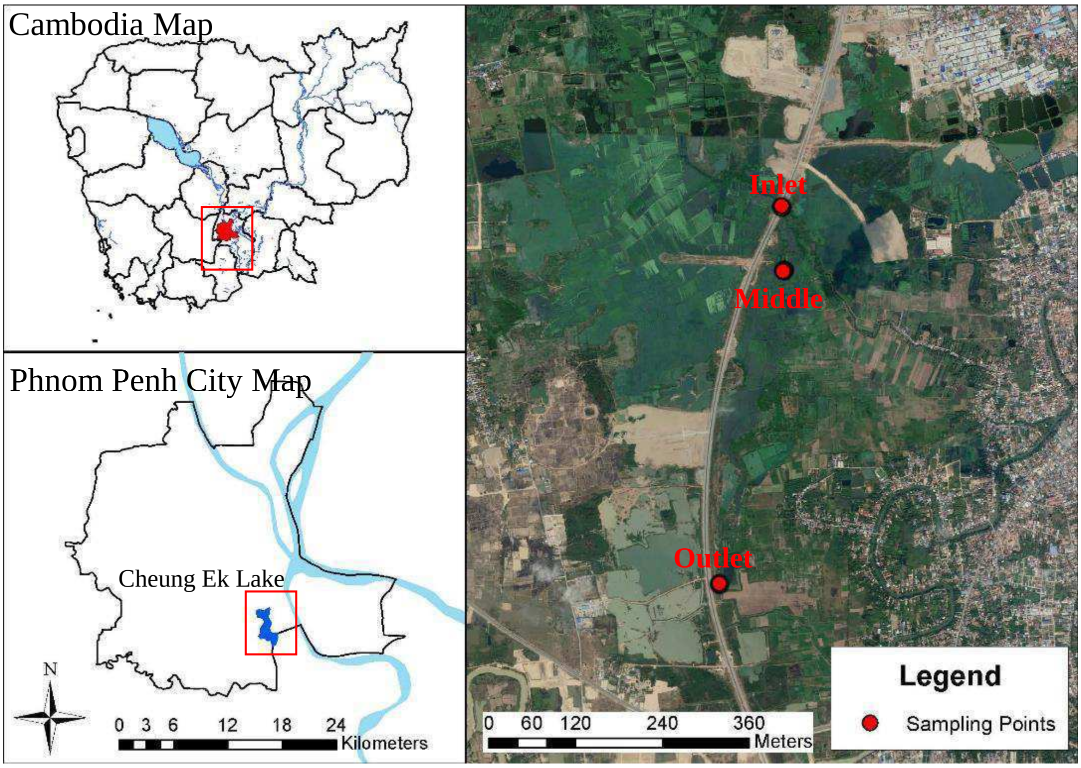

Figure 2-2 Geographical map of Cambodia, Phnom Penh City (bottom left) and sampling points (Google map)

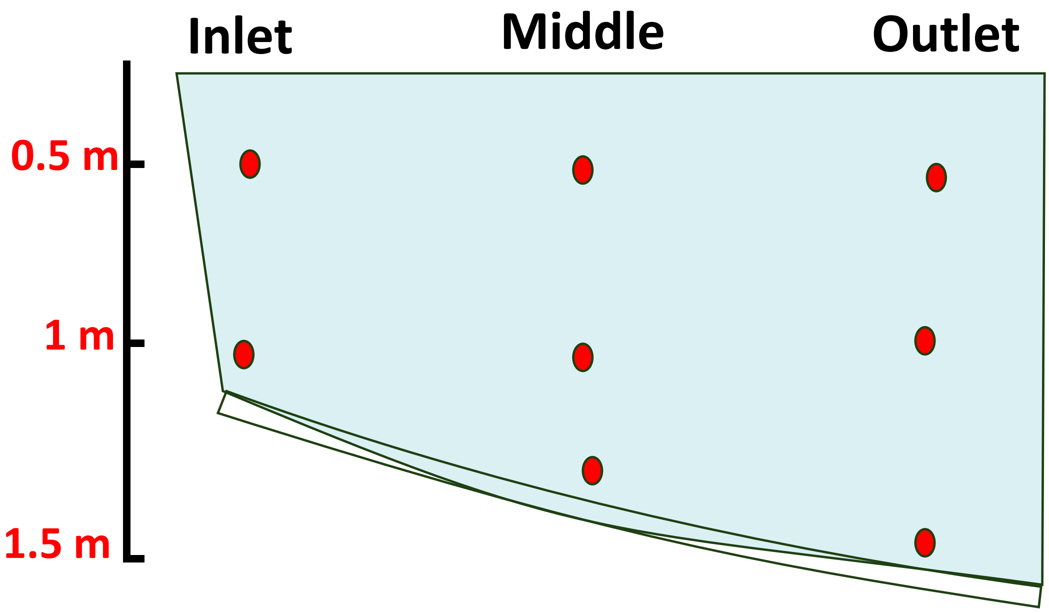

Figure 2-3 Sampling locations

Water samples were analyzed for pH, electrical conductivity (EC), iron (Fe), dissolved oxygen (DO), phosphate (PO_4^{3-}), ammonium (NH_4^+) and nitrate (NO_3^-). Samples were collected at the inlet, middle and outlet for a week of each sampling sample (Figure 2-4).

The physicochemical properties such as pH, EC and DO of the sampled water were promptly determined on-site using a using pH and EC meter LAQUAtwin and HACH DR 900 portable data-logging colorimeter instrument. While for the iron (Fe), dissolved oxygen (DO), phosphate (PO_4^{3-}), ammonium (NH_4^+) and nitrate (NO_3^-) were transported to the lab within 3 hours in the cool box for analysis. Before each measurement, a plastic beaker underwent three rinses with sample water, after which the probes were submerged into the beaker. After each analysis, the probes underwent a rinsing procedure using deionized water. Regular calibration of the probes was carried out using suitable standards as per the manufacturer's guidelines.


Figure 2-4 Water sampling and analysis

2.4 Results and discussion

2.4.1 Water quality in Cheung Ek Lake

The results from Tables 2-1 to 2-4, which display water quality analysis from 2019 to 2022, indicate that the pH levels in both seasons ranged from 7.06 to 7.7. These pH values suggest that the water in the lake tends to be in an alkaline state. For electrical conductivity (EC) decreased from the rainy to the dry season. One of the primary factors influencing the change in electrical conductivity (EC) levels in the water body could be rainwater. During the rainy season, the run-off carries organic matter and ions into the lake, leading to an increase in EC levels. This influx of organic material from rainwater runoff can contribute to changes in water quality parameters, including EC.

Iron (Fe) concentrations in the inlet point ranged from 0.03 to 0.39 mg/L, indicating an increase in Fe levels over the past four years. Similarly, at the middle point, Fe concentrations ranged from 0.05 to 0.37 mg/L. The observations over the four-year period suggest a trend of increasing Fe levels, particularly evident in the last observation in August 2022. This upward trend in Fe concentrations raises concerns about water quality and potential environmental impacts. Elevated levels of iron can affect aquatic ecosystems and may indicate the presence of other pollutants or changes in water chemistry. However, it's important to note that based on the water pollution control standard in Cambodia for public water areas (20 mg/L), there are no signs of Fe^{2+} contamination (RGC, 2009). Nevertheless, caution should be exercised as the levels continue to increase, and further monitoring and mitigation efforts may be warranted to prevent potential adverse effects on the ecosystem.

The dissolved oxygen (DO) levels at the inlet point of the lake decreased significantly from 5.14 mg/L (Table 2-1) to 1.05 mg/L during the rainy season (Table 2-4). At the outlet point, DO levels appeared to fluctuate over the four-year observation period, ranging between 3.55 mg/L and 7.10 mg/L. This decline of DO level in the inlet point concentration suggests a substantial decrease in the amount of oxygen dissolved in the water at the inlet point, particularly during the rainy seasonThe increased rainfall during the rainy season can result in greater runoff, leading to an influx of organic matter and pollutants into the lake. These substances can consume oxygen through biological processes like decomposition. However, due to the strong flow of wastewater during the rainy season, organic matter may only decompose significantly in the middle and outlet points of the lake. Conversely, during the dry season when the flow is weaker, organic matter decomposition may primarily occur near the inlet point.

Phosphate (PO_4^{3-}) concentrations at the inlet point showed a decreasing trend over the four-year observation period, declining from 5.29 mg/L in 2019 to 2.30 mg/L in 2022. However, at the outlet point during the rainy season, PO_4^{3-} concentrations increased from 1.90 mg/L in 2019 to 2.43 mg/L in 2022. Interestingly, despite this increase at the outlet point, PO_4^{3-} concentrations still generally decreased from the inlet to the outlet point in both seasons. One possible explanation for the drop in PO_4^{3-} concentration at both the middle and outlet points is the influence of agricultural activities occurring on the lake's surface. These activities may involve the absorption or uptake of available phosphate by plant cultivation, thereby reducing the concentration of PO_4^{3-} in the water.

Similar to PO_4^{3-}, nitrate (NO_3^-) concentrations were observed to be decreasing in the dry season rainy season and increased again in the rainy season. The higher nitrate (NO_3^-) levels in the lake during the rainy season could be attributed to runoff carrying organic matter and ions from nearby households into the lake. Additionally, the reduced input of chemical fertilizer application during the dry season may also contribute to this phenomenon.

The observations for ammonium (NH_4^+) were conducted only in the last two sampling periods (Table 2-3 and Table 2-4). In the first observation (Table 2-3), NH_4^+ concentrations indicated a decreasing trend from the inlet to the outlet point, ranging from

0.51 mg/L to 15.50 mg/L. However, in the rainy season of 2022 (Table 2-4), high concentrations of NH_4^+ were observed at all sampling points, especially at the outlet point. This increase in NH_4^+ concentrations, particularly during the rainy season, could be intensive agricultural activities occurring in the middle point of the lake. Typically, the low season for the cultivation of water morning glory in Cheung Ek Lake occurs from May to September, mainly due to factors such as diseases and wind damage to the plants' roots. The increased application of chemical fertilizers during the low season of cultivation could lead to elevated levels of NH_4^+ in the lake water, especially during periods of heavy rainfall when runoff carries excess nutrients into the water body. This could explain the observed spike in NH_4^+ concentrations in the last observation compared to the dry season.

Table 2-1 Chemical water parameters of the inlet, middle and outlet of the lake in rainy season 2019

Sampling location	pH	EC (mS/cm)	Fe (mg/L)	DO (mg/L)	PO_4^{3-} (mg/L)	NO_3^- (mg/L)
Inlet	7.06 ± 0.30	0.75 ± 0.04	0.03 ± 0.03	5.14 ± 2.24	5.29 ± 2.26 a*	0.66 ± 0.29
Middle	6.98 ± 0.27	0.72 ± 0.01	0.05 ± 0.05	6.06 ± 1.99	1.42 ± 0.59 b*	0.11 ± 0.16
Outlet	7.15 ± 0.36	0.66 ± 0.02	0.06 ± 0.03	3.55 ± 0.66	1.90 ± 0.50 b*	0.55 ± 0.18

*Note: Values are mean ± SD (n=3), * p< 0.1*

Source: Data from analysis in 9th – 11th Sep, 2019

Table 2-2 Chemical water parameters of the inlet, middle and outlet of the lake in dry season 2020

Sampling Location	pH	EC (mS/cm)	Fe (mg/L)	DO (mg/L)	PO_4^{3-} (mg/L)	NO_3^- (mg/L)
Inlet	7.7±0.18	0.37±0.04 a*	0.08±0.04	3.25±0.96 α*	4.64±0.91 ab*	0.4±0.05
Middle	7.7±0.28	0.36±0.01 a*	0.06±0.18	6.40±1.02 β*	3.66±0.25 ab*	0.3±0.26
Outlet	7.6±0.23	0.33±0.01 b*	0.03±0.09	6.75±0.97 β*	2.56±0.54 AB*	0.1±0.33

*Note: Values are mean ± SD (n=7), * $p< 0.1$*

Source: Data from analysis in 19th – 25th Dec, 2020

Table 2-3 Chemical water parameters of the inlet, middle and outlet of the lake in dry season 2022

Sampling Location	pH	EC (mS/cm)	Fe (mg/L)	DO (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)	NH_4^+ (mg/L)
Inlet	7.28±0.1	0.73±0.1	0.1±0.3	5.02±0.1 α*	1.11 ±0.3	3.62±3.1	15.5 ±0.3
Middle	7.48±0.1	0.67±0.1	0.08±0.1	6.42±2.6 β*	0.27 ±0.2	2.47±0.3	12.64 ±2.2
Outlet	7.52±0.1	0.45±0.1	0.05±0.1	7.10±1.4 β*	0.18±0.2	0.33±0.1	0.51 ±0.4

*Note: Values are mean ± SD (n=7), * $p< 0.1$*

Source: Data from analysis in 2nd – 10th Feb, 2022

Table 2-4 Chemical water parameters of the inlet, middle and outlet of the lake in rainy season 2022

Sampling Location	pH	EC (mS/cm)	Fe (mg/L)	DO (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)	NH_4^+ (mg/L)
Inlet	7.29±0.1	0.52±0.1	0.39±0.2	1.05±0.6 a*	1.05 ±0.5	2.30±1.3	22.17 ±7.1
Middle	7.48±0.1	0.52±0.1	0.37±0.2	4.15±1.7 b*	0.98 ±0.7	3.16±0.8	25.80 ±9.3
Outlet	7.52±0.1	0.55±0.0	0.17±0.1	4.74±1.0 b*	0.27±0.2	2.43±0.9	25.17 ±2.7

*Note: Values are mean ± SD (n=7), * $p< 0.1$*

Source: Data from analysis in 20th – 25th Aug, 2022

2.4.2 Load calculation of water quality in Cheung Ek Lake

According to concentration with the discharge, the load of the nutrient in the inlet and outlet site were summarized in Table 2-5. The finding for the Fe and DO indicate a positive trend over the 4 year observation period. The same goes with PO_4^{3-}, NO_3^- and NH_4^+ in the first 3 observations indicating the reduction of the load from the inlet to the outlet.

This finding agrees with the other research stated that Cheung Ek Lake has effective at changing the concentrations of nitrate, ammonium, phosphate, total suspended solids (TSS), total dissolved solids (TDS), dissolved oxygen (DO), chromium (Cr), detergents, and E. coli to acceptable levels at outlet streams connected to the Bassac River (Takeuchi et al., 2005; Irvine et al., 2008; Visoth et al., 2015; JICA, 2016).

Table 2-5 Nutrient load of the inlet and outlet in the rainy and the dry season from 2019-2022

Parameter	Discharge (m^3/s)	Inlet	Outlet
Rainy season 2019			
Fe^{2+} (g/s)	42.12	1.26	2.03
DO (g/s)	33.91	216.50	120.38
PO_4^{3-} (g/s)		28.08	18.65
NO_3^- (g/s)		222.81	64.42
Dry season 2020			
Fe^{2+} (g/s)	27.45	2.19	0.94
DO (g/s)	31.40	89.21	211.95
PO_4^{3-} (g/s)		127.37	80.38
NO_3^- (g/s)		10.98	3.14

	Dry Season 2022		
Fe^{2+} (g/s)	24.48	2.45	1.19
DO (g/s)	23.86	122.89	169.41
PO_4^{3-} (g/s)		88.61	7.96
NO_3^- (g/s)		27.17	4.29
NH_4^+ (g/s)		379.44	12.27
	Rainy season 2022		
Fe^{2+} (g/s)	19.50	7.61	4.27
DO (g/s)	25.12	20.48	119.07
PO_4^{3-} (g/s)		44.85	61.04
NO_3^- (g/s)		20.48	6.78
NH_4^+ (g/s)		432.32	632.27

However, the observation during the rainy season of 2022 presents a contrasting scenario, as the pollutant load at the inlet is lower than that at the outlet for both PO_4^{3-} and NH_4^+ (Figure 2-5). Furthermore, the discharge observed during the rainy season of 2019 was notably higher compared to that of 2022.

