Environment and Natural Resources Journal
Volume 23
Issue 4
2025

A Comprehensive Carbon Footprint Analysis and Emission Reduction in Wastewater Treatment Plants: A Case Study in Pattaya City

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ARTICLE INFO

Received: 16 Nov 2024
Received in revised: 27 Mar 2025
Accepted: 1 Apr 2025
Published online: 16 May 2025
DOI: 10.32526/ennrj/23/20240303

Keywords:
Carbon footprint/ Greenhouse gas/ GHG emission reduction/ Pattaya City/ Domestic wastewater/ Wastewater treatment plant

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ABSTRACT

This study analyzes the contributions of greenhouse gas (GHG) emissions in the wastewater treatment plants (WWTP) at Pattaya City to the areas of Naklua, Pattaya City, and Jomtien. This analysis was carried out 2021-2023 by visiting the sites, interviewing plant managers, filling out scientifically designed questionnaires and by processing the data obtained using computational methods developed by the Intergovernmental Panel on Climate Change. It was found that the total carbon footprint (CF) from both the Pattaya City and Jomtien WWTPs had the potential to contribute 5,610.61-6,020.18 tCO_2eq/year and that carbon intensity ranged between 0.45-0.47 kg CO_2eq/m^3 in treated wastewater. The study found that the main sources of emissions were the wastewater collection system (34.47-44.61%), activated sludge process (43.02-45.74%), and electricity consumption (30.02-39.48%). Therefore, the study suggests three options for GHG reduction. Installing solar cells on the office building roof could generate 156,780 kWh annually, resulting in a reduction of CO_2 emissions by 108.70 tCO_2eq/year, and a savings of 35,658.52 USD. This is equivalent to a 2.38% reduction in the WWTP's GHG emissions. Installing solar cells in the plant could also generate 823,680 kWh annually, leading to a reduction in GHG emissions of 571.06 tCO_2eq/year, or 12.50%, and a savings of 187,304.58 USD. Installing a WWTP at station PS12 with a capacity of 60,874.65 m^3/day could also reduce the GHG footprint from the wastewater collection system by 1,219.44 tCO_2eq/year, or 36.41%, and result in a savings of 239,091.57 USD. To reach carbon neutrality and energy sustainability, the approaches for resource recovery, nutrient recycling, water reuse, and energy production on-site with combined heat and power (CHP) from biogas should be investigated in the future.

1. INTRODUCTION

As cities develop, the amount of municipal wastewater increases, necessitating the use of wastewater treatment plants to enhance water quality and reduce pollutants before discharging into water sources (Wang et al., 2022). The domestic wastewater system of Pattaya City has centralized wastewater treatment plants (WWTPs) that consist of the central combined sewer, pumping station, and central WWTP. There are two sites. The Pattaya City WWTP is located at Soi Nhong Yai and receives wastewater from the Pattaya and Naklua areas, and the Jomtien WWTP is located at Soi Wat Boon Kanjanaram and receives wastewater from the Jomtien area. The wastewater collection system consists of wastewater interceptors, wastewater delivery pipes, and pumping stations. There are 38 pumping stations located in the Pattaya and Naklua areas, 20 in the Jomtien area and also 15 water drainage pumping stations to prevent flooding. In addition, the system contains 1 water retardation reservoir, water diversion buildings (2 in the Pattaya and Naklua areas and 8 in the Jomtien area), and 4 storm water gates. The sewage pump is an automatic system.

