



## Eutrophication Evaluation and the Estimation of Methane Gas Emissions from Eutrophic Reservoirs

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**Abstract** Eutrophic reservoirs play a pivotal role in the carbon cycle by releasing methane (CH<sub>4</sub>) from water into the air. However, efforts to estimate these emissions are limited by high analysis costs and inconsistent methodological approaches. Therefore, we surveyed and evaluated the occurrences of violent eutrophication in two reservoirs and estimated CH<sub>4</sub> emissions based on the Intergovernmental Panel on Climate Change guidelines. We studied the physicochemical characteristics of water, nutrient ratio, and trophic state status in two reservoirs, Bueng Si Than and Bueng Kaen Nakhon, in Khon Kaen Province, Thailand. The results demonstrate a violent eutrophication phenomenon at a hypertrophic level. The Total Kjeldahl Nitrogen to Total Phosphorus (TKN:TP) ratio was high at 20.24 in Bueng Si Than, indicating a TP limitation, whereas a low TKN:TP ratio of 4.87 in Bueng Kaen Nakhon indicated that TKN was a limiting nutrient factor for algal blooms. The trophic state index (TSI) (TP) and TSI Chlorophyll *a* (Chl *a*) of greater than 70 confirmed hypertrophic status in both reservoirs. The average scores, ranging from high to low, were: TSI (Chl *a*), TSI (TP), and TSI (SD), with a significant difference ( $p < 0.001$ ) between the two reservoirs. Furthermore, the estimation of CH<sub>4</sub> gas emissions was achieved on the average of  $303.41 \pm 25.12$  and  $1,449.23 \pm 186.77$  kgCH<sub>4</sub>/day in Bueng Si Than and Bueng Kaen Nakhon, respectively. In addition, the relationship between Secchi depth and Chl *a* with the estimated CH<sub>4</sub> gas emissions was obtained in this study. However, the maximum Secchi depth in the range of 0.38-0.43 m. obtained from the simulation was preliminarily recommended for the estimation of CH<sub>4</sub> gas emissions from eutrophic reservoirs.

**Keywords** eutrophication, greenhouse gas, chlorophyll *a*, nutrients, eutrophic reservoir

### INTRODUCTION

Eutrophication phenomena in reservoirs occur because of the water and environmental characteristics that impact photosynthesis, including sunlight, carbon dioxide (CO<sub>2</sub>), and nutrients. Eutrophication leads to the growth of phytoplankton, aquatic plants and macroalgae. The assessment of eutrophication had been achieved using the trophic state index (TSI) (KatKaew and Chamchoi, 2024; Zhang et al., 2023; Mamun and An, 2017). Additionally, changes in eutrophication or trophic state levels can be evaluated through a combination of site surveys and routine monitoring of nutrient levels (Chen et al., 2024). Interestingly, eutrophic reservoirs play an important role in the deterioration of water quality and increasing carbon emissions but are a poorly constrained source of methane (CH<sub>4</sub>) to the atmosphere (Deemer and Holgerson, 2021). Likewise, the global warming potential of CH<sub>4</sub> gas emissions has been mentioned, and the emission release was dominated by CH<sub>4</sub> from eutrophic lakes (Sun et al., 2021). A variety of factors affecting CH<sub>4</sub> gas emissions from eutrophic reservoirs to the atmosphere were studied, in particular temperature, productivity of

phytoplankton and algae expressed as chlorophyll *a*, surface area, and water depth. The temperature dependency of CH<sub>4</sub> diffusion and ebullition is strongly modulated by trophic status when total phosphorus is a limiting factor in the system (DelSontro et al., 2016). The high CH<sub>4</sub> gas emissions in summer were due to high CH<sub>4</sub> production in the sediment, which resulted in the high dissolved CH<sub>4</sub> concentration in the surface water, accordingly (Iwata et al., 2020). The study by Sepulveda-Jauregui et al. (2018) indicated that increasing water temperature by 2°C leads to a net increase in CH<sub>4</sub> gas emissions of 101-183% in hypertrophic lakes. High productivity expressed as chlorophyll *a* (Chl *a*) under eutrophication promotes anoxic conditions via associated organic matter respiration, resulting in high CH<sub>4</sub> gas emissions. This is in line with the study by Bartosiewicz et al. (2021), who stated that anoxia associated with algal blooms and heatwaves enhanced CH<sub>4</sub> effluxes by up to 10 times. A study by Xiong et al. (2025) revealed that warming stimulates CH<sub>4</sub> gas emissions in shallow eutrophic lakes. Nevertheless, a study by Li and Xue (2023) pointed out that the higher CH<sub>4</sub> fluxes were mostly found in the littoral zone of large and shallow lakes. This finding may also have occurred in the shallow reservoir because the littoral zone has abundant organic matter available in the sediment from high productivity under eutrophication phenomena.