Despite the reduced discharge, the concentration of pollutants was exceedingly high in the last rainy season observation, leading to pollution at the outlet point of the lake. These results were contrasted with the previous findings by other research in the past decade. This discovery underscores a significant shift, signaling that Cheung Ek Lake is no longer effective as a wastewater treatment facility for NH_4^+ and PO_4^{3-} removal.

The shift in remediation capabilities can be attributed to the extensive construction activities in the Cheung Ek Lake area, resulting in a reduction in the lake's size. There was an observed increase in nutrient concentrations in the middle of the lake. With the reduction in lake size, farmers faced challenges in maintaining stable income, prompting changes in aquaculture practices. Farmers began to increase the amount of fertilizer application to shorten the production cycle, and this could have also contributed to changes in water quality at the outlet point.

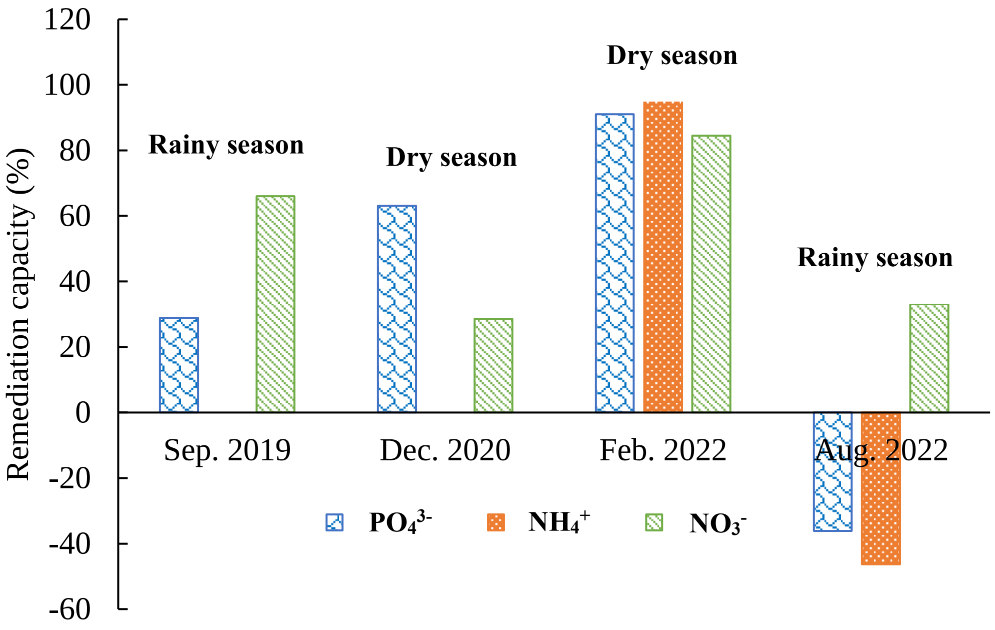

Figure 2-5 Remediation capacity of Cheung Ek Lake from 2019-2022

2.5 Conclusion of this chapter

With the commencement of land reclamation in Cheung Ek Lake, there was initially limited research attention dedicated to staying abreast of the water quality in this area. The findings from this chapter indicate that urbanization has had an impact on the alterations in water quality within the lake in the indirect way.

The results observed in this chapter indicated an increase in nutrient concentrations in the middle of the lake. With the reduction in lake size, farmers faced challenges in maintaining stable income, prompting changes in aquaculture practices. Farmers began to intensify fertilizer application to shorten the production cycle, which may have contributed to alterations in water quality at the outlet point as well.

In the rainy season 0f 2022, the lake has lost its remediation capacity to treat PO_4^{3-} and NH_4^+, due to the change of agriculture activities that resulted from the limited cultivated area in the lake. This further indicates that the lake itself is contributing to additional pollution in the water environment. A suitable method to consider for implementation in the lake to prevent farmers from using excess chemical fertilizer could be the adoption of sustainable agricultural practices. Collaborative efforts involving government agencies, agricultural extension services, non-governmental organizations, and local communities can help support the successful implementation of such methods in the lake's agricultural areas.

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Chapter 3

Assessment of economic and quality analysis of water morning glory production

3.1 Introduction of the chapter

Aqua-cultivation stands as a crucial economic asset for farmers in Cheung Ek Lake. With its fertilization from wastewaters and diverse aquatic life, this practice not only provides sustenance for local communities but also serves as a source of income generation.

The study by Sar et al., 2010, the economic value of the Cheung Ek Lake from the direct beneficiaries of the human activities on the lake. The average profits earned over a six-month period in the dry season are estimated to be over 1 million USD, of which water morning glory production contributes 65%, fishing 20%, water mimosa production 13%, duck raising 1%, and dry season rice production 0.7%. The 2017 update study conducted by Ro et al. (2020) revealed that the total annual profit from agriculture in the lake amounted to 12 million USD. However, the disparity in the latest study, based on 2017 data, indicates a 40% reduction in profits compared to the study by Sar et al in 2010.

Besides the advantages derived from agriculture in the lake, concerns have been raised regarding the reuse of untreated wastewater for agricultural purposes. This practice may affect the quality of production and potentially compromise the safety of consumption. A previous investigation conducted by Marcussen et al. (2009) has highlighted that the uptake of heavy metals by water morning glory growth in Cheung Ek Lake presents a low food safety risk concerning potentially toxic elements (Table 3-5). The study reported that the highest concentrations of certain elements in water morning glory were observed at the inlets, with the following values measured: As 0.19, Cd 0.022, Cu 2.95, Fe 251, Pb 0.206, and Zn 9.08 mg/kg. In another conducted by Pheng et al. (2008), water morning glory samples were collected from locations near the inlet, middle, and outlet of the Cheung Ek Lake. The analysis revealed that the concentration of Cu ranged from 0.15 to 0.23 mg/kg, while Cr ranged between 0.38 to 0.70 mg/kg. These findings suggest that the levels of Cu and Cr in water morning glory remained within the permissible range according to standard regulations.

However, with the land use change and increasing use of chemical fertilizers in agricultural activities within Cheung Ek Lake, the pressing question arises: Should farmers persist in cultivating within the lake, or should alternative approaches be considered?

3.2 Objective of this chapter

Given the advantageous benefits that Cheung Ek Lake offers to numerous households, a socio-economic impact study will be conducted to assess the extent to which the lake contributes to improving household income. As the results in Chapter 2 have indicated the change in water quality in the lake, indeed caused concern about the quality of the aqua-cultivation in the lake. Therefore, this chapter also examines the water morning glory plant and its possible source of contamination.

3.3 Methodology

3.3.1 Questionnaire survey

The interview (Appendix 1) was carried out in September 2019. Due to time constraints, the questionnaire survey can only involve 35 respondents from the farmers, 10 from middlemen, 10 from wholesalers and 10 from retailers to gather data on socio-economic characteristics (Table 3-1). Nevertheless, a similar trend appears evident among both farmers and sellers. The semi-structured questionnaires were distributed to the farmers, middlemen, wholesalers and retailers involved in water morning glory productions and sales. The social characteristics of the farmers, economic returns and efficiency for the production of water morning glory were analyzed.

Figure 3-1 Questionnaire survey with middlemen

Table 3-1 Sample of the category of questionnaire survey used in the study

Category	Related question	Details
1. General information	Social characteristics of respondents	Name, age, gender, education level
	Production area	Cultivation area
2. Production cost and income	Input and output cost of water morning glory production	Input cost, income, price of water morning glory
3. Market chain	The market channel of water morning glory production	The final market, number of wholesaler and retailer

3.3.2 Wastewater and fertilizer sampling

Wastewater samples were collected from 5 locations: S1 inlet, S2 inlet, S3 middle, S4 middle and S5 outlet (Figure 3-2) in August 2022 for a week time. In each location, the water was taken according to different depths. Fertilizer and 78 wastewater samples were collected and analyzed for chemical properties: pH, EC, DO, NO_3^-, PO_4^{3-}, NH^{4+}, Fe, Cr, and Cu.

The water samples were sent to the laboratory shortly after collection for analyze. The pH and EC were measured in the field using a pH and EC meter (LAQUAtwin HORIBA). The DO, NO_3^-, PO_4^{3-}, NH_4^+, Fe, Cr, and Cu were also measured using a spectrophotometer HACH DR 900.

3.3.3 Sediment and water morning glory sampling

The sediment from the inlet (S2) and middle (S3) were collected and measured for Cu using the atomic absorption spectrophotometry method and Cr using the ICP emission spectrometry method.

Fresh water morning glory plants (*Ipomae Aquatica*) from Cheung Ek Lake were also collected from the farmers. After collection, the plants were air dry for a week and grain into powder and measured for Cu, Cr, Cd, Pb and As using the atomic absorption spectrophotometry method.

Figure 3-2 Map of sampling point in Cheung Ek Lake (Google map)

3.4 Results and discussion

3.4.1 Socio-economic characteristics of water morning glory producer

The average household size was 6.1 people, which is higher than the national average of 4.8 person for the urban areas (NIS, 2019). On average, experience in farming water morning glory was 10.4 years, indicating a considerable level of expertise within the farmers (Table 3-2). Interestingly, findings from the survey indicate that none of the farmers surveyed were owners of the cultivation areas they worked on. Instead, these areas within the lake were rented from a private company, with rental prices ranging between 100-250 USD per year. On average, each household rented a cultivated area of 2.15 hectares. The average harvest per day per ha was 164.5 bunch and the average price was 0.37 USD per bunch.

Table 3-2 Socio-economic characteristics of water morning glory producers

Number of household	20
Average family size (persons per family)	6.1
Average age of famer (year)	37.80
Average experience in water morning glory production (year)	10.4
Average planted area per household (ha)	2.15
Average harvest per day per ha (bunch)	164.50
Average price per bunch (USD)	0.37

3.4.2 Water morning glory production cost and economic return

This study comprehensively investigated various indicators concerning the economic return from production, encompassing gross revenue, gross margin, total cash income, and net profit. Gross revenue was calculated as the total income generated without deducting production costs. Gross margin, on the other hand, represented the deduction from gross revenue, specifically accounting for hired labor expenses. Total cash income was derived by subtracting total cash expenses from gross revenue. Finally, net profit was determined by subtracting the total variable cost and total fixed cost from the gross revenue. These indicators provide a comprehensive understanding of the economic performance of the production process.

Table 3-3 presents the findings regarding the production cost and economic return per day per hectare of water morning glory. The analysis revealed that the total production cost amounted to 29.58 USD per day per hectare. Remarkably, labor costs constituted the predominant portion, accounting for approximately 76% of the total expenses incurred during production. This underscores the significant role of labor expenses in the overall cost expense of water morning glory cultivation in Cheung Ek Lake.

Table 3-3 Total production cost and economic return of water morning glory

Item	Price (USD)	Item	Price (USD)
Pesticide	3.57	Bamboo	0.29
Gasoline	1.55	Boat	0.15
Plastic	0.22	Sprayer	0.01
Boat reparations	0.16	Container	0.01
Rope	0.34	**Total fix cost**	**1.15**
Variable cost	5.85	**Total production cost**	**29.58**
Family labor	7.98	**Gross revenue**	**53.35**
Rent labor	14.59	**Gross margin**	**30.77**
Total labor	22.58	**Total cash expense**	**20.44**
Total variable cost	28.43	**Total cash income**	**32.90**
Land rent	0.68	**Net profit**	**23.77**

3.4.3 Water morning glory economic efficiency

The result shows that the net profit from the production was 23.77 USD per day/ha. Although the farmer spent a lot on labor, the return from the sale was good enough. The production's economic efficiency was 1.80 (Table 3.4), suggested that the business with this product is profitable. The value 1.80 of economic efficiency could be interpreted as follows: if 1 USD is spent on the production 1.80 USD will be received from the sale of products. So, net profit will be 0.80 USD per unit of expense.

Table 3-4 Economic efficiency of water morning glory

Income (USD)	Total Expense (USD)	Net Profit (USD)	Economic Efficiency
53.35	29.58	23.77	1.80

3.4.4 Prices and market chain of water morning glory production

Figure 3-3 shows the price chain in water morning glory production between farmers, middlemen, wholesalers and retailers. The price of the water morning glory product varies from month to month according to its availability and demand. The results of the questionnaire survey showed that the price of water morning glory is lower in the dry season than the rainy season. The average market price range for farmers and retailers was between 0.22 to1.38 USD per bunch. A highly significant difference in the price can be seen between the first and final suppliers.

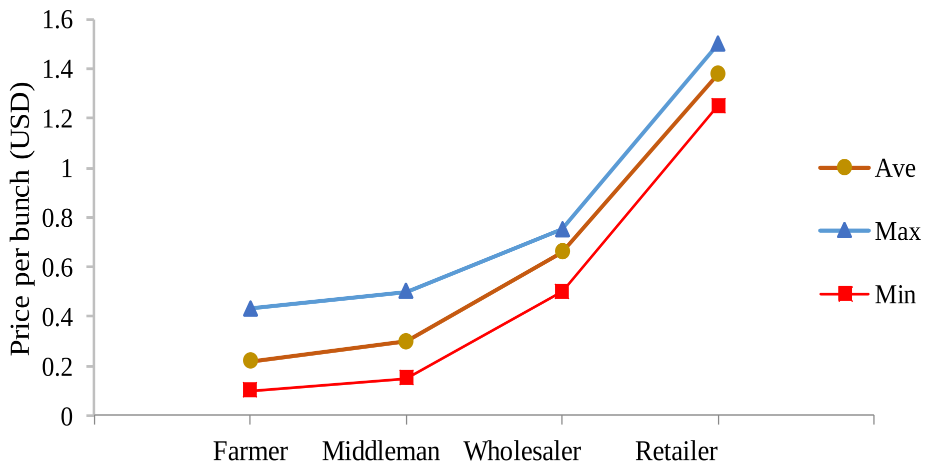


Figure 3-3 Price chain in the water morning glory production

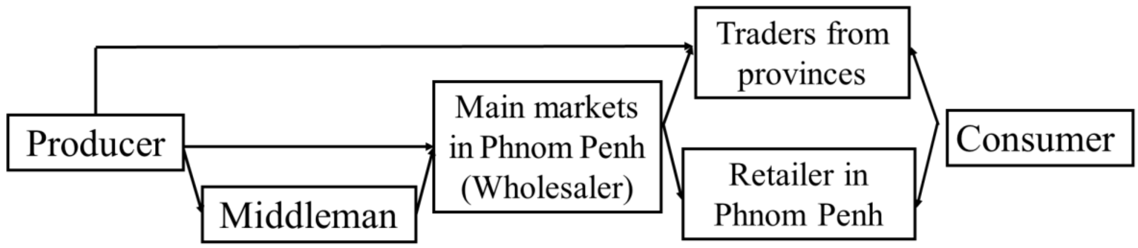


Figure 3-4 Market chain of water morning glory production

3.4.5 Water morning glory quality analyze

In Table 3-5. the concentration of heavy metals such as Cu, Cr and Pb in the water morning glory was higher than the guidelines for intake value from FAO and WHO. It indicated that the plant was highly contaminated and not safe for consumption, especially by Cu and Cr. Daily consumption of a product that contains a high dose of Cu can cause damage to the liver, brain, kidneys, cornea, gastrointestinal system, lungs, immunological system, and hematological system (Jaishankar et al.,2014; Kumar et al, 2015). Additionally, long-term inhaled Cr compounds are respiratory tract irritants, resulting in airway irritation, airway obstruction, and lung, nasal, or sinus cancer. Dose, exposure duration, and the specific compound involved can determine chromium's adverse health effects (Dayan et al., 2001, Lindberg et al.,1983).