Citation: Phongphalee W, Suwansaard A, Khemkhao M. A comprehensive carbon footprint analysis and emission reduction in wastewater treatment plants: A case study in Pattaya City. Environ. Nat. Resour. J. 2025;23(4):289-298 (https://doi.org/10.32526/ennrj/23/20240303)

Most municipalities implement wastewater treatment plants to reduce harmful wastewater discharge into receiving water bodies (Enger et al., 2000). However, there are many potential sources of greenhouse gas (GHGs) emission from WWTPs during treatment. GHG can be released from WWTPs either directly or indirectly. The direct GHG emissions occur during wastewater and sludge treatment processes (IPCC, 2007), while the indirect GHG emissions occur from the consumption of energy, fuel, and chemicals required for wastewater treatment (Fitzsimons et al., 2016). WWTPs have been reported to be one of the largest minor GHG generators of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Corominas et al., 2012; Yerushalmi et al., 2013; Kyung et al., 2015). These GHGs all contribute to global warming. As stated by Myhre et al. (2013), the global warming potentials (GWP) of CO_2, CH_4, and N_2O account for 1, 34, and 298, respectively, over a 100-year period.

The carbon footprint (CF) is now seen as a way to measure sustainability in the wastewater sector and to measure how WWTPs affect climate change overall (Delre et al., 2019). As a result, reducing the CF has become one of the main topics of discussion in methods of improving WWTP performance (Ødegaard, 2016; Xu et al., 2017). All relevant forms of energy demand, i.e., electricity, heat, chemicals, fossil fuels, and transport, as well as GHG emissions of CO_2, CH_4, and N_2O, are now commonly accounted for in the CF assessment (Maktabifard et al., 2018).

It has been estimated recently that the GHG emissions of the waste sector in Thailand account for 3.74-4.73% of the total GHG emissions in Thailand (Ministry of Natural Resources and Environment, 2021). This sector is therefore one of the targets for reducing emissions in Thailand. In addition, GHG emissions from wastewater treatment and discharge accounted for 45.71% from the waste sector. Because of possible strict regulation by international climate change prevention protocols in the future, WWTPs could soon face the challenge of reducing their GHG emissions and maintaining the required quality of treated wastewater (Shahabadi et al., 2009). Therefore, it is necessary to accurately estimate the carbon footprint or GHG emissions from wastewater treatment plants in Thailand.

In a previous study by Phoolsap (2020), 4 WWTPs managed by the wastewater management authority in Chonburi province were assessed for GHG emissions. However, although Pattaya City is located in Chonburi province, there have been no studies done before on GHG emissions from Pattaya City. Therefore, the main aim of this study is to assess GHG emissions from WWTPs located in Pattaya City and to propose possible methods of reducing these emissions.

2. METHODOLOGY

2.1 Define study site, organizational boundaries, the scope of operations, and data collection

In this paper, the study site of the GHG emissions related to wastewater treatment were Pattaya City and Jomtien WWTPs. Pattaya City and Jomtien WWTPs span 0.128 and 0.021 km^2, respectively, with treatment capacities of 65,000 and 43,000 m^3/day, respectively.

There are three scopes for assessment of GHG emissions. The first scope is the direct GHG emissions, including stationary and mobile combustion, the wastewater treatment process including wastewater inflow rate (m^3/day), the influent and treated effluent concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total Kjeldahl nitrogen (TKN), and fugitive emission. The second scope are indirect GHG emissions from electricity usage. The third scope are other indirect GHG emissions including from chemicals, tap water, lubricants, etc. The boundaries and scopes for the Pattaya City and Jomtien WWTPs are shown in Figure 1.

The data included in this study was based on the daily operation reports of Pattaya City WWTPs and also on the annual operating data for the year 2021-2023 that was collected by visiting the plants, interviewing plant managers, filling out scientifically designed questionnaires using field data and by processing the data using computational methods developed by the Intergovernmental Panel on Climate Change.