Previous studies have revealed that the measurement and estimation of CH<sub>4</sub> emissions from eutrophic freshwater sources involves two primary approaches. The first approach focuses on assessing greenhouse gas concentrations within water systems, utilizing sophisticated techniques and technologies such as Gas Chromatography (GC) and Infrared Gas Analyzers to extract, isolate, and precisely measure dissolved gases in water. The second approach evaluates gas flux at the critical air-water interface using three primary techniques: mathematical concentration-based calculations, floating chamber methods, and the eddy covariance technique (Bartosiewicz et al., 2021; Deemer and Holgerson, 2021; Iwata et al., 2020). These methods quantify the complex gas exchange processes between water bodies and the atmosphere. Recently, a methodology based on the Intergovernmental Panel on Climate Change (IPCC) guidelines for estimating CH<sub>4</sub> emissions has provided a variety of average emission rates from reservoirs located in different climate zones (Beaulieu et al., 2020). The appropriate procedures while optimizing costs will pose a challenge and provide benefits for the management of greenhouse gas emissions under eutrophication situations in reservoirs.

According to CH<sub>4</sub> gas emissions from natural surface water sources, particularly small artificial water bodies, including eutrophic reservoirs, have been criticized for missing accounted value from the entire greenhouse gas determination (Grinham et al., 2018). Measuring CH<sub>4</sub> gas samples requires expertise, high analysis costs, and collection techniques that account for the complex gas exchange processes occurring between water bodies and the atmosphere, which pose significant obstacles. Estimating CH<sub>4</sub> emissions using standard water quality monitoring data may help address these issues. Therefore, in this study, we conducted water sampling and analysis and evaluated the trophic state level and violent eutrophication phenomenon in two freshwater reservoirs. The observations were supplemented with an estimation of CH<sub>4</sub> gas emissions based on the IPCC guidelines. The results provide useful information for monitoring and managing the eutrophication status in small-scale reservoirs with related effects of climate change caused by CH<sub>4</sub> emissions. Further studies are required to verify the CH<sub>4</sub> gas emissions from reservoirs, which are targeted for collection as part of Thailand's national greenhouse gas inventory.

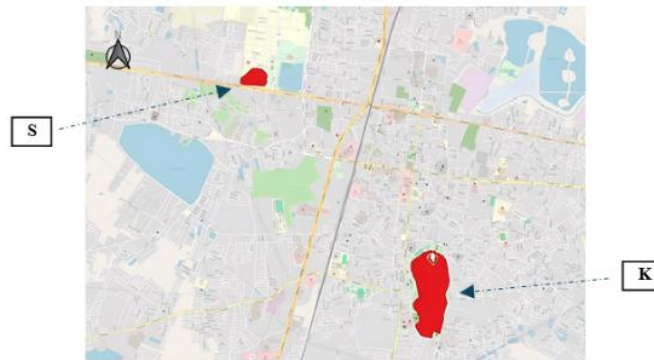
## **OBJECTIVE**

The objectives of this study were to evaluate the eutrophic levels and estimate CH<sub>4</sub> gas emissions from two different-sized reservoirs based on the IPCC guidelines.

## **METHODOLOGY**

### **Study Area**

The selected study area was in Khon Kaen Province, Thailand, including two small-scale artificial recreational reservoirs, Bueng Si Than (16°44'37.3"N 102°81'18.0"E) and Bueng Kaen Nakhon (16°24'57.5"N 102°50'18.2"E). Both reservoirs primarily receive rainwater and a portion of the effluent from a nearby domestic wastewater treatment plant. The two reservoirs were selected to compare eutrophic levels and estimate CH<sub>4</sub> gas emissions between a larger and deeper reservoir and a smaller and shallower reservoir. Bueng Kaen Nakhon is larger and deeper than Bueng Si Than, with respective areas of 0.9648 km<sup>2</sup> and 0.0864 km<sup>2</sup> (Fig. 1). The water depth in Bueng Kaen Nakhon is approximately 4.0 and Bueng Si Than's depth is approximately 1.6 meters.