Table 3-5 Heavy metal analyze of water morning glory

Parameter	Observed value[a]	Value by Marcussen et al.,2009	FAO/WHO permission value
Cu	4 mg/kg	0.51-2.01 mg/kg	1.5 - 2 mg/kg
Cr	3 mg/kg	-	0.05 - 0.2 mg/kg
Cd	< 1 mg/kg	0.008-0.032 mg/kg	0.2 mg/kg
Pb	1 mg/kg	0.104-0.189 mg/kg	0.3 mg/kg
As	< 1 mg/kg	0.033-0.0139 mg/kg	0.16 mg/kg

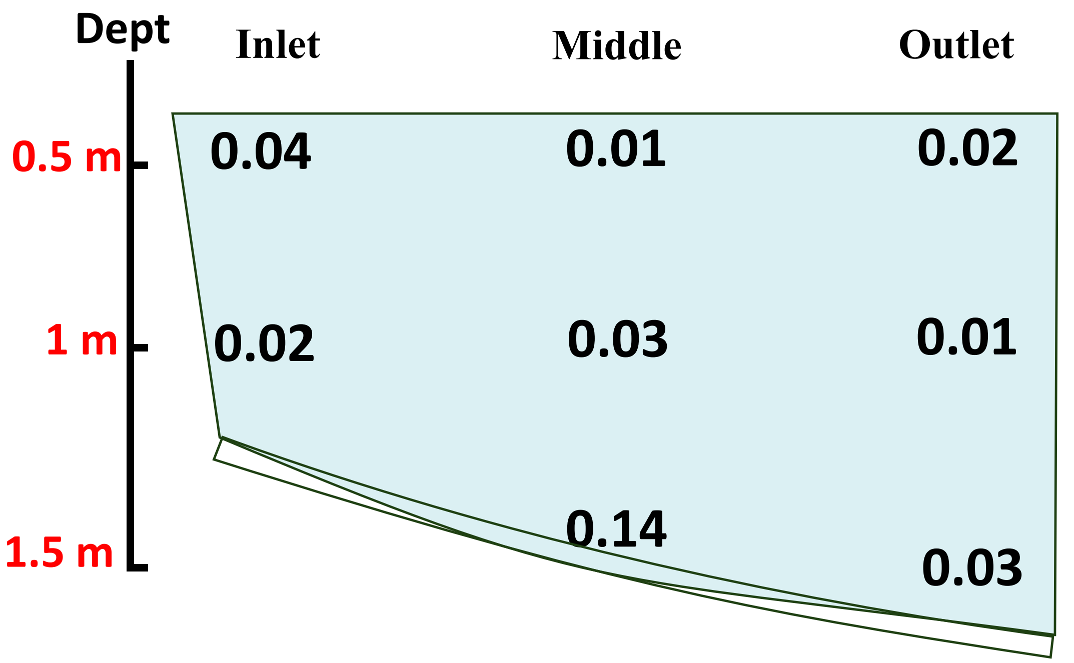
[a] Data from the experiment in August 2022

Based on the results obtained from the analysis of water morning glory (as shown in Table 3-5), it is indicated that water morning glory cultivation in Cheung Ek Lake might be exposed to elevated levels of heavy metal pollution, particularly with regards to Cu, which measured at 4 mg/kg, and Cr, which measured at 3 mg/kg. These concentrations exceed typical thresholds and suggest a potential risk of heavy metal contamination in water morning glory cultivated in this area. Consequently, further investigation and remedial actions may be warranted to ensure the safety and quality of water morning glory produced in Cheung Ek Lake.

Compared to previous findings (Mucarcee et al., 2009 and Peng et al., 2018), the recent results underscore a degraded quality of water morning glory over the past decade. This degradation is evident in the elevated levels of heavy metal contamination, notably Cu and Cr, detected in the plant. Prolonged consumption of such contaminated produce may pose serious health risks to consumers. The presence of heavy metals in water morning glory grown in this area raises significant concerns regarding the safety and quality of the produce, highlighting the urgent need for further investigation and remedial action to address this potential health hazard.

3.4.6 Heavy metal analysis in the wastewater

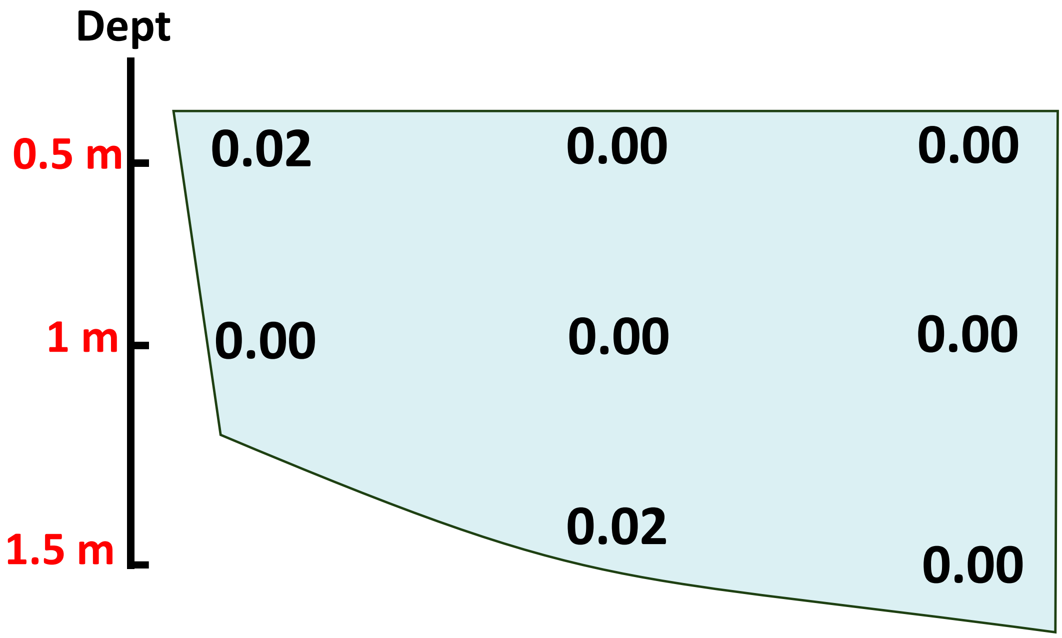
The Cu analysis results depicted in Figure 3-5 indicate that at a depth of 0.5 meters, the inlet point exhibits the highest concentration of Cu, with an inflow of 0.04 mg/L originating from the city via the pumping station. For the depths of 1 m and 1.5 m, the Cu concentration seems to be high in the middle point compared to the other points with 0.03 mg/L and 0.14 mg/L, respectively. It's noteworthy that the values detected in the wastewater samples, ranging from 0.1 to 0.14 mg/L, remain within the standard permissible level of 0.2 mg/L for discharging wastewater in public water areas (RGC, 2009). This indicates that, according to regulatory standards, the concentration of heavy metals in the wastewater falls within acceptable limits for disposal into public water bodies. However, despite meeting regulatory criteria, the uptake of Cu by water morning glory plants, resulting in concentrations of 4 mg/kg, suggests a potential accumulation and bioconcentration effect within the plant tissue.



*Number refers to concentration (mg/L)

Figure 3-5 Cu analysis in wastewater in Cheung Ek Lake

Table 3-6 presents the concentration of Cr results from the inlet points investigated. At a depth of 0.5 meters, Cr was detected with a concentration of 0.02 mg/L, while at a depth of 1 m, the value of Cr was less than 0.00 mg/L, indicating minimal to no presence of chromium. The concentration of Cr in the wastewater samples also indicates no sign of pollution, as it falls within the regulatory standards ranging from 0.05 to 0.2 mg/L (RGC, 2009). Interestingly, no detectable levels of Cr were found at the outlet point of the lake, neither at the surface nor at the lower depth. These findings suggest that most of the heavy metal was absorbed and settled at the middle point, with only a small amount reaching the outlet point.



*Number refers to concentration (mg/L)

Figure 3-6 Cr analysis in wastewater in Cheung Ek Lake

The results from the fertilizer analysis in Table 3-6 reveal a high concentration of Cu, measured at 1.68 mg/L. When compared to the analysis of wastewater, which ranged from 0.01 mg/L to 0.14 mg/L, this value significantly exceeds typical levels found in wastewater. According to Lita et al.,2021, major sources of Cu metals in agriculture are fertilizer, pesticides and livestock manures. Cu concentration in N fertilizer ranges from 2-1450 mg/kg worldwide and EU (Alloway, B.J., 2013). This disparity strongly suggests that the application of fertilizer during cultivation activities is the primary contributing factor to the elevated concentration of Cu observed in the water morning glory.

Cr was found in the fertilizer at a concentration of 0.02 mg/L, which may have been caused by farmers blending chemical fertilizer using wastewater from the lake.

The notable presence of NH_4^+ in the fertilizer used during water morning glory cultivation raises concerns about its potential contribution to pollution in the lake water. High levels of NH_4^+ in the fertilizer may indeed serve as a significant source of pollution.

Table 3-6 Chemical water parameters of fertilizer

pH	EC (mS/cm)	DO (mg/L)	NO_3^- (mg/L)	NH_4^+ (mg/L)	PO_4^{3-} (mg/L)	Fe (mg/L)	Cr (mg/L)	Cu (mg/L)
6.70	2.31	5.60	3.80	266.50	1.60	0.14	0.02	1.68

Note: Values are mean (n=3)

The sediment analysis results in Table 3-7 indicated a high value at the inlet point and a decrease at the middle point. The concentration of Cu was measured at 20.6 mg/kg in the inlet point and decreased to 5.8 mg/kg in the middle point of the lake. This observation suggests that the majority of the Cu concentration settled down in the inlet point rather than being transported to the middle point. This settling effect likely explains the higher concentration detected at the inlet point. The sediment analysis highlights the localized accumulation of Cu near the inlet, indicating a potential source of contamination in that area. Similarly, the concentration of Cr in the inlet was measured at 26 mg/kg, which decreased to 5.1 mg/kg in the middle point of the lake. This pattern mirrors that of Cu, indicating a localized accumulation of Cr near the inlet point.

According to Marcussen et al. (2009), where Cu concentrations in the inlet point ranged from 49.7 to 149 mg/kg, the observed decrease in concentration in the inlet point could be attributed to the implementation of policies aimed at relocating medium and large-sized factories out of the city in 2010. This policy likely contributed to a reduction in industrial pollution inputs into the lake, resulting in decreased levels of Cu observed in the inlet point over time.

Table 3-7 Heavy metal analysis of sediment in the inlet (S1) and middle (S3)

Parameter	S1	S3
Cu	20.6 mg/kg	5.8 mg/kg
Cr	26 mg/kg	5.1 mg/kg

3.4 Conclusions of the chapter

Cheung Ek Lake plays a crucial role in the socioeconomic landscape for farmers who rely on its resources for livelihoods. Serving as a source of aquatic vegetables and fish for urban citizens, the lake has been utilized for aquatic cultivation for nearly four decades. A study conducted by the Ministry of the Environment of Cambodia estimated that approximately 20% of the total daily vegetable consumption in Phnom Penh is sourced from these aquatic vegetables cultivated within the city's wastewater lake (Muong et al., 2004).

According to the result of the study in socio-economics, in one hectare of cultivation, the farmers were able to supply 165 kg/hectare of water morning glory to the market daily. The farmers can receive an average profit of 23.77 USD/day/hectare ha with economic efficiency of 1.80 from water morning glory. These findings indicate that the production system maintains a low-cost input with a high return profit, demonstrating its economic viability. However, there is a significant gap in prices observed between farmers and retailers. Furthermore, the water morning glory market chain involves three additional parties before reaching the consumers. To enhance profitability, it is recommended that farmers reduce the involvement of middlemen in the market chain, thereby increasing their share of the profit from production.

From another perspective, this study has uncovered contamination of heavy metals in wastewater and fertilizer, which has had an adverse impact on water morning glory plants. The results indicate a high potential risk of heavy metal contamination, raising serious health concerns for consumers.

Despite the potential health risks associated with wastewater-fed aquatic vegetables, they remain vital in supplying the vegetable markets of Phnom Penh city. However, given the contamination concerns highlighted by this study, it is imperative to enhance monitoring efforts, closer attention should be paid to fertilizer application practices by farmers to mitigate the risk of heavy metal pollution in agricultural produce.

As urbanization has resulted in the reduction of the lake's size, farmers in Cheung Ek Lake have faced the challenge of maintaining their income levels. Concurrently, to sustain their livelihoods, farmers have increased their production by intensifying their fertilizer application, inadvertently leading to pollution of copper (Cu) and chromium (Cr) in the water morning glory plants. Therefore, an alternative kind of fertilizer is necessary to consider for the future of the cultivation of this lake. This is why in Chapter 4, the development of new absorbed to recover nutrients was discussed.

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Chapter 4

Development of calcium silicate hydrate (CSH) for fertilizer production

4.1 Introduction of this chapter

4.1.1 Overview of wastewater treatment method

Nitrogen and phosphorus are essential nutrients for the growth and vitality of living organisms. However, the discharge of nutrient-rich waste steam into aquatic ecosystems can lead to eutrophication, a harmful process characterized by excessive nutrient levels and subsequent algal blooms. To mitigate these environmental impacts, it is crucial to remove nutrients from wastewater to meet stringent discharge standards. Additionally, nutrient recovery from waste streams is essential for promoting a circular economy, as it allows for the reuse and recycling of valuable nutrients rather than their depletion as finite resources.

The various reports on nutrient levels in Cheung Ek Lake provide evidence of its potential for nutrient recovery. Irvine (2011) reported nitrate levels 4.2 mg/L and TP levels from 4.2 mg/L at the inlet point of dry season. Nara et al. (2013) documented TN levels between 5.6 and 11.6 mg/L and TP levels ranging from 2.4 to 1.5 mg/L. Visoth et al. (2015) reported TP levels varying from 5 to 9 to 20.8 mg/L across different locations within the lake. Samuel et al. (2019) indicated ammonium levels at approximately 50 mg/L and phosphorus at 8 mg/L in the inflow to Cheung Ek Lake. Moreover, investigations in Chapter 2 revealed ammonium levels between 15 and 25 mg/L and phosphate levels ranging from 3 to 5 mg/L at the inlet point. Collectively, these findings underscore the potential of Cheung Ek Lake for nutrient recovery efforts.

Furthermore, in 2021, Cambodia reportedly imported approximately 1.4 million tons of chemical fertilizer, equivalent to 210 million USD. The escalating prices of imported fertilizer have led to financial losses for Cambodian farmers, prompting some to abandon their farmland over the past two years (IRRI, 2022).

Existing information on different conventional as well as advanced treatment technologies that are commonly practiced for the removal of nutrients from domestic wastewater. The wastewater treatment method can be categorized into five main groups, as illustrated in Figure 4-1. The advantages and disadvantages of each method have been extensively discussed (Qasem et al., 2021).

