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論 文 内 容 の 要 旨

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 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 raised on water quality degradation.

The objectives of this study are to evaluate the impact of urbanization on the lake's remediation capacity and propose a suitable method to improve water quality and nutrient reproduction in Cheung Ek Lake in 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 raised. Therefore, this chapter deals with changes in remediation capacity of Cheung Ek Lake from 2019 to 2022. The 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. Based on these results, it can be said that Cheung Ek Lake lost its remediation capacity due to urbanization in the city.

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. Therefore, the objective of this chapter 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 20 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 the 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 a higher production causes heavy metal contamination either in water morning glory or the lake water. This change in agriculture activities also leaded to an increase in nutrient concentration at the outlet of the lake.

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

The findings in Chapter 3 highlighted the substantial contribution of chemical fertilizers to water morning glory and water contaminations. Therefore, this chapter deals with the development of CSH and evaluate its capacity in 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 PO43-, 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 to the remediation capacity of Cheung Ek Lake.

Chapter 5 Used CSH as a Fertilizer for Agricultural Productions

From Chapter 4, the developed CHS can be used to remove nutrients in the lake. In other words, CSH can be used to recovery nutrients (fertilizer reproduction) for agriculture productions. This chapter focused on examining the function of used (nutrient absorbed) CSH as a fertilizer. Additionally, an elution experiments were carried out to investigate the release of nutrients from used CSH. This, in turn, contributes to the determination of used 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. The soil fertility (N, P, K) was also measured to assess nutrient improvement in the soils.

From the elution experiments, used 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.

Chapter 6 Conclusions and Recommendations

From this research, it was found out that a rapid urbanization of Phnom Penh caused a loss of 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) for higher production in the lake. 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 made from calcium hydroxide and rice husk ash, because raw material for making CSH are available in Cambodia. The approach involved a simple and easily adaptable of 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. These 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.

邦文要旨

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。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，湖水の水質改善と肥料再生のための適切な方法について論議を進めた。

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 2021 年までの 3 年間で，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 年には都市化に伴う埋め立てによる湖面の減少が進み，チュンエク湖の自然浄化機能が失われ，都市化による沈砂湖が有する浄化機能の低下を明らかにした。

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，一方で空心菜の生育には 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おり，空心菜および沈砂湖の重金属汚染源が明らかとなった。

そこで本研究では，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 を開発し，NH_4^+とPO_4^{3-}等の吸着能力を測定した。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 が農地や水耕栽培における再生肥料の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 の適用による肥料再生の一事例を明示することができた。

審 査 報 告 概 要

本研究では，カンボジア国プノンペン市における都市化がチュンエク湖の水質に与える影

響を評価し，湖水の水質改善と肥料再生のための適切な方法について論議を進めた。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結果，2019 年度から 2021 年までの 3 年間で，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，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 8 月には都市化の影響に伴う埋め立てによる湖面の減少が進み，流出地点における栄養塩類や重金属の流出負荷は流入負荷を上回る傾向を示した。その結果よりチュンエク湖の自然浄化機能が低下していることを明らかにした。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，一方で空心菜の生育には Cu（1.68 mg/L）が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た。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 汚染は都市排水，Cu 汚染は化学肥料に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，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 を開発し，NH_4^+と PO_4^{3-}等の吸着能力を測定した。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 に達し，一定の評価を与えられた。更にその養分吸着に使用した CSH（使用済）を媒体として，農地や水耕栽培に与える再生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実験に加えて，施用による土壌肥沃度の変化と小松菜（*Brassica rapa var. perviridis*）の生長を調べた結果，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，本研究は使用済 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 の適用による肥料再生の一事例を明示することができた。有益で新規性のある知見を得たことから，審査員一同は博士（農学）の学位を授与する価値があると判断した。