**Fig. 1 Study areas: Bueng Si Than (S) and Bueng Kaen Nakhon (K)**

### Sampling and Measurement of Water Variables

Water sampling was performed during the rainy season (May-October), as defined by the Thai Meteorological Department. Water quality analysis for temperature, pH, dissolved oxygen (DO), electrical conductivity (EC), Secchi depth (SD), biochemical oxygen demand (BOD), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) was conducted following the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). Chl *a* was measured using a UV/VIS spectrophotometer (Hitachi UH-5300).

### Evaluation of the Data

#### Evaluation of the eutrophication phenomenon

**The physicochemical properties and nutritional parameters of water:** The water's physicochemical properties, Secchi depth (SD), biomass (Chl *a*), and nutritional parameters (TP and TKN) were selected to evaluate the trophic state level and eutrophic phenomenon in the reservoirs (Carlson and Simpson, 1996). The differences in the overall physicochemical properties, biomass, and nutritional parameters between the two reservoirs were interpreted using statistical analysis (t-test).

**Relationships between water quality parameters and Chl *a*:** The relationship between Chl *a* and nutrients (TKN and TP) in the observed reservoirs was evaluated using Pearson's correlation.

**Variations in the TKN:TP, Chl *a*: TKN, and Chl *a*:TP ratios:** The differences in the ratios, which indicated the type of nutrient limitation required for algal growth in each reservoir, were compared using a t-test.

**Trophic state index:** The trophic state index (TSI), such as TSI (TP), TSI (SD), and TSI (Chl *a*), for evaluating eutrophication intensity in the reservoirs was considered in accordance with Mamun and An (2017). The four classifications of trophic states included Oligotrophic (TSI: 30-40), Mesotrophic (TSI: 40-50), Eutrophic (TSI: 50-70), and Hypertrophic (TSI >70). The differences in the TSI scores obtained between the two reservoirs were assessed using ANOVA.

#### Estimation of CH<sub>4</sub> emissions

The estimation of CH<sub>4</sub> gas emissions from the reservoirs was based on the default emission factors and equations according to IPCC (2019). The principal equation is given by Eq. (1).

$$\text{CH}_4 \text{ gas Emissions} = [(\text{TOW} - \text{S}) * \text{EF} - \text{R}] \quad (1)$$

Where, CH<sub>4</sub> gas Emissions is the CH<sub>4</sub> gas emissions from the reservoirs (kg.CH<sub>4</sub>), TOW the total organic matter in the water (kgBOD), S the sludge removal (kgBOD/month [for reservoirs, S = 0]), EF the emission factor (kgCH<sub>4</sub>/kgBOD) and R the amount of CH<sub>4</sub> recovered (kgCH<sub>4</sub>/kgBOD [for reservoirs, R = 0]).

## RESULTS AND DISCUSSION

### Evaluation of Eutrophication Phenomenon During the Rainy Season

**Overall physicochemical properties and nutritional parameters of water:** The overall physicochemical properties and nutritional parameters of water in the two reservoirs during the rainy season are shown in Table 1. The measured physicochemical properties for evaluation of eutrophication occurrence include the average values of Secchi depth (SD), the biomass (expressed as Chlorophyll *a*), the TP, and the TKN demonstrate the violent of the eutrophication phenomenon in Bueng Si Than and Bueng Kaen Nakhon. Based on these variables, the trophic state of the reservoirs was evaluated at the hypertrophic level (Carson and Simpson, 1996). According to the measured SD, reservoirs can be classified as shallow, where no thermal stratification results in a greater seasonal variation in temperature and DO in the hypolimnion compared to deep reservoirs (Zhong et al., 2023). High Chl *a* content was found due to nutrients supplied by high runoff from rain, as postulated by Qi et al. (2024), and increased precipitation accelerated phosphorus (P) leaching to the reservoir. Nevertheless, the results of the t-test indicated a significant difference in the physicochemical properties and nutritional parameters between the two reservoirs (p<0.05). A significant difference in Chl *a* was also observed between the two reservoirs (p<0.001). The larger water capacity and water surface, Bueng Kaen Nakhon, the higher Chl *a* content (994.33±251.09 µg/L) and TKN (6.85±2.83 mg/L). Whereas the average content of TP (145.11±34.96 µg/L) in this reservoir showed a lower amount than that recorded in Bueng Si Than (295.91±130.23 µg/L) (Table 1). A high supply of nutrients and consequently high Chl *a* content would lead to a high probability of CH<sub>4</sub> emissions, as indicated in a previous report by Sun et al. (2021).