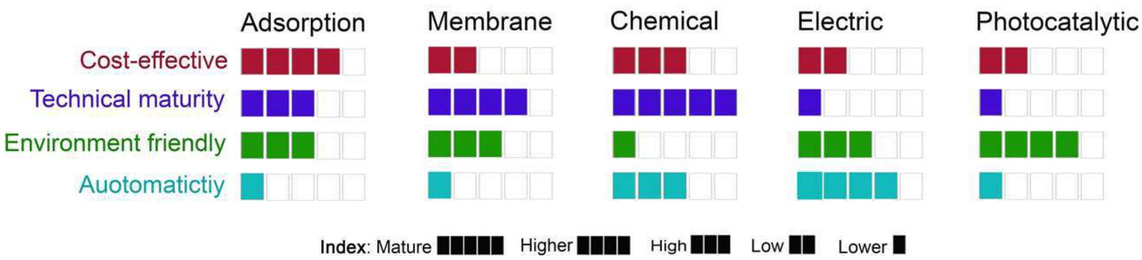

Figure 4-1 Methods of wastewater treatment

The adsorption mechanism relies on the physicochemical properties of both the adsorbent material and the heavy metals present, as well as various operating conditions such as temperature, the amount of adsorbent used, pH levels, adsorption duration, and the initial concentration of ions in the solution. This method has been noted for its low operating costs, high removal capacity, ease of implementation, and straightforward treatment process through regeneration of the adsorbed ions (Yang et al., 2019; Qiu et al., 2021).

Over the years, advancements in membrane technology have facilitated the widespread adoption of membranes for the filtration and extraction of nutrients from wastewater. Membrane methods have become increasingly prominent in wastewater treatment and are considered a promising option for addressing water quality challenges. They are particularly well-suited for certain separation applications, such as desalination. However, membrane fouling and biofouling, low recovery rates for the amount of feed wastewater, process complexity, the need for pre-treatment, periodic membrane cleaning, and high costs are some of the limitations associated with this method. The development of novel membrane materials with improved thermal and chemical stability will be crucial for industrial wastewater treatment. These advancements are necessary to achieve better anti-fouling properties and enhance membrane selectivity for target ions (Rahmati et al., 2019). Additionally, there is a need for further implementation and improvement of automatic operation systems in industrial plants using both adsorption and membrane methods.

Chemical methods for removing heavy metals from wastewater have been established and utilized for quite some time. These methods include precipitation, coagulation-flocculation, and flotation, among others. However, challenges such as the high cost of anodes and cathodes, low throughput, and high energy consumption hinder the widespread adoption of this technique (Kumar et al., 2021). To address these challenges, coupling different types of electrochemical treatment methods and driving them with renewable energy sources could be a promising approach.

In an electrochemical system, oxidation takes place at the anode (positive side), where electrons are transferred to the cathode (negative side), facilitating the reduction process. These two simultaneous chemical reactions constitute a redox (reduction-oxidation) reaction, ultimately leading to water purification through the removal of ions (Martinez et al., 2018). The ion exchange method shares similarities with adsorption techniques, where the stability and reusability of the ion exchange materials require further investigation to address potential issues. On the other hand, the photocatalyst method offers a simple treatment approach with minimal or no chemical usage and no sludge production. However, it is still in the research phase and faces challenges such as low throughput, dependence on pH, and inefficiency when dealing with mixtures of different metals (Hu et al., 2020).

The photocatalytic process was reported as a simple process for wastewater treatment that uses light and semiconductor (Barakat et al., 2011). Three key steps are taken in this process: charged carrier photogeneration, charged carrier separation and diffusion to the photocatalyst surface, and redox reaction on the photocatalyst surface (Dabrowski et al., 2004; Crini et al., 2019).

Among all wastewater treatment methods in Figure 4-1, adsorption has emerged as one of the most favored approaches in recent years. It offers several advantages, including easy operation, low cost, and high sorption capacity. A notable trend in current research is the development of eco-friendly and cost-effective adsorbents derived from waste materials. However, a significant challenge associated with this method is the disposal of used adsorbents after the adsorption process, which must be managed carefully to avoid environmental risks.

Adsorption onto activated carbon (AC) has been identified as a feasible method for industrial-scale applications due to its effectiveness in removing pollutants. However, further research is needed to optimize adsorption processes for removing pollutants at low trace levels and to develop efficient regeneration methods for used adsorbents. Additionally, assessing the economic feasibility of implementing adsorption-based wastewater treatment methods in industrial applications is crucial for their widespread adoption. Overall, while adsorption shows great promise, ongoing research and development efforts are essential to address existing challenges and enhance its efficiency and applicability in wastewater treatment.

In the context of developing countries like Cambodia, the adsorption method appears to be the most suitable among various wastewater treatment methods. A review of the utilization of agricultural waste as an absorbent has been studied, revealing its effectiveness in nutrient removal (Table 4-1). However, a notable limitation is that many adsorbents are effective in removal but lack the feasibility for reuse.

Table 4-1 Adsorbent and their activator, dosage, efficiency (%) and adsorption (mg/L) used for nitrogen and phosphorus removal in aqueous environment

Adsorbent	Dosage	Activator	Efficiency	Adsorption capacity	Reference
		Nitrogen			
Coal fly ash	5g	NaOH	97	64.9 mg/L	Zhao et al., 2023
Coconut husk biochar	-	Thermal	74	88.3 mg/L	Hafhide et al., 2019
Sewage sludge	30g	Acid-base	58.20	-	Chen et al., 2019
Sugarcane residue biochar	-	MgO and pi-pi electron electrostatic attraction	-	22 mg/L	Li et al., 2017
Municipal organic waste	100-300kg/m^3		78	-	Manyuchi et al., 2018

Adsorbent	Dosage	Activator	Efficiency	Adsorption capacity	Reference
		Phosphorus			
Cry-CSH	10g	-	98	65.4	Tarawee et al., 2022
Coconut husk biochar	-	Thermal	10	1.3	Hafhide et al., 2019
Sugar beet tailings	1g	MircroNaOH	73	-	Yao et al., 2011a
Sugar beet tailing	-	-	1-5	-	Yao et al., 2011a
Sugarcane residue biochar	-	MgO and pi-pi electron electrostatic attraction	-	212.3	Li et al., 2016
Sugar beet tailing	-	Ferric hydroxide	8	-	Yao et al., 2011a
Municipal waste	100-300kg/m^3	-	64	-	Manyuchi et al., 2018

4.1.2 Characteristics of CSH

Calcium silicate hydrates (CSH) are compounds containing calcium and silicate ions and are a primary component of Portland cement. They have been the subject of extensive study for several decades. CSH exhibits a wide range of chemical compositions, with studies indicating that its molar ratio of calcium to silicon (Ca/Si) can vary from 0.7 to 2 or more. However, in most cases, this ratio is approximately 1.7 (Gmira et al., 2002).

The investigation of the CSH removal ability with different forms of CSH have long been studied. According to Guan et al., 2013, the porous CSH tends to have a stronger capacity for calcium ion release than crystalline CSH as well as higher phosphate species recovery performance. In the gel phase of CSH, pores constitute approximately 25% of the total volume of the gel, known as gel pores. These pores are defined as those with diameters smaller than 20 nm. Pores with diameters larger than 20 nm are referred to as capillary pores. During the hydration reaction of cement, capillary pores decrease in size as cement hydrates grow. An increase in capillary pores is associated with decreased strength and durability, as well as increased permeability of the final product. However, it's important to note that capillary pores are inherent to cement, persisting even after hydration. The presence of water is a key factor contributing to the formation of these pores (Felix et al., 1997).

Indeed, research has shown that amorphous calcium silicate hydrates (A-CSHs) have significant potential for phosphorus recovery, surpassing conventional crystalline CSH in terms of phosphorus removal efficiency. Studies conducted by Okano et al. (2013, 2015, 2016) have highlighted the superior performance of A-CSHs in phosphorus removal processes. Moreover, the challenge of separating fine crystallites after crystallization from CSH remains a significant obstacle, limiting the practical applications of CSH in wastewater treatment and phosphorus recovery (Peng et al., 2018).

The study from Taweekarn et al., 2022, indicated the calcium silicate hydrate composite starch cryogel (Cry-CSH) has capacity of 98% (2.5 mgPO_4^{3-}/g) removal of phosphate from the wastewater. This Cry-CSH also can biodegraded into the fertilizer within 10days. While Lee et al., 2018, indicated that conventional CSH ($CaO_3Si.nH_2O$) in a dose of 15 mg/L was able to recover the phosphate from the sewage sludge about 89.6%.

Indeed, the manufacturing process of calcium silicate hydrate (CSH) in previous studies is often complex, which may raise questions about its adaptability by farmers or for widespread adoption in practical applications. The complexity of the manufacturing process could pose challenges in terms of scalability, cost-effectiveness, and accessibility, particularly for farmers or small-scale users. Therefore, simplifying the manufacturing process of CSH or developing alternative methods that are more user-friendly and economically viable would be crucial for its successful adoption and implementation in various sectors, including agriculture and wastewater treatment. The method of synthesizing calcium silicate hydrate (CSH) is very critical and significantly impacts its reactivity and its ability to absorb chemicals. Specifically, the Ca/Si ratio plays a pivotal role in determining the internal structure of CSH. A higher Ca/Si ratio often results in a more porous structure within the CSH material. This porous structure is critical for facilitating the absorption and subsequent release of nutrients from the CSH material.

The primary aim of this study is to create the simplest method for manufacturing calcium silicate hydrate (CSH) that can be readily implemented by local communities in Cambodia. The focus is on utilizing locally available and affordable materials to develop a straightforward manufacturing process that aligns with the resources and capabilities of the target population. By identifying a simple and practical method for producing CSH, the study aims to empower local communities to address environmental challenges, such as wastewater treatment and phosphorus recovery, using locally sourced materials and accessible techniques. This approach not only promotes sustainability but also ensures the feasibility and effectiveness of implementing CSH-based solutions in Cambodia settings.

4.2 Objective of this chapter

This chapter aims to deal with the development of CSH and evaluate its capacity for nutrient removal from wastewater. To achieve this objective the selected materials such as rice husk ash and calcium hydroxide were used to manufacture the CSH. Additionally, the absorption experiment will be conducted to determine the removal capacity of the CSH.

4.3 Methodology

4.3.1 CSH manufacture procedure

Calcium silicate hydrate (CSH) material in this study was synthesized with the calcium hydroxide $Ca(OH)_2$ and rice husk charcoal (RHA). The mixture of CSH was the mass-based ratio of $Ca(OH)_2$:1 and RHA:4 and 75% deionized water was added for hydrothermal reaction. After mixing, it was processed with vibration for 1-3 minutes (Figure 4-2). SEM images of the CSH are shown in Figure 4-3, revealing an agglomeration of crystalline particles with rough surfaces.

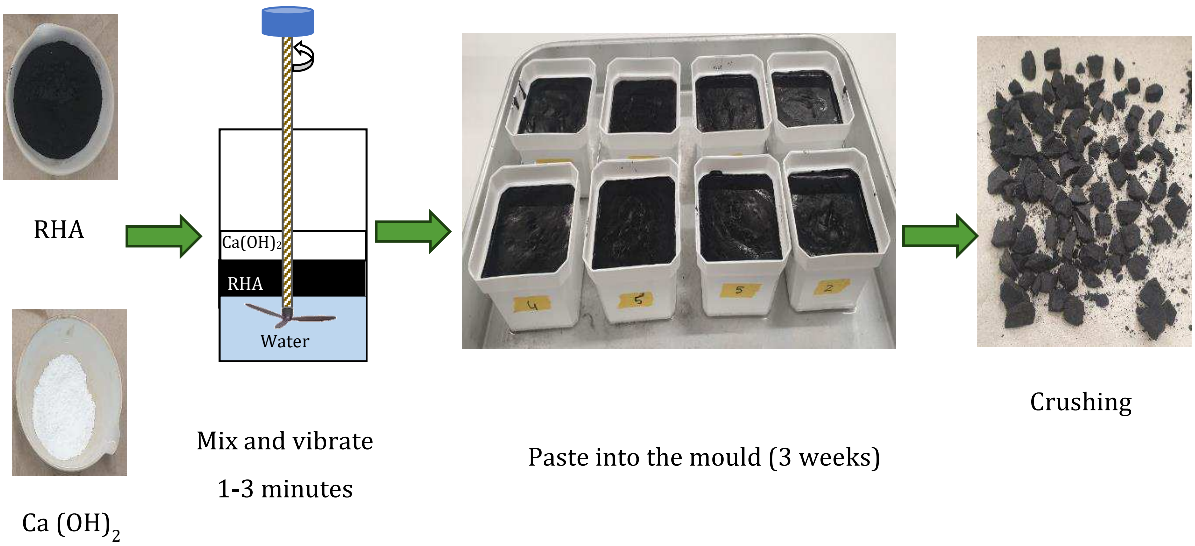

Figure 4-2 CSH preparation

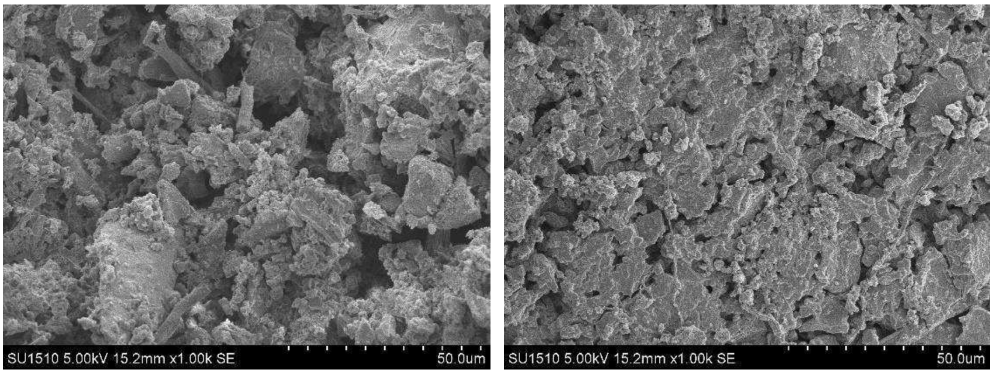

Figure 4-3 SEM image of the CSH sample. (a)1 minute and (b)3 minute vibration 1,000x

4.3.2 Preparation of absorption experiment

The CSH material was prepared using different cases of 1, 2, and 3 minutes vibration and put in the mould for 3 weeks at room temperature (25°C) for the hydration process. The 4 g of obtained CSH products (1 minute, 2 minute, and 3 minutes vibration) were immersed in 40 ml of deionized water for 3 hours to test for the chemical component in CSH shown in Table 1.

Table 4-2 Chemical components of CSH

Case	pH	EC (mS/m)	Ca (mg/L)	K (mg/L)	Si (mg/L)
Case 1	12.03	121.70	300	3	5.8
Case 2	12.09	79	270	1	6.9
Case 3	12.28	103	390	2	3.4

Following the analysis of the initial chemical components, the produced calcium silicate hydrate (CSH) was subjected to air-drying before being immersed once more in a wastewater solution consisting of 20 ml. Over a period of 14 days, the CSH was monitored to assess its capacity for removing nutrients from the solution. The initial composition of the wastewater solution was meticulously examined, and the findings are detailed in Table 4-3.

Table 4-3 Initial solution concentration of wastewater

Solution	pH	EC (mS/m)	Ca (mg/L)	K (mg/L)	PO_4^{3-} (mg/L)	NH_4^+ (mg/L)
Wastewater	6.60	55.0.5	31.5	160	23.4	13.4

4.3.3 Evaluation of ammonium and phosphate recovery performance

The amount of adsorbed ammonium and phosphate at time t (Q_t: $mgNH_4^+/g$) and (Q_t: $mgPO_4^{3-}/g$) was calculated as the difference between concentrations in solution initially (C_i: mgL^{-1}) and at time t (C_t: mgL^{-1}) using the following equation (1) and (2)

$$Q_t = (C_i - C_t)V / W \ 100\% \qquad (1)$$

Where V is the volume of solution (L) and W is the dry mass of adsorbents (g). The nutrient efficiency (RE) was calculated using equation (2) where C_e is the nutrient concentration at equilibrium (mgL^{-1}).

$$\% \ RE = (C_i - C_e)W / V \qquad (2)$$

4.4 Results and discussion

4.4.1 Ammonium and phosphate removal performance of CSH

According to Figure 4-5, the pH levels in the wastewater solution peaked within the first 24 hours of the experiment and remained stable until Day 14. Throughout the entire experimental process, there was minimal variation in pH levels between the different cases. Concurrently, calcium (Ca) was progressively released from the calcium silicate hydrate (CSH) material into the wastewater, with concentrations ranging from

400-450 mg/L on Day 1 and steadily increasing to peak values of 577-650 mg/L by Day 2. The significant increase in Ca concentrations likely contributed to the observed elevation in pH levels within the wastewater solution.