2.2 Overall configuration of WTTPs

The studied WWTPs consisted of preliminary, primary, secondary, tertiary, sludge treatments, and wastewater treatment pools that were used to treat wastewater before discharging the treated water into the receiving water body (Figure 2). As shown in Figure 2, the wastewater entered into an inclined screw-type vortex grit chamber which removes sand from the incoming wastewater. After that, the wastewater is passed through a rotary drum screen. In the second step, an activated sludge (AS) system removes organic matter from the wastewater. This AS system consists of two main parts: the aeration tank and the sedimentation tank. The Pattaya City WWTP has a conventional AS, while the Jomtien WWTP has step feed biological nitrogen removal (BNR). In the fourth step, the Jomtien WWTP treated its wastewater with sodium hypochlorite in a chlorine contact tank and then collected it in an effluent pond before discharging it into the receiving water body. On the other hand, the Pattaya City WWTP-treated wastewater underwent filtration using a moving bed sand filter, followed by UV and chlorine disinfection. The treated water from both plants was also used for watering trees, lawns, and washing floors both inside and outside WWTP. The solids and extra sludge from the clarifier tank were then transferred into the storage tank and a cationic polymer was added for flocculation, and a gravity belt thickener was used to remove water from the sludge.

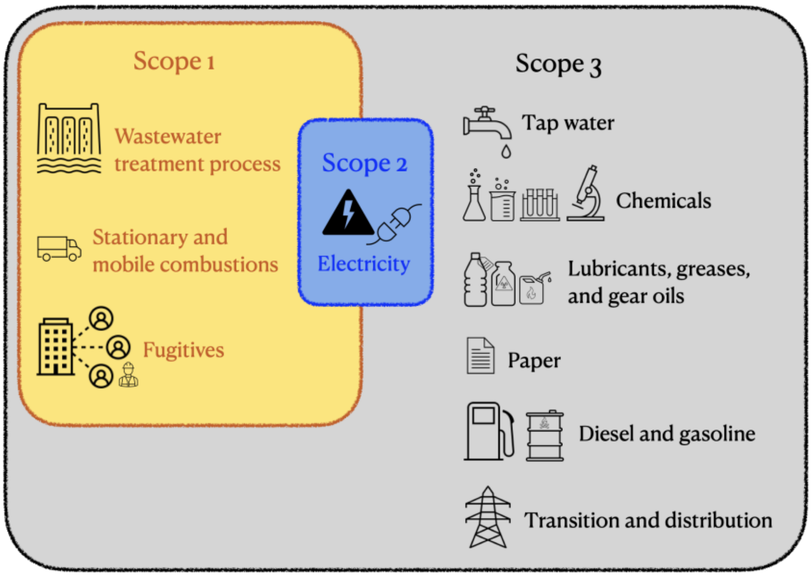


Figure 1. The boundaries and scopes for GHG emission from WWTP

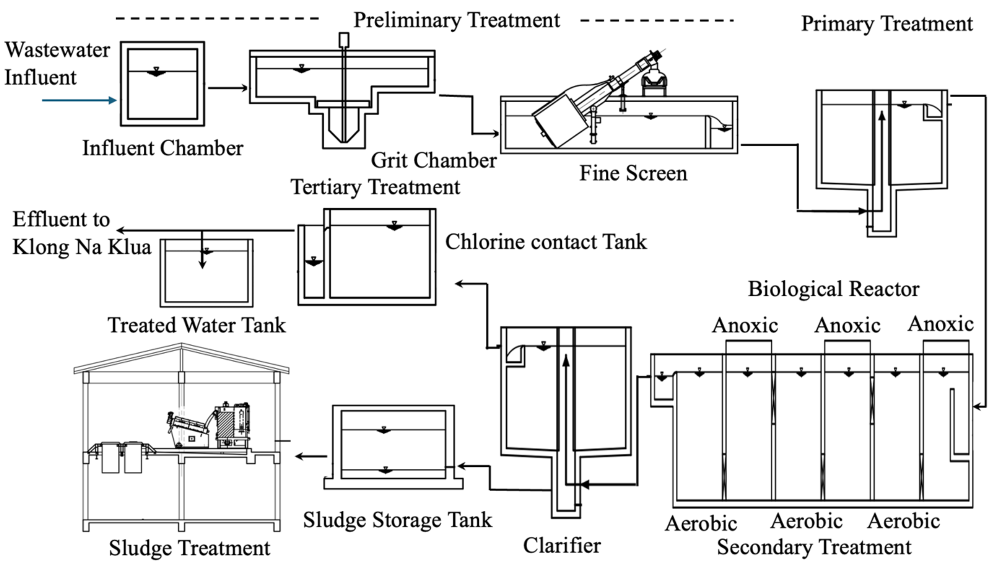


Figure 2. Overall wastewater treatment plant layout

2.3 GHG emission assessment from WWTPs

The GHG emissions of domestic Pattaya City WWTPs were analyzed according to the criteria "Guidelines for assessing an organization's carbon footprint" by the Thailand Greenhouse Gas Management Organization (TGO, 2015) with a level of limited assurance and a level of materiality of 5% (Threshold). The IPCC Vol. 2 for Scope 1 (April 1, 2022), the Thai National LCI Database for Scope 2 (July 2021), and the industry group for Scope 3

(January 1, 2023) were used to provide the emission factor (EF) for the evaluation of GHG emission (Table S1). In this study, the GHG footprint from the wastewater treatment plant was calculated in Equation (1).

$$GHG_i = AD_i \times EF_i \quad (1)$$

Where; GHG_i refers to the GHG emission from activity i ($kgCO_2eq$ or tCO_2eq), AD_i refers to activity data i (kg, m^3, kWh) and EF_i refers to emission factor of activity i ($kgCO_2eq$/unit).