**Table 1 Classification of the rainy season trophic state level and the physicochemical properties and nutritional parameters in Bueng Si Than and Bueng Kaen Nakhon**

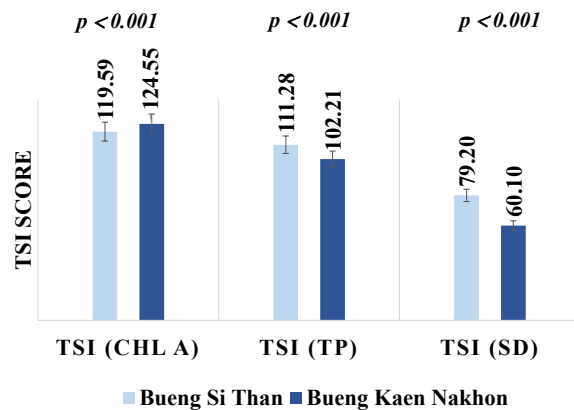
Parameters	Bueng Si Than (Mean±SD)	Bueng Kaen Nakhon (Mean±SD)	p-value*	Trophic state**
Temperature (°C)	29.98±0.45	28.48±0.17	< 0.001	-
pH	9.30±0.15	8.71±0.21	< 0.001	-
DO (mg/L)	9.92±0.56	8.55±0.22	< 0.001	-
EC (µs/cm)	389.70±2.66	200.99±2.47	< 0.001	-
BOD (mg/L)	10.49±0.83	15.89±2.51	< 0.001	-
TKN (mg/L)	4.65±1.20	6.85±2.83	0.010	
TP (µg/L)	295.91±130.23	145.11±34.96	< 0.001	Hypertrophic
Secchi Depth (cm)	26.57±2.93	25.81±1.46	< 0.001	
Chlorophyll <i>a</i> (µg/L)	589.68±103.40	994.33±251.09	< 0.001	

\*Significant difference at the 0.05 level (2 tailed), \*\*Trophic state evaluation based on Carson & Simpson (1996).

**Relationships between water quality parameters and Chlorophyll *a*:** Pearson correlation analysis indicated a positive relationship between Chl *a* and TP in Bueng Kaen Nakhon during the rainy season (r = 0.601, p = 0.014), consistent with previous reports (Kim et al., 2021; Mamun and An, 2017). High DO concentrations and high pH values recorded in this study confirmed the occurrence of eutrophication in the reservoirs, as indicated by the high Chl *a* content. Under eutrophication conditions, photosynthesizing algae cover the surface area and compete for light, resulting in high dissolved oxygen levels during the daytime. Meanwhile, the chemical byproducts of photosynthesis increase the pH of the water. In contrast, in Bueng Si Than, there was no relationship between Chl *a* and TP, which implies that the algal biomass in this reservoir was dominated by the non-nutrient

factor, BOD (Katkaew and Camchoi, 2024; Jargal et al., 2023; Zou et al., 2020). This was confirmed by the significant correlation of  $r = 0.395$ ,  $p = 0.041$ . However, the measured BOD values higher than the surface water quality standard of Thailand reflected the accumulation of organic matter in the reservoir, which is possibly a source of methane emissions, since it is primarily produced from organics, as mentioned in the IPCC (2019).

**Variations in the TKN:TP, Chl *a*: TKN, and Chl *a*:TP ratios:** In the current study, the TKN:TP, Chl *a*: TKN, and Chl *a*:TP ratios were used to evaluate the nutrient limitations in the observed reservoirs. The average ratios of TKN:TP, Chl *a*: TKN, and Chl *a*:TP at 20.24, 0.13, and 2.60, respectively, were obtained from Bueng Si Than, respectively. Meanwhile, a higher ratio of Chl *a*: TKN, and Chl *a*:TP at 1.70 and 6.95 was recorded in Bueng Kaen Nakhon. In contrast, a lower TKN:TP ratio of 4.87 was found in this reservoir. Moreover, the results of the statistical analysis (T-test) revealed that there had been a significant difference in the ratios of TKN:TP, Chl *a*: TKN, and Chl *a*:TP between Bueng Si Than and Bueng Kaen Nakhon ( $p < 0.001$ ,  $p < 0.001$ ,  $p < 0.001$ ). In addition, the current results of the TKN:TP ratio indicated that more TP limitation was discovered in Bueng Si Than because the ratio was above 20.0 (Wu et al., 2022), whereas the low value of the TKN:TP ratio of 4.87 indicated that TKN was a limiting nutrient factor for algal bloom in Bueng Kaen Nakhon. Different TKN:TP ratios indicating nutrient limitation have been reported depending on how restrictive the ratio is for each type of water source, which is related to the purpose of water usage and climatic conditions. In the study by Elser et al. (2009), nitrogen: phosphorus (N:P) ratios greater than 16 reflect that the aquatic environment is limited by P, and N:P ratios less than 14 indicate that the limiting factor is N. While the N:P ratio of  $2.9 \pm 0.5$  was suggested that N has been the limiting element (Cardoso-Silva et al., 2018). Meanwhile, the P had been reported that it was a limiting nutrient for the occurrence of eutrophication in the water-supply reservoir (Guo et al., 2018). In addition, Dou et al. (2019) stated that if the light condition is set to a fixed value, the effect of phosphorus on algae growth is greater than that of N.