The electrical conductivity (EC) measurements consistently demonstrated an increasing trend across all cases throughout the duration of the experiment. Starting at 50 mS/cm on Day 1, the EC levels steadily rose to reach 258 mS/cm by Day 14. Throughout the course of the experiment, the potassium (K) levels remained relatively stable, exhibiting only slight variations. Starting at 150 mg/L at the beginning of the experiment, the concentration of K experienced a marginal increase, reaching values between 177 mg/L to 207 mg/L by the end of the testing period. It is likely that Case 1 exhibited higher values for both electrical conductivity (EC) and potassium (K) concentrations compared to the other cases throughout the experiment.

The concentration of phosphate ions (PO_4^{3-}) exhibited a notable decrease throughout the duration of the experiment. Initially, the concentration started at 23.4 mg/L and decreased further to a range of 10.8-14.7 mg/L by Day 1. Subsequently, the concentration continued to decline steadily, reaching a final value of 0.7 mg/L by the end of the experiment. This significant reduction in phosphate ion concentration indicates the effective removal or uptake of phosphorus from the experimental system over time. The progressive decrease in PO_4^{3-} concentration suggests that the calcium silicate hydrate (CSH) material or the experimental conditions facilitated the efficient removal of phosphate ions from the wastewater solution.

The concentration of ammonium exhibited a gradual decrease over the course of the experiment. Initially ranging from 9.5-10 mg/L on Day 1, the concentration gradually decreased to 6.2-7.6 mg/L by Day 4. By Day 7, the concentration of ammonium had significantly decreased to 0.3 mg/L across all cases, remaining consistently low thereafter. These results suggest that the calcium silicate hydrate (CSH) material was effective in removing both phosphate and ammonium from the wastewater solution within the 7 day experimental timeframe.

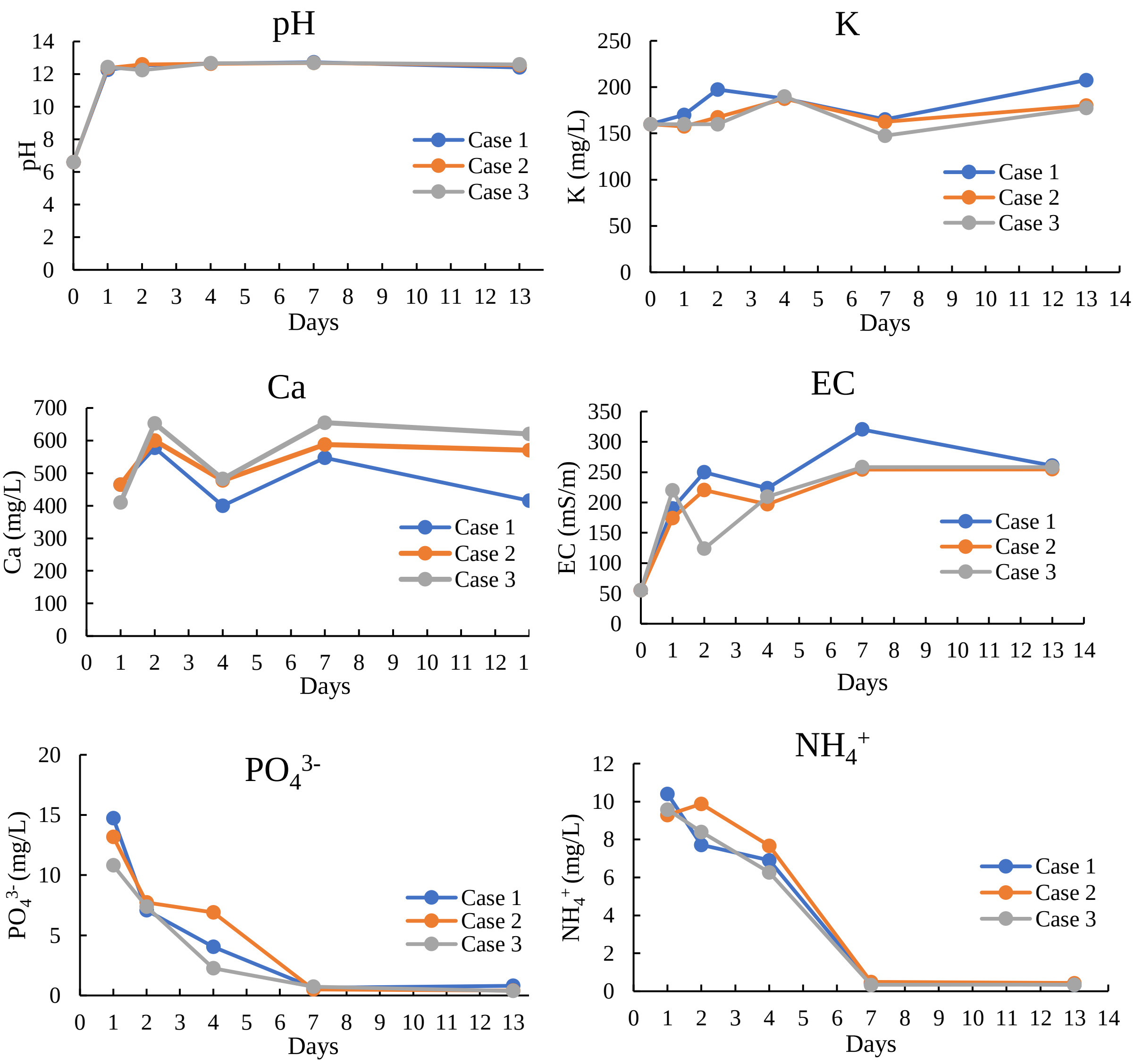

Figure 4-4 Absorption results of CSH

Figure 4-6 illustrates the average results of 1-3 minute vibration for CSH. On day 1, the removal rate for NH_4^+ was 27%, gradually increasing to reach equilibrium at

97% by Day 7 and remaining stable until Day 14. Similarly, for PO_4^{3-}, the removal rate starts from 45% on Day 1, gradually increasing to 98% by Day 7, and maintaining the same through Day 14. The results indicate that varying vibration times do not have an impact on the removal capacity of CSH. The phosphate and ammonium adsorption capacity of CSH was determined to be 0.11 PO_4^{3-}-mg/g, and 0.065 NH_4^+-mg/g. The adsorption of NH_4^+ and PO_4^{3-} is lower than reported of activated carbon (29 mg-N/g, 14.1 mg-P/g) and bio-adsorbent (45 mg-N/g, 12 mg-P/g) (Vassileva et al ., 2009; Wang et al., 2012; Yadav et al., 2015; Kizito et al., 2015). The variation in absorbent rates can be primarily attributed to the physical properties of CSH, characterized by its macroporous structure, in contrast to activated carbon and biochar, which exhibit a micro-mesoporous type configuration. From SEM image in Figure 4-3. confirmed that CSH derived from rice husk charcoal and calcium dioxide had macropores with an average of 50-100 µm and high porosity, which led to a lower surface area. The micro-mesoporous type possesses a larger surface area, enabling it to effectively absorb ions to a greater extent compared to structures with larger pores. Furthermore, according to Kizito et al. (2015), the optimal pH range for absorption is 4-8. In this experiment, the CSH was eluted at a high pH (11-12) in the solution during the adsorption process, which affected its removal capacity. Despite having a lower removal capacity compared to other materials, this CSH exhibits a unique characteristic in its ability to elute back nutrients without additional activators, a feature that is not present in other absorbent materials.

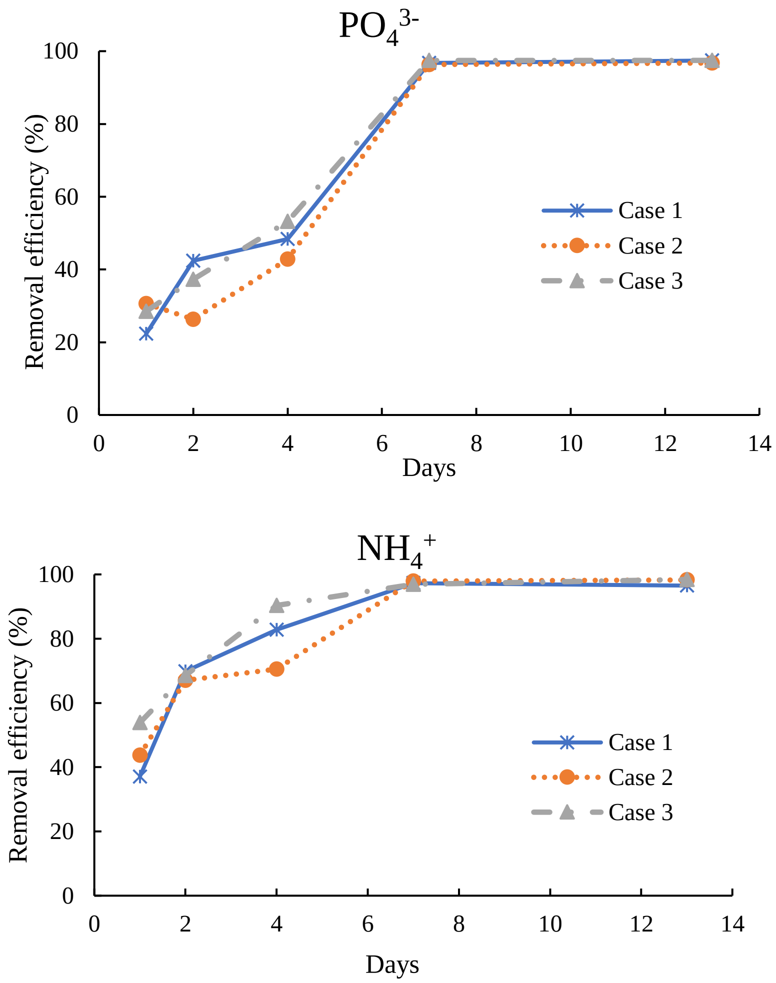

Figure 4-5 Removal efficiency of CSH on PO_4^{3-} and NH_4^+

4.4.2 Cr removal result

The examination of calcium silicate hydrate (CSH) for chromium (Cr) removal in a low concentration Cr environment yielded no significant changes over the course of a week-long experiment. The concentration of Cr remained relatively stable, decreasing only marginally from 0.33 on day 1 to 0.29 on day 14. These findings suggest that the CSH derived from rice husk and calcium dioxide may lack the capacity to effectively remove Cr from wastewater under the conditions tested.

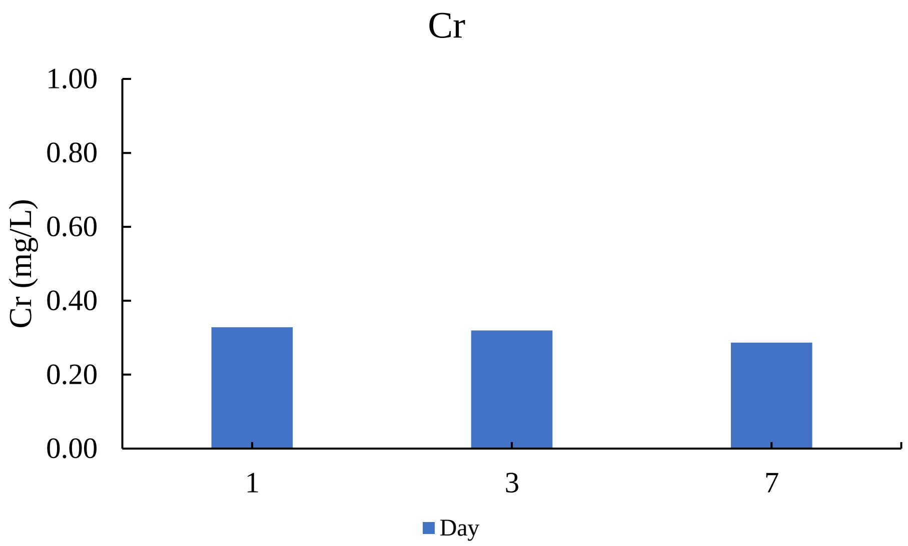

Figure 4-6 Cr removal capacity of CSH

4.5 Conclusion of this chapter

This chapter focuses on developing calcium silicate hydrate (CSH) material for nutrient removal from wastewater. The results indicate that CSH synthesized from calcium hydroxide ($Ca(OH)_2$) and rice husk charcoal exhibits high efficiency in absorbing phosphate ions (PO_4^{3-}) at a rate of 98% and ammonium ions (NH_4^+) at a rate of 97% within 7 days. The absorption capacities on Day 7 were measured at 0.11 mg- PO_4^{3-} /g-CSH and 0.065 mg- NH_4^+/g-CSH, respectively. Interestingly, variations in vibration time did not significantly impact absorption capacity, as equilibrium was reached by Day 7 and remained unchanged until Day 14. This straightforward manufacturing process makes CSH easily adaptable for farmers. Overall, CSH demonstrates effectiveness in nutrient removal, particularly NH_4^+ and PO_4^{3-}, suggesting its potential application to enhance the remediation capacity of Cheung Ek Lake.

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Chapter 5

Used CSH as a fertilizer for agricultural productions

5.1 Introduction

5.1.1 Background

From Chapter 4, the developed CHS can be used to remove nutrients in the lake. In other words, CSH can be used to recover nutrients and then the used CSH can be used as a fertilizer for agricultural productions. This chapter focused on examining the function of used (nutrient-absorbed) CSH as a fertilizer. Additionally, elution experiments were carried out to investigate the release of nutrients from used CSH. This, in turn, contributes to the determination to use CSH as a fertilizer for aqua-cultivation.

Plants, like all other living organisms, require nutrients for their growth and development. These essential elements play crucial roles in processes such as germination, growth, defense against diseases and pests, and reproductive functions. The primary nutrients, namely nitrogen (N), phosphorus (P), and potassium (K), each serve different functions in plant development.

Phosphorus is essential for aiding seed germination and promoting the growth of roots. This is particularly important for young plants and root vegetables, as a strong root system supports overall plant health and vigor.

Nitrogen is necessary for synthesizing amino acids, which are the building blocks of proteins. Proteins are vital for the growth of leaves and stems, as well as for important physiological processes such as respiration and photosynthesis.

Potassium plays a crucial role in flower and fruit development. Additionally, it contributes to disease resistance in plants and regulates water uptake in the roots and its release through the leaves. This helps maintain proper hydration and nutrient distribution within the plant.

There are several advantages of using CSH for phosphorous crystallization in a phosphorous-rich solution (Jiang and Wu, 2012; Yamashita et al., 2013; Okano et al., 2015): (1) it requires no CO_2 degassing and pH adjustment as a pretreatment, (2) it exhibits better settleability than using conventional calcium compounds, (3) it has high capacity of soluble phosphate that can be used directly as fertilizer, and (4) it offers the potential for effective inactivation of harmful microorganisms. Chen et al. (2009) used another type of CSH, Xonotlite, for phosphate removal and recovery from an aqueous solution. Guan et al. (2013) synthesized porous CSHs with different Ca/Si ratios for phosphorus recovery from wastewater. Although previous studies have evaluated the use of CSH for phosphorous recovery from synthetic wastewater (Chen et al., 2009; Jiang and Wu, 2012; Guan et al., 2013a, 2013b; Okano et al., 2015; Zeggel et al., 2017), no previous publication considered its direct use (without pre-treatment) to recover phosphorous from solutions eluted from wastewater.