The calculation of the corresponding CO_2eq uses the global warming potential (GWP) of 29.8 kg CO_2eq/kg CH_4 (fossil origin), 27.2 kg CO_2eq/kg CH_4 (non-fossil origin), and 273 kg CO_2eq/kg N_2O, based on a time period of 100 years (IPCC Sixth Assessment (AR6), 2024).

3. RESULTS AND DISCUSSION

3.1 Influent wastewater and properties of wastewater

Figure 3 shows the influent loading of incoming wastewater and its properties before and after treatment. The flow rate of wastewater from Pattaya City WWTP in 2021 increased from 47,083.43 m^3/day up to 57,171.44 m^3/day in 2022 but slightly increased to 58,757.04 m^3/day in 2023 (Figure 3(a)). The increase in population in Pattaya and Naklua was due to fast-growing tourism and hospitality after COVID-19. In contrast, the flow rate of Jomtien WWTP remained relatively constant between 2021 and 2023, ranging from 15,169.19 to 15,561.73 m^3/day. In both regions, these WWTPs were not overloaded since Pattaya City WWTP had a wastewater treatment capacity of 65,000 m^3/day, while Jomtien WWTP had a capacity of 45,000 m^3/day.

Treated wastewater from both sites has been tested and meets Thai national effluent quality criteria for discharge to the receiving water body (Figures 3(b)-3(c)). The removal efficiencies of COD and BOD from Pattaya City WWTP were 65.96±13.28% and 82.62±8.96%, respectively, whereas those from Jomtien WWTP were lower, at 54.78±17.58% and 60.23±16.61%, respectively. However, the TKN removal efficiency from Jomtien WWTP was 89.19±4.98%, slightly higher than that from Pattaya City WWTP, which was 81.92±9.56%. This is attributed to Jomtien WWTP's use of step feed BNR. In addition, the treated effluent was used as water reuse, which can produce 4,800 m^3/day, whereas the treated effluent from the Pattaya City WWTP after disinfection was discharged to Naklua Canal.

Nevertheless, these treated effluents are not proper for reuse in human or food contact applications (Kanchanapiya and Tantisattayakul, 2022). This is because new groups of emerging pollutants, such as per- and polyfluoroalkyl substances (PFAS), persistent organic pollutants (POPs), antibiotics, and pharmaceutical residues (Kunacheva et al., 2011; Schultz et al., 2006; Wang et al., 2022), were not included in the Thai national effluent quality. These pollutants may affect human health and the environment (Kanchanapiya and Tantisattayakul, 2022). In the future, freshwater sources could be in short supply in many areas and therefore these contaminants should be removed if the water is to be reused as a source of drinking water.