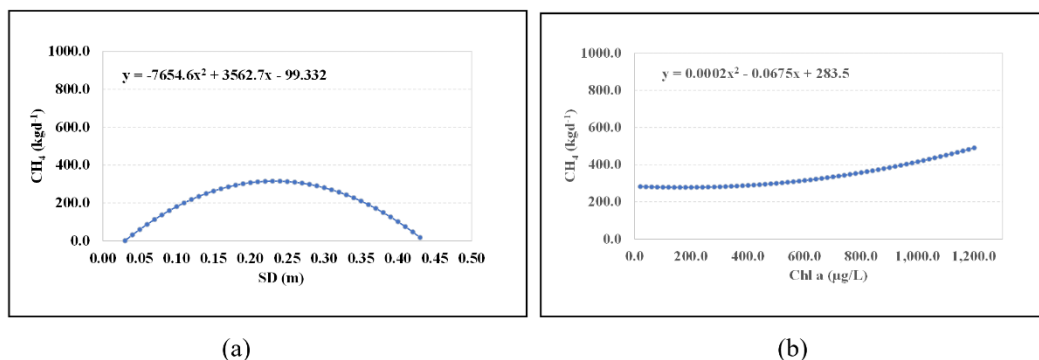
**Fig. 2 Comparison of the Rainy Season TSI scores in Bueng Si Than and Bueng Kaen Nakhon**

**The trophic state index:** In our study, the obtained TSI for evaluating eutrophication violence included a TSI (TP) and a TSI (Chl *a*) of higher than 70, indicating that hypertrophic conditions had occurred in Bueng Si Than and Bueng Kaen Nakhon during the rainy season. A slightly lower than 70 scores of TSI (SD), 60.1, were found in Bueng Kaen Nakhon, which also indicated that a eutrophic condition occurred in this reservoir. However, the physical factor, SD, can be an accurate and intuitive observation of the trophic status in the lower-mesotrophic level, while the hypertrophic level is susceptible to being driven by nutrients such as N and P (Du et al., 2019). In addition, the statistical analysis results from ANOVA revealed the significant difference between the TSI (Chl *a*), TSI (TP), and TSI (SD) scores in each reservoir ( $p < 0.001$ ) (Fig. 2). The maximum to minimum scores and average scores ranged in the following order: TSI (Chl *a*), TSI (TP), and TSI (SD), which is consistent with the study by KatKaew and Chamchoi (2024). The study by Zhang et al. (2023)

indicated that the TSI (SD) and the TSI (TP) scores were different from the TSI (Chl *a*) at approximately 10 score deviations. Moreover, the obtained coefficient of range in each index demonstrated that a high coefficient of range of TSI (TP) (13.14% and 4.89%) was observed in Bueng Si Than and Bueng Kaen Nakhon during the rainy season. All obtained TSI scores confirmed the occurrence of hypertrophy in both reservoirs.

### Estimation of CH<sub>4</sub> Gas Emissions Using the BOD, Secchi Depth, and Chlorophyll *a*

Eutrophic levels have been reported to be positively correlated with CH<sub>4</sub> emissions (Wang et al., 2022). Under hypertrophic levels existed in the current observed reservoirs, the estimated CH<sub>4</sub> gas emissions of 303.41±25.12 and 1449.23±186.77 kgCH<sub>4</sub>/day were obtained in Bueng Si Than (volume of 253,810.5 m<sup>3</sup>) and Bueng Kaen Nakhon (larger volume of 800,000 m<sup>3</sup>) based on the default emission factors and equations according to IPCC (2019). Total CH<sub>4</sub> gas emissions of 2,768.61 and 13,224.18 t CO<sub>2e</sub> per year were obtained accordingly. Moreover, Deemer et al. (2016) indicated that a greater amount of greenhouse gas emissions, the majority of which was CH<sub>4</sub>, released from reservoir water surfaces, accounts for 0.8 (0.5-1.2) Pg CO<sub>2e</sub> per year. In addition to the calculated CH<sub>4</sub> gas emissions based on BOD values, the projected images of the CH<sub>4</sub> gas emissions using SD and Chl *a* in Bueng Si Than are depicted in Fig. 3. The maximum SD of 0.38 m was suggested as a limitation criterion for estimating CH<sub>4</sub> emissions from this reservoir. Concurrent results were obtained for the other reservoir, Bueng Kaen Nakhon, with a limitation criterion of a maximum SD of 0.43 m.