Therefore, this study's final chapter will examine the performance of direct use of the used CSH. The characteristics of the final product and its available phosphorous and nitrogen contents were also determined to assess its potential value as fertilizer.

5.2 Object of this chapter

This chapter aims to examine the function used CSH as a fertilizer in both farmland and aqua-cultivation. To fulfill this objective, an elusion test will be conducted to assess the release of phosphorus (P) and nitrogen (N). Additionally, a comparison in the plant growth experiment will be made between in treatments with and without added used CSH.

5.3 Methodology

5.3.1 Preparation of elusion experiment

The elusion experiment was conducted to assess its potential value as fertilizer. The elution experiment with 3 different cases: case 1 (1-minute vibration), case 2 (2-minute vibration and case 3 (3-minute vibration) of CSH.

For the 1st elution test, the used CSH that was obtained from the absorption experiment was air dry and placed into a test tube and eluted in the deionized water in the ratio of 4g g CSH and 40 mL for 24 hours to see the release of the NH_4^+, and PO_4^{3-}.

Following the same process of 1st elusion test, the 2nd elusion test CSH was removing out from the test tube in 1 elution test and air dried. Subsequently, the CSH material was placed back in the test tube and eluted with newly deionized water for another 24 hours and evaluated the second time release of the NH_4^+, and PO_4^{3-}.

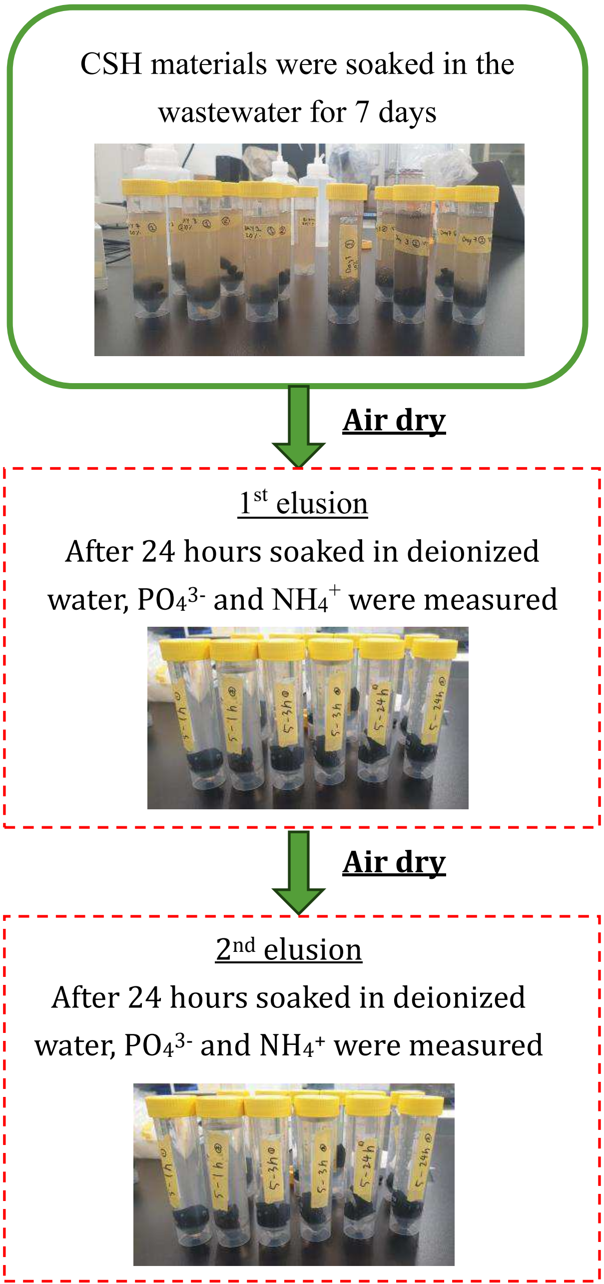


Figure 5-1 Elusion experiment preparation

5.3.2 Preparation of plant growth experiment

The pots experiment was conducted in the summer of 2022 in the laboratory at the temperature 20^0C-25^0C with 3 treatments: control treatment C1 (without CSH), CSH without treated T1 (5% of CSH) and CSH with treatment T2 (5% of used CSH) (Figure 5-2).

The CSH produced, sized at 5cm x 4cm, was subsequently crushed into smaller pieces ranging from 1cm to 3cm for further experimentation. Following the crushing process, the smaller CSH pieces were soaked in wastewater at a ratio of 1g CSH to 10mL of wastewater for 1 week. The initial chemical properties of the wastewater use in this soaking were analyzed and summarized in the Table 5-1.

Table 5-1 Initial solution concentration of wastewater

Solution	pH	EC (mS/m)	Ca (mg/L)	K (mg/L)	PO_4^{3-} (mg/L)	NH_4^+ (mg/L)
Wastewater	6.60	55.0.5	31.5	160	23.4	13.4

After the soaking process, the sandy loam soil was prepared in the As One New Wagner Pot, with dimensions of 123 x 116 x 145 mm and a volume of 1/10000 (Figure 5-2). Each treatment consisted of 3 replications, resulting in a total of 9 pots for the experiment. In each pot, 6 seeds were planted. Water was added to the pots every 2 days in equal amounts of 20 mL to ensure consistent moisture levels for plant growth. The plant growth experiment spanned one month, from December 20, 2023, to January 20, 2024.

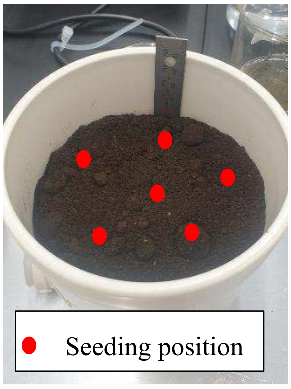


Figure 5-2 Seeding position of pot experiment

Both untreated and treated CSH were mixed with the soil to a depth of 5 cm below the soil surface. In the control treatment (C1) of the plant growth experiment, 800 g of sandy loam soil was added to each pot. For treatment T1, a mixture of 760 g of sandy loam soil and 40 g of untreated CSH was added to each pot. Similarly, for treatment T2, a mixture of 760 g of sandy loam soil and 40 g of treated CSH was added to each pot.

The height of the spinach was observed and measured in three-day intervals. After 1 month, the spinach was harvested and measured for the total plant area. The plant growth data were measured using the ImageJ.

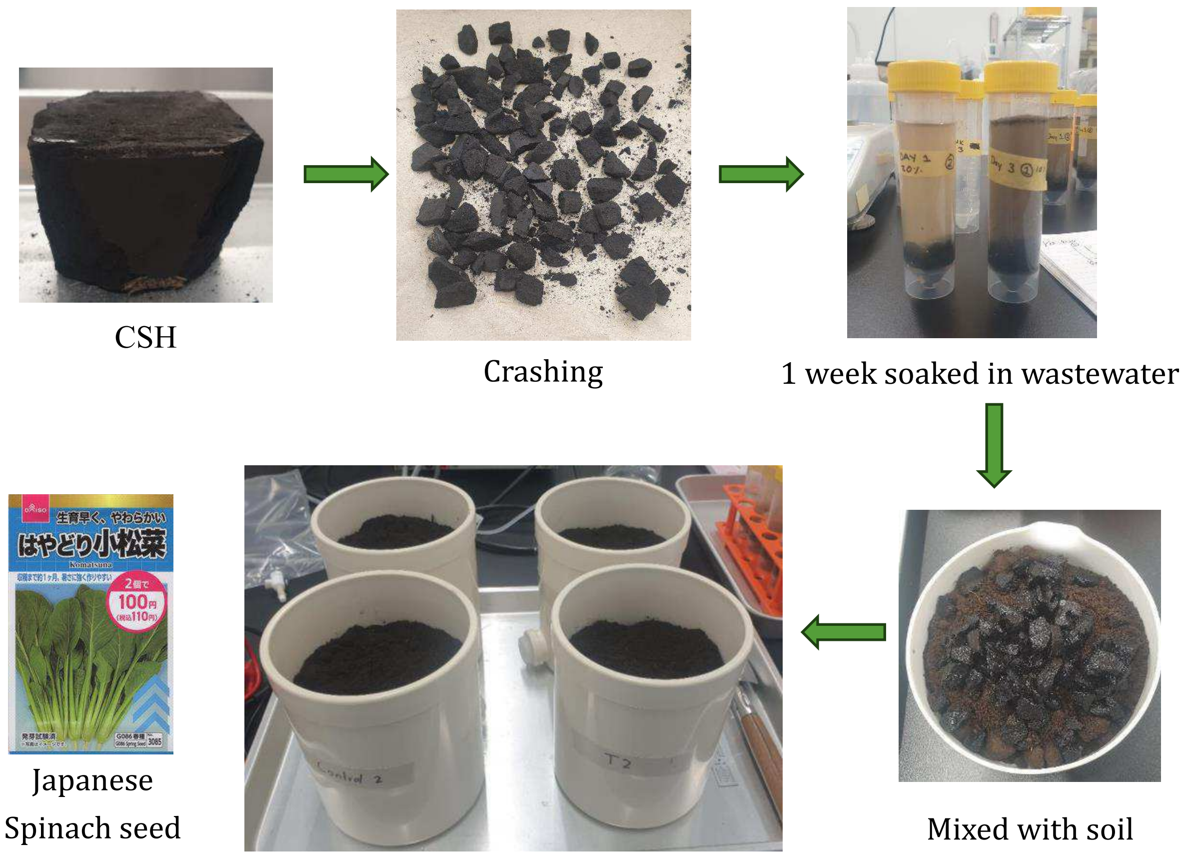


Figure 5-3 Plant growth experiment preparation

5.4 Results and discussion

5.4.1 Elusion test of ammonium and phosphate with used CSH

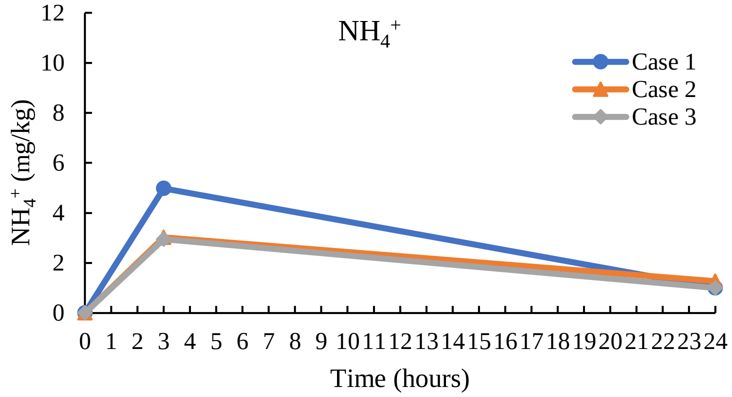
The elution test was carried out to assess the amount of ammonium and phosphate that could be recovered from CSH in deionized water without any additional pre-treatment, such as pH adjustment. In Figure 5-4, CSH exhibited the releasing of ammonium ranging from 3-5 NH_4^+-mg/kg and 6.6-7.7 PO_4^{3-}-mg/kg at the 3 hours of elution. The reduced phosphorus adsorption capacity in the 24 hours of CSH is due to the presence of Ca^{2+} ion in CSH which led to the formation of calcium phosphate ($Ca_3(PO_4)_2$). Under neutral or alkaline condition, direct precipitation $Ca_3(PO_4)_2$ and $Ca_5(PO_4)_3OH$ are readily achieved most likely follow as:

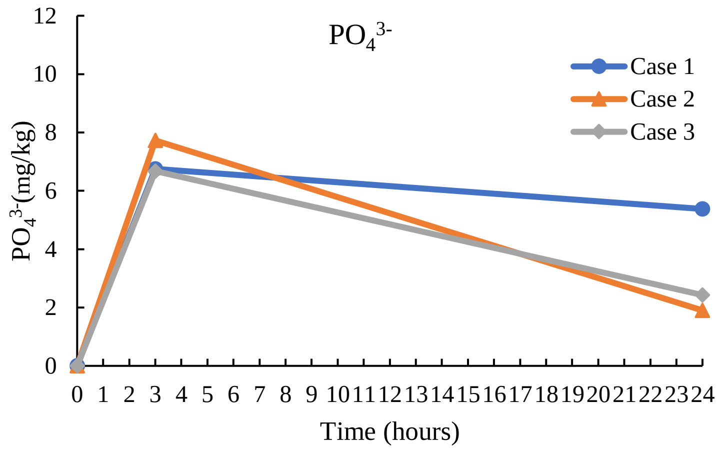
$$5Ca^{2+} + 3HPO_4^{2-} + 4OH^- = Ca_5(PO_4)_3OH + 3H_2O \quad (3)$$

$$3Ca^{2+} + 2HPO_4^{2-} + 2OH^- = Ca_3(PO_4)_2OH + 2H_2O \quad (4)$$

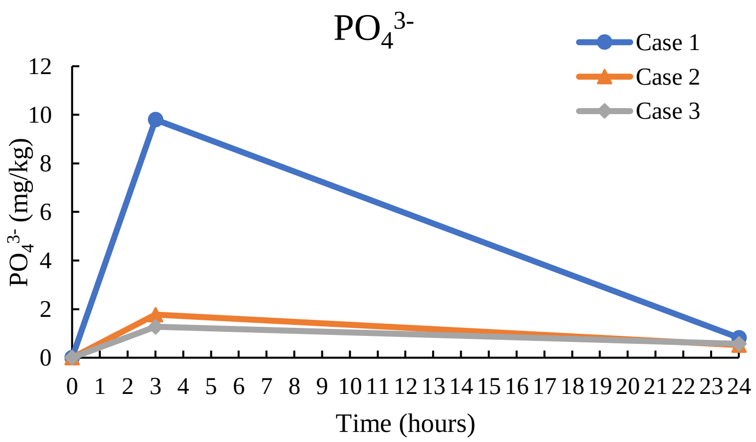
Where increases in OH^- allow the chemical precipitations to occur more readily resulting in higher removals. However, a large excess of OH^- would appear to impair $Ca_5(PO_4)_3OH$ precipitation allowing a dissolution back into solution with increased reaction times (Kim et al., 2020). The results of the second elution test demonstrate a sustained release of ammonium and phosphate into the deionized water over a period of 3 hours, followed by a subsequent decrease within 24 hours. This pattern aligns with the observations from the first elution test. Nevertheless, in the second elution test, Case 1 exhibited the highest rate compared to the other cases, suggesting that CSH with 1 minute of vibration is optimal for release capacity, likely attributed to its high porosity. In contrast to commercial chemical fertilizers, this CSH exhibits a gradual release of nutrients, making it highly suitable for application in farmland soil as a fertilizer.