**Fig. 3** Estimation of CH<sub>4</sub> gas emissions from Bueng Si Than during the rainy season based on IPCC guideline (2019) (a) SD vs. CH<sub>4</sub> (b) Chl *a* vs. CH<sub>4</sub>

The potential error margins in CH<sub>4</sub> gas emission estimation could arise from the fluctuating addition of organics from sewer discharges, which is generally expected to increase CH<sub>4</sub> emissions in the receiving reservoirs (IPCC, 2019). Conducting multiple sampling points in each sampling was essential to obtain representative organic values for the reservoirs. Nevertheless, the CH<sub>4</sub> gas emission estimates in this study would be more intense if they included the proportion of CH<sub>4</sub> emitted from carbon deposited in sediments. Additionally, the error might arise from daily fluctuations in CH<sub>4</sub> gas emission fluxes in the reservoirs, which introduce additional uncertainties when a single-timepoint sampling approach is employed (Zhang et al., 2025). Furthermore, the sensitivity of CH<sub>4</sub> gas emissions to seasonal variations was reported by Iwata et al. (2020); CH<sub>4</sub> gas emissions from the littoral zone of a shallow mid-latitude lake area showed clear seasonal variations, reflecting temperature variations. Higher CH<sub>4</sub> gas emissions were observed in summer due to higher CH<sub>4</sub> production in the sediment, resulting in a higher dissolved CH<sub>4</sub> concentration in the surface water. Although various approaches to estimating CH<sub>4</sub> flux at the critical air-water interface in previous studies provide theoretical reference and data support for CH<sub>4</sub> gas emissions from eutrophic fresh water sources, the complex gas exchange processes occurring between water bodies and the atmosphere may limit accurate quantification. Currently, the procedure estimates CH<sub>4</sub> emissions based on the amount of organic matter generated (BOD) and an emission factor that indicates how much organic matter produces CH<sub>4</sub> (IPCC, 2019). According to the IPCC guidelines, this document

provides emission factor-based guidance for calculations expressed as mass per area, enabling comparisons of CH<sub>4</sub> gas emissions among reservoirs. (Ion and Ene, 2021). Future directions of the quantification and improvements of CH<sub>4</sub> gas emissions allow direct assessment, such as flux measurement techniques incorporating either process-based models (Zhang et al., 2023) and the alignment with methodology-based IPCC guidelines for better representing overall, global, and regional CH<sub>4</sub> gas emissions from eutrophic reservoirs.

## CONCLUSION

Attempts to estimate CH<sub>4</sub> gas emissions and evaluate eutrophic occurrences in the reservoirs during the rainy season were accomplished based on IPCC guidelines and trophic state indices. Under the current procedure, the main water characteristics of BOD and the trophic state index of TP, Chl *a*, and SD were utilized. The results of the TSI (TP) and the TSI (Chl *a*) of higher than 70 scores indicated the hypertrophic status in the observed reservoirs. Meanwhile, the TKN:TP ratio was suitable for interpreting nutrient limitations in the reservoirs. Finally, under the worst-case scenario, the estimated CH<sub>4</sub> gas emissions of 303.41±25.12 and 1449.23±186.77 kgCH<sub>4</sub>/day were obtained from Bueng Si Than and Bueng Kaen Nakhon. A larger and deeper reservoir (not exceeding 4.0 m depth) with a high supply of nutrients faces high productivity (Chl *a*) and consequently high CH<sub>4</sub> gas emissions. Therefore, the size and depth of artificial reservoirs require careful design considerations to manage eutrophication and methane emissions. The estimation of CH<sub>4</sub> gas emissions in the sediment, combined with the estimated concentration in surface water, is required for future research. Remarkably, the maximum SD in the range of 0.38-0.43 meters was recommended for further assessment of CH<sub>4</sub> gas emissions from eutrophic reservoirs.

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