1st Elusion test





2nd Elusion test



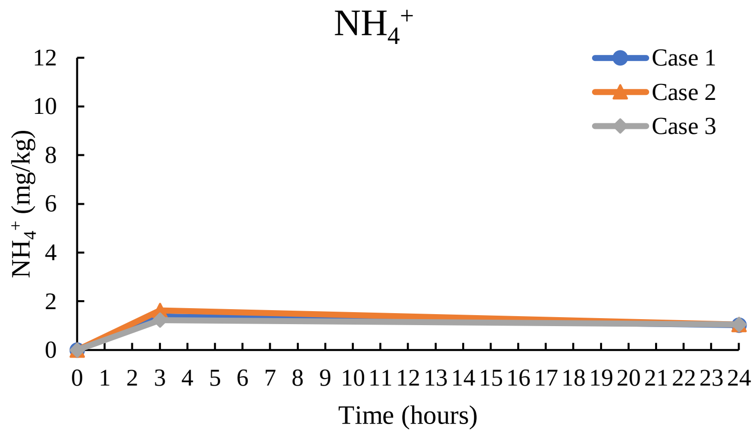
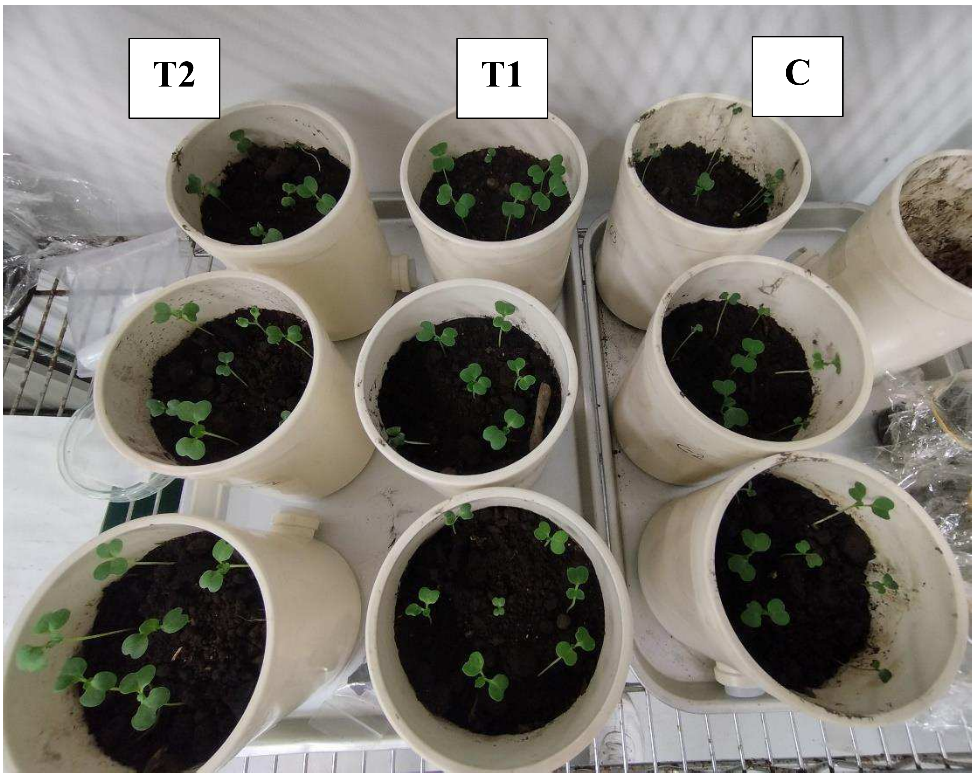


Figure 5-4 Elusion experiment result on PO_4^{3-} and NH_4^+

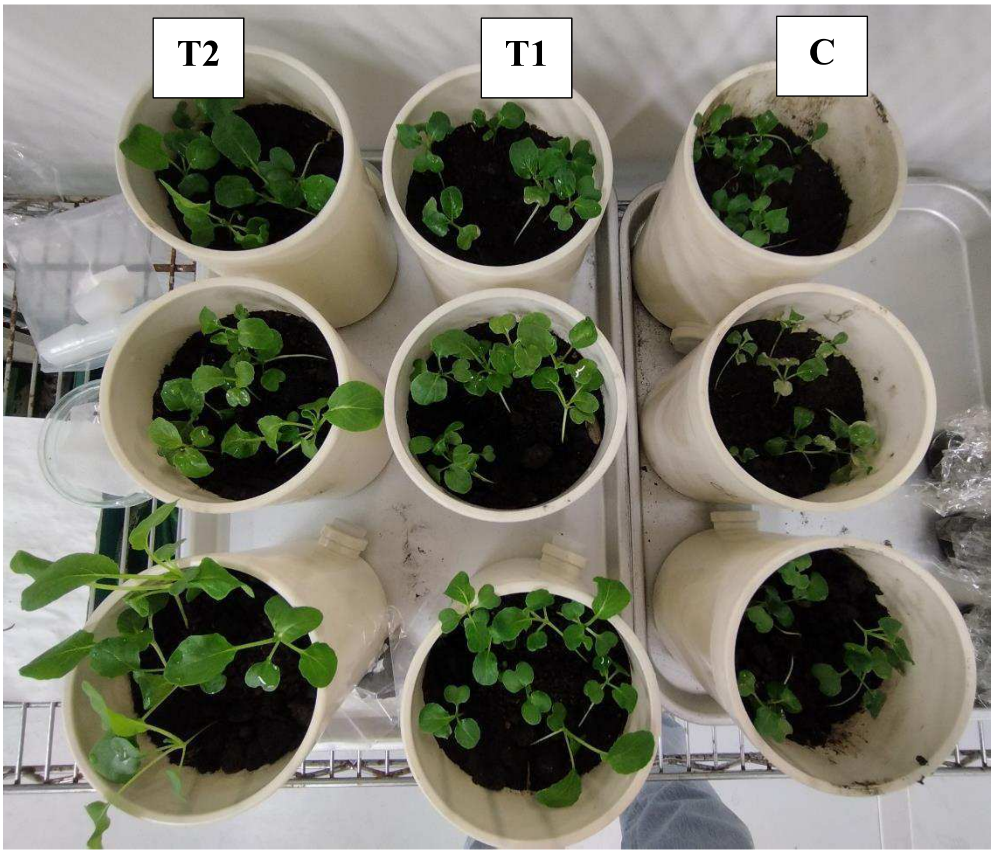
Crop fertilization has indeed been a cornerstone of agricultural practices, especially since the green revolution that unfolded after World War II. During this period, advancements in agricultural science and technology, including the development of synthetic fertilizers, pesticides, and high-yielding crop varieties, led to a significant increase in global food production (Havlin et al., 2014; Weil et al., 2017). However, the excessive use of fertilizers, in addition to being economically inefficient, can lead to environmental contamination. This is mainly caused by nitrogen (N) fertilizers, due to the leaching of nitrates into groundwater and aquifers (Yang et al., 2018; Poikane et al., 2019) and the emission of N oxides into the atmosphere (Coyne et al., 2008; Pelster et al., 2011). An alternative that can help to overcome the problem of the application date is to use slow- and/or controlled-release fertilizers and to apply them earlier. These fertilizers, containing nutrients in less soluble or less bioavailable forms after application, can reduce the risks of nutrient loss (Trenkel et al., 2010; Arrobas et al., 2011; Zhang et al., 2019; Rodrigues et al., 2019) and may offer a viable alternative to conventional fertilization.

5.4.2 Plant growth changes with adding CSH

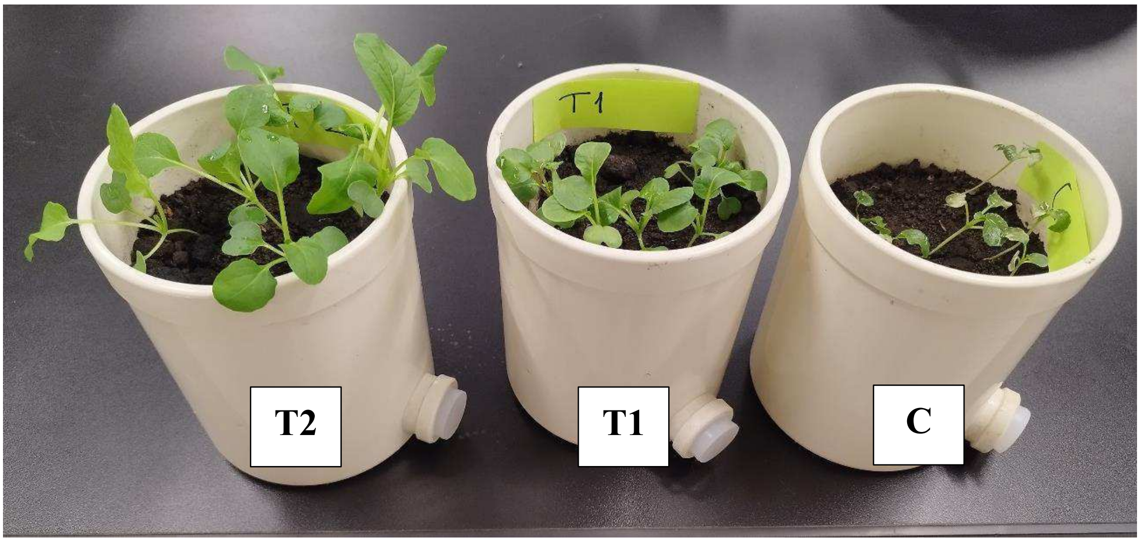
Figure 5-5 presents a comparison of plant performance under three distinct treatments: control, CSH-treated, and untreated. Initially, there are no noticeable differences across all treatments during the first two weeks. However, starting from week 3, variations in plant height become evident. This divergence can be attributed to the plants utilizing stored glucose from the seed for germination and initial growth during the initial two-week period. Subsequently, once the seed's glucose reserves are depleted, the plant begins to depend on nutrient uptake from the soil, resulting in differential growth patterns among the treatments. Consequently, by week 3, plants in the CSH-treated treatment displayed greater growth (total plants area 38.6 cm) compared in total area to those in the CSH without treatment (16.7 cm) and control treatments (11.1 cm) (Figure 5-5).



2nd Week of plants growth



4^{th} Week of plant growth



Compare the treatment in 4^{th} week of plant growth

Figure 5-5 Plant growth performance

The results obtained from the image analysis using the ImageJ program, as illustrated in Figure 5-6, reveal a significant impact of the used CSH treatment on various parameters including plant height, root development, leaf length, and leaf width (38.6 cm^2). However, compared to the control (11.12 cm^2), the CSH without treatment (16.7 cm^2) also seemed to improve the plant performance as well, but less if compared to the treated one. This suggests that the application of the CSH has influenced the overall growth and development of the plants, indicating its potential efficacy in promoting plant growth compared to the untreated control group.

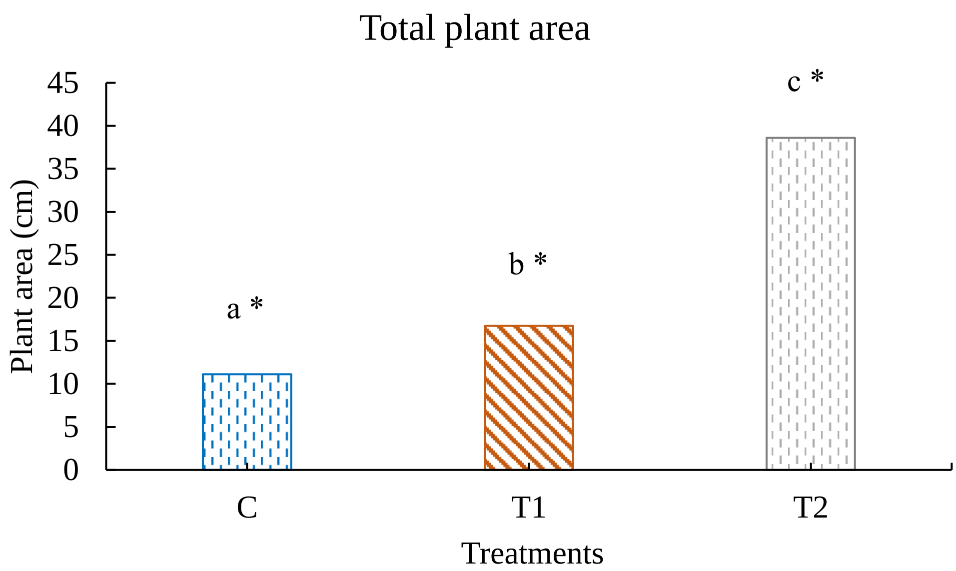


Figure 5-6 Plant growth analysis with ImageJ

The results presented in Table 5-2 demonstrate a significant improvement in soil fertility with a 5% addition of CSH. Compare the control treatment (C1) to the 5% added treated CSH treatment (T2), indicating a twofold increase in nitrogen (N), phosphorus (P), and a threefold increase in potassium (K). This suggests that the treated CSH effectively released nutrients back into the soil. In both CSH treatments, T1 and T2, there was an increase in pH from 5.3 to 7.5. Consequently, the application of this CSH is particularly beneficial for acidic soil, as it contributes to an increase in soil pH. It's worth noted that, in the T1 with the untreated CSH was also found to be an increase in soil fertilizer as well. This can be the result of the preparation of the soil mixed with the CSH. The process of mixing the soil with CSH in the preparation of plating helps increase oxygen in the soil which increases the decomposition level in the soil with the ration from CSH material. These findings suggest that CSH is effective and has the potential to serve as a viable alternative to chemical fertilizers in agricultural practices. And in the figure 5-7 and 5-8 indicate the close relation between the weight of the plant and the area of the plant.

Table 5-2 Effect of CSH on soil fertility

Treatment	pH	EC (µs/cm)	N (mg/kg)	P (mg/kg)	K (mg/kg)
C	5.39	272.33	19.11	26.67	54.11
T1	7.55	360.25	24.88	35.63	71.38
T2	7.58	729.11	51.11	72.33	145.00

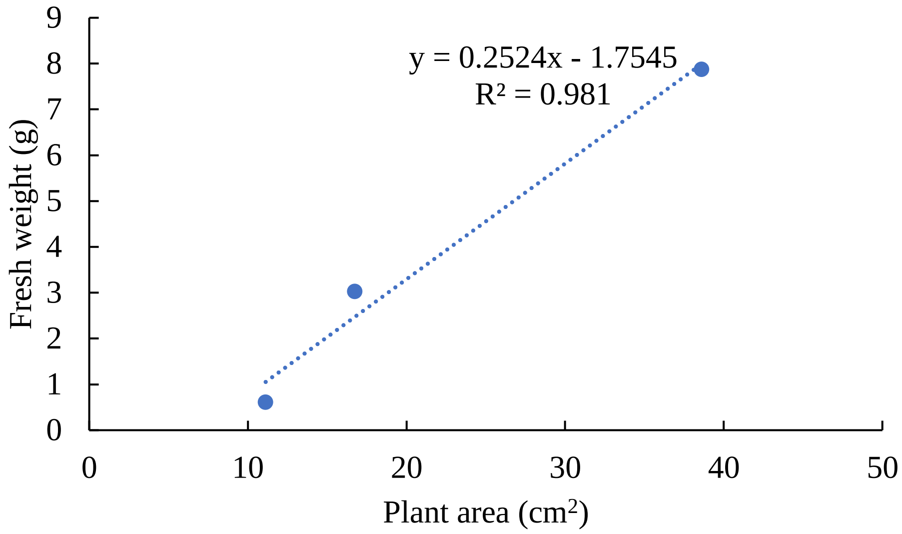


Figure 5-7 Correlation graph of fresh weight and plant area

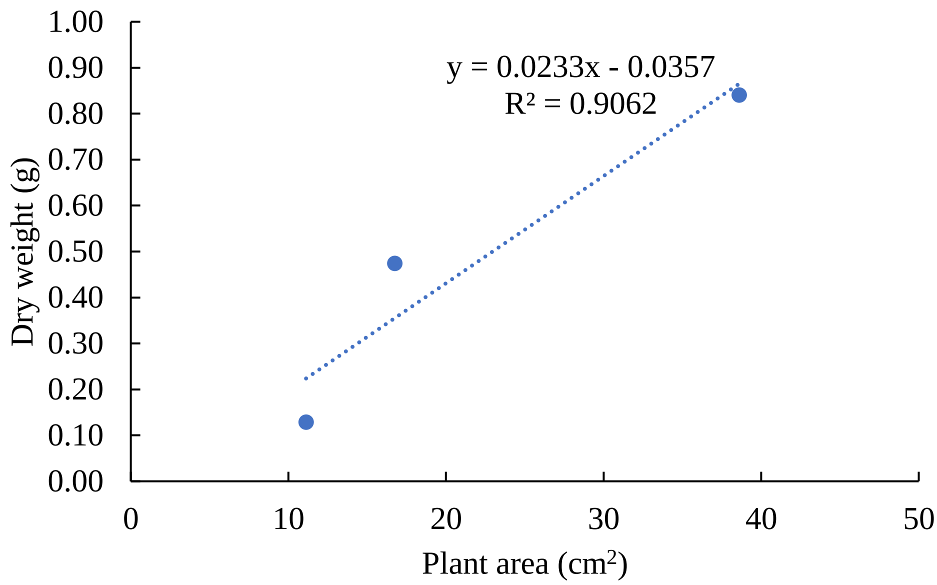


Figure 5-8 Correlation graph of dry weight and plant area

5.5 Conclusion of this Chapter

This chapter primarily focuses on investigating the potential of used (nutrient-absorbed) CSH as a fertilizer. Elution experiments were conducted to examine the nutrient release from used CSH, contributing to the decision to employ CSH as a fertilizer for aquaculture. Additional experiments were carried out to evaluate the growth of spinach in soils containing 5% used CSH compared to soils without CSH. Various growth parameters, such as weight, height, root length, leaf length, and leaf width, were measured. Soil fertility levels for nitrogen (N), phosphorus (P), and potassium (K) were also assessed to gauge nutrient enhancement in the soils.

Results from elution experiments indicated that CSH released nutrients into the water, with concentrations of 3.23 mg/kg for NH_4^+ and 7.05 mg/kg for PO_4^{3-}. This suggests that used CSH can effectively serve as a fertilizer in aquaculture. The inclusion of used CSH led to improved growth rates, reflected in increased plant weight, height, root length, leaf length, and leaf width. Furthermore, soil nutrient levels (NPK) demonstrated a significant three-fold increase, implying enhanced soil fertility. This chapter concludes that CSH has the potential to be a viable substitute for chemical fertilizers in both farmland and aquaculture applications.

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Chapter 6

Conclusions and recommendations

Overall conclusion of this dissertation

The fastest-growing economies in Cambodia are leading to significant environmental pollution. Wastewater management has become a concern for the Royal Government of Cambodia since the population in Phnom Penh has grown from 1.4 million in 2008 to 2.1 million in 2018. Until now, the city still doesn't have a proper wastewater treatment facility, while its population continues to grow as well as the expansion of the city. In the past, the wastewater from this city was directly discharged into three wetlands, namely Tumpon Lake, Trabek Lake, and Cheung Ek Lake. The wastewater is discharged using a combined sewer system and pumped and stored in Cheung Ek Lake before its discharge to the Bassac River. Thus, Cheung Ek Lake is known as a sedimentation lake for natural wastewater treatment and aqua-cultivation. Recently, the lake's area has declined due to urbanization, and agricultural activities have changed, a concern has been raised about water quality degradation.

To confirm, in Chapter 2 the water samples were examined from 2019 to 2022. Water samples were collected in different locations in the lake and analyzed for their physical and chemical properties, i.e., water discharge, pH, EC, Fe, NO_3^-, NH_4^+, PO_4^{3-}, DO, Cr, and Cu. The results revealed a reduction in nutrient concentrations (28% to 84% for NO_3^-, 29% to 91% for PO_4^{3-}, and 96% for NH_4^+) between the inlet and the outlet points in 2019-2021. Unfortunately, increasing tendencies (36% for PO_4^{3-}, 46% for NH_4^+ and 28% for Cu) were observed in 2022, as the lake area has been decreased. The comparison of flow rates from the inlet between the rainy and dry seasons of 2022 suggests that urban wastewater runoff may not be the primary factor contributing to the decline in the treatment capacity of Cheung Ek Lake. However, agricultural productivity within the lake during the rainy season, spanning from May to December, appears to be significantly low.

In response to this, farmers tend to increase fertilizer usage to maintain stable harvests, potentially impacting water quality. These findings imply that Cheung Ek Lake has experienced a loss in its remediation capacity, possibly influenced by changes in agricultural practices during the rainy season. Therefore, there is an urgent need for the development of new methods to increase the water capacity of Cheung Ek Lake.

Aqua-cultivation stands as a crucial economic asset for farmers in Cheung Ek Lake. When the water quality was found to be degraded and can no longer treated for PO_4^{3-}, NH_4^+ and Cu, the question led to how it can affect to the water morning glory production. Therefore, the objective of chapter 3 is to assess the impact of changes in water quality on both the economic aspects and the quality analysis of water morning glory production in Cheung Ek Lake. In 2019, a survey involving 35 farmers was carried out to assess the profitability of production. Water morning glory plants were collected from the lake for analyzing heavy metal concentrations, such as Cr, Cu, Cd, Pb, and As. Additionally, fertilizers and lake sediment were collected for analyzing heavy metal and chemical properties.

The results from the economic analysis indicated the profit from water morning glory production was 8,712.55 USD/year/ha. Compared to the previous research in 2017 (13,656.40 USD/year/ha), the profit from production in 2019 reduced by 36%. Moreover, it was found out that water morning glory produced in the lake was contaminated by heavy metals, i.e., Cr = 4 mg/kg and Cu = 3 mg/kg. It was also observed that the fertilizer applied in the field contained a high concentration of Cu (1.68 mg/L) and NH_4^+ (266.50 mg/L), serving as the primary cause of the contamination in water morning glory. The inflow of wastewater into the lake contributed to Cr contamination. From this chapter, water morning glory production provides economic benefits to farmers; however, excess use of chemical fertilizers for higher production causes heavy metal contamination either in water morning glory or the lake water. This chapter confirms that a change in agricultural activities led to an increase in nutrient concentration at the outlet of the lake.

Reducing the reliance on chemical fertilizers is imperative to safeguard the ecological balance of Cheung Ek Lake. However, such a shift may directly impact farmers' production. Hence, introducing alternative fertilizers tailored to the lake's needs is essential to ensure both productivity and product safety.

The findings in Chapter 3 highlighted the substantial contribution of chemical fertilizers to water morning glory and water contaminations. Therefore, chapter 4 deals with the development of CSH and evaluates its capacity for nutrient removal from wastewater. The CSH was produced by mixing calcium hydroxide ($Ca(OH)_2$) with rice husk ash and vibrated for 1 to 3 min. Absorption tests were conducted to examine the capacity of developed CSH in removing NH_4^+ and PO_4^{3-}.

In the absorption test for PO_4^{3-}, the removal efficiency increased from 44% on Day 1 to 98% on Day 7, remaining stable until Day 14. As for NH_4^+, the removal efficiency was 29% on Day 1, reaching 97% on Day 7. The absorption capacity was 0.11 mg-PO_4^{3-}/g-CSH and 0.065 mg-NH_4^+/g-CSH on Day 7. It can be concluded that CSH is effective in the removal of nutrients, specifically NH_4^+ and PO_4^{3-}, which can be used to increase the remediation capacity of Cheung Ek Lake.

From Chapter 4, the developed CHS can be used to remove nutrients in the lake. In other words, CSH can be used to recover nutrients (fertilizer production) for agricultural production. This final chapter focused on examining the function of used (nutrient-absorbed) CSH as a fertilizer. Additionally, elution experiments were carried out to investigate the release of nutrients from used CSH. This, in turn, contributes to the determination to use CSH as a fertilizer for aqua-cultivation. Other experiments were conducted to assess the growth rate of spinach in soils with 5% of used CSH and without CSH. The growth rates, for example, weight, height root, leaf length, and leaf width, were measured. Soil fertility (N, P, K) was also measured to assess nutrient improvement in the soils.

From the elution experiments, CSH released nutrients back into the water in the concentration of 3.23 mg/kg for NH_4^+ and 7.05 mg/kg for PO_4^{3-}, indicating that the used CSH can be used as a fertilizer in aqua-cultivation. The addition of used CSH provided better growth rates, in which plant weight, height, root, leaf length, and leaf width increased. Additionally, the soil NPK levels indicated a notable three-fold increase, suggesting an improvement in soil fertility. From this chapter, it is suggested that CSH can be used as a viable replacement for chemical fertilizers in both farmland and aqua-cultivation.

From this research, it was found out that the rapid urbanization of Phnom Penh indirect caused a loss of the ability to treat wastewater in Cheung Ek Lake due to a decline in the lake area and changes in agricultural activities (excess use of chemical fertilizers). This, in turn, contaminated water morning glory, which provided economic benefits to farmers. Therefore, a new method is required to treat wastewater in the lake.

It is recommended to use CSH, which is made from calcium hydroxide and rice husk ash because the raw materials for making CSH are available in Cambodia. The approach involved a simple and easily adaptable manufacturing process, specifically designed for implementation by farmers. The experimental results showed that the developed CSH could absorb nutrients, and the used (nutrient absorbed) CSH could be used as a fertilizer in both farmland and aqua-cultivation. This ensures that CHS and be used for wastewater treatment and national fertilizer reproduction in Cambodia. Additionally, the research strives for indirect outcomes, including the reduction of agricultural waste input, i.e., rice husk, and an associated increase in income for farmers.

Appendix

Questionnaire survey

Section A: General Information about the household

A1	What is your full name?			
A2	Sex of respondent	1.Male 2.Female		
A3	What is your phone number?			
A4	What year were you born?		years	
A5	a. Are you the head of this household?	0.No 1.Yes		
	b. If No, what is your relationship to the household?	1.Spouse 2.Son /daughter	3.Hired labor 4.Other:	
A6	How many members in your household?			
A7	a. How many years have you been in charge of farm decisions? b.How many years have you grown Water Morning Glory?			
A8	a. How much of agricultural land do you planting? b. How much of this do you rent out? c. How much do you rent in?			
A9	How many types of crop you captivated in this area?	1. 2. 3.		
A10	How much of your annual agricultural income you get from producing of Water Morning Glory?	%(0-100)		
A11	Are you able to read and write Khmer?	0.No 1.Yes		
A12	What is your highest education level?	_	Grade	1.Primary school 2.Secondary 3.Hight school

Section B: Management of Water Morning Glory

B1	a. How many plot of Water Morning Glory did you grow this season? b. What was the total area?		Plots m
B2	a. In what month did you start planting this plot? b. In what month did you finish harvest this plot? c. How many time can you harvest from this plot?		month(1-12) month(1-12) times
B3	a. How many months you harvest per year? b.How many week you harvest per month? c.How many day you harvest per week? d. What was the total harvest? e. What was the total marketable harvest? f. What is the average price you sold it for? g. What was the amount of money you received?		times times times kg kg KHR/kg KHR
B4	a. What is the name of the variety you planted? b. How did you acquire the seed? c. How many seed did you use on each plot? d. If Saved, once in how many years do you buy new seed? e. If Bought, did it have brand name? f. If Bought, how much did you spent on it?	1.Bought 2.Saved from privious harvest 0.No 1.Yes, what brand?	3.Received from another famer 4.Other, specify: grams years KHR
B5	Did you use fertilizer or not?	0.No 1.Yes	if No, go to section D
B6	Did you use chemical pesticides or not?	0.No 1.Yes	if No, go to section E

Section C: Fertilizer use

C3	a. How many year of using chemical fertilizer?		years	
	b. Time of apply chemical fertilizer each plot?		times	
	c. How long do you wait after spray before re-entering to work in the field again?		hours	
	d. How long was it after final spraying before you started the harvest?		hours	
	e.Did you mix than one fertilizer in one application?	0.No 1.Yes		
	f. If yes, how many fertilizer did you mix together?		number	
	g. What type of spraying eqipment did you use?	1.Electric pump backpack sprayer	2.Manual pump backpack sprayer	3.Other:
	h. Which of follow did you wear while spraying fertilizer?	1.Hat 2.Face mask 3.Glasses 4.Gloves	5.Raincoat 6.Coverall 7.Long-sleeved 8.Rubber boots	9.Long trousers 10.Respirator 11.Other:
C2	a. After cleaning the spraying equipment, where does the wastewater go?	0.Do not clean 1.Plot 2.Road	3.Directly in lake 4.Other:	
	b. Do you wash hand with soap directly after spraying?	0.No 1.Yes		
	c. Do you take a bath directly after spraying?	0.No 1.Yes		
	d. Do you change clothes directly after spraying?	0.No 1.Yes		
	e. Do you eat or drink in the field when spraying?	0.No 1.Yes		
	f.What do you usually do with empty fertilizer containers?	0.No 1.Yes		

Section D: Pesticide use

D1	a. How many year of using chemical pesticides?		years	
	b.Time did you apply pesticide each plot?		times	
	c. How long do you usually wait after spray before re-entering to work in the field again?		hours	
	d. How long was it after final spraying before you started the harvest?		hours	
	e.Did you mix pesticide in one application?	0.No 1.Yes		
	f. If yes, how many presticide mix together?		number	
	g. What type of spraying eqipment did you use?	1.Electric pump backpack sprayer	2.Manual pump backpack sprayer	3.Other:
	h. Which of follow did you wear while spraying pesticides?	1.Hat 2.Face mask 3.Glasses 4.Gloves	5.Raincoat 6.Coverall 7.Long-sleeved 8.Rubber boots	9.Long trousers 10.Respirator 11.Other:
D2	a. The cleaning of spraying equipment, where does the wastewater go?	0.Do not clean 1.Plot 2.Road	3.Directly in lake 4.Other:	
	b. Wash hand with soap directly after spraying?	0.No 1.Yes		
	c. Do you take a bath directly after spraying?	0.No 1.Yes		
	d. Do you change clothes directly after spraying?	0.No 1.Yes		
	e. Do you eat or drink in the field when spraying?	0.No 1.Yes		
	f.What do you usually do with empty pesticide containers?	0.No 1.Yes		

Section E: Cost of other input in Water Morning Glory

Please estimate how much you spend on the following inputs:

	Variable inputs	Total Value	if unable to tell,then ask:		
	1. Chemical fertilizers		Quantity	Unit	Price
E1	_ NPK				
	Other:				
	2. Hormones				
	3.Bamboo stick				
	4. Plastic bags				
	5. Tray or containers				
	6. Electricity				
	7. Gasoline				
	8. Other:				

Please estimate how many working days you and other spent on the following tasks:

	Labor use	Own labor		Hired labor	
		Days worked	Hour/day	Days worked	Price/day
E2	Preparation and planting				
	Apply chemical ferilizer				
	Apply pesticides				
	Harvest, cleaning, sorting				
	Transporting, selling				
	Other:				

E3 How much money did you borrow to produce this crop?

E4 What was the interest rate? %per year %per month

Soil property experiment result of plant growth experiment

Treatment	pH	EC (µs/cm)	N (mg/kg)	P (mg/kg)	K (mg/kg)
C1	5.5	316	18	28	57
	5.6	276	22	26	63
	5.5	287	20	31	52
C2	5.1	258	18	25	51
	5.4	238	18	25	51
	5.1	237	17	23	47
C3	5.3	285	20	28	56
	5.5	267	19	26	53
	5.5	287	20	28	57
T1-1	7.2	357	25	35	71
	7.2	327	22	32	64
	7.5	321	23	33	66
T1-2	8	460	32	45	91
	8.1	313	22	31	62
	8	264	18	26	52
T1-3	7.2	446	30	43	87
	7.2	345	24	35	69
	7.2	406	28	40	80
T2-1	7.7	742	52	74	148
	7.7	742	52	74	148
	7.7	739	52	73	147
T2-2	8	744	53	74	148
	7.9	731	57	73	150
	8	750	53	74	150
T2-3	7.1	732	52	73	146
	7	672	42	63	126
	7.1	710	47	73	142

Photo during data collection