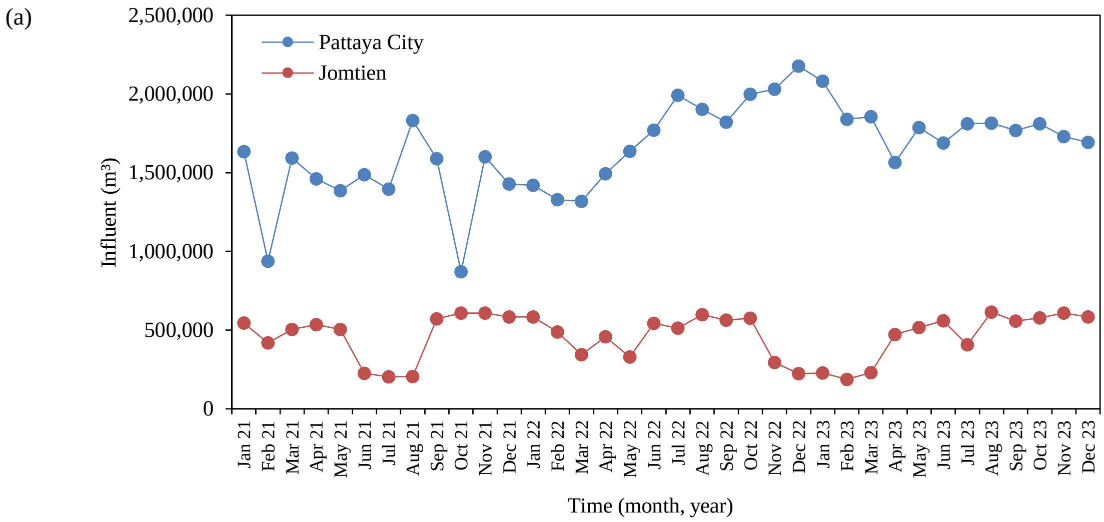
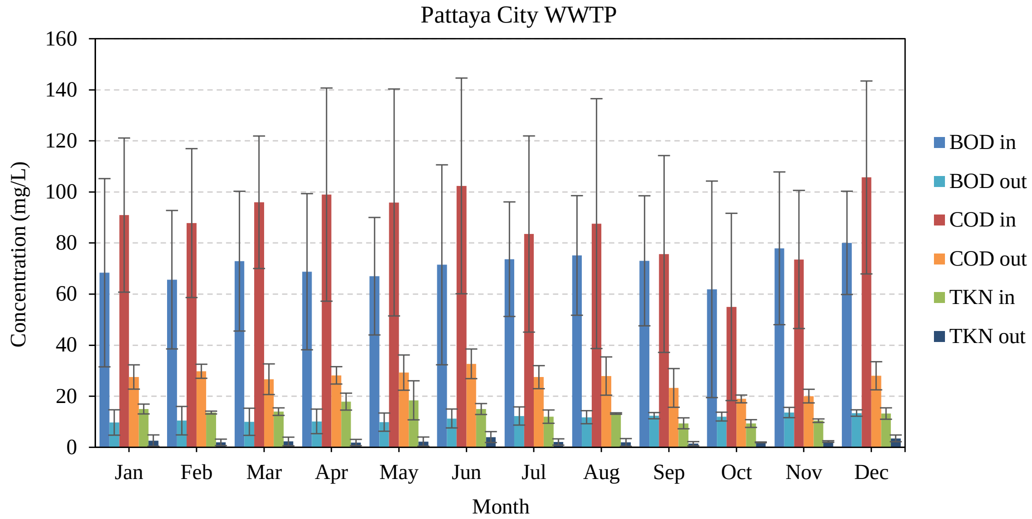


Figure 3. Wastewater loading and the properties of wastewater before and after treatment

(b)



(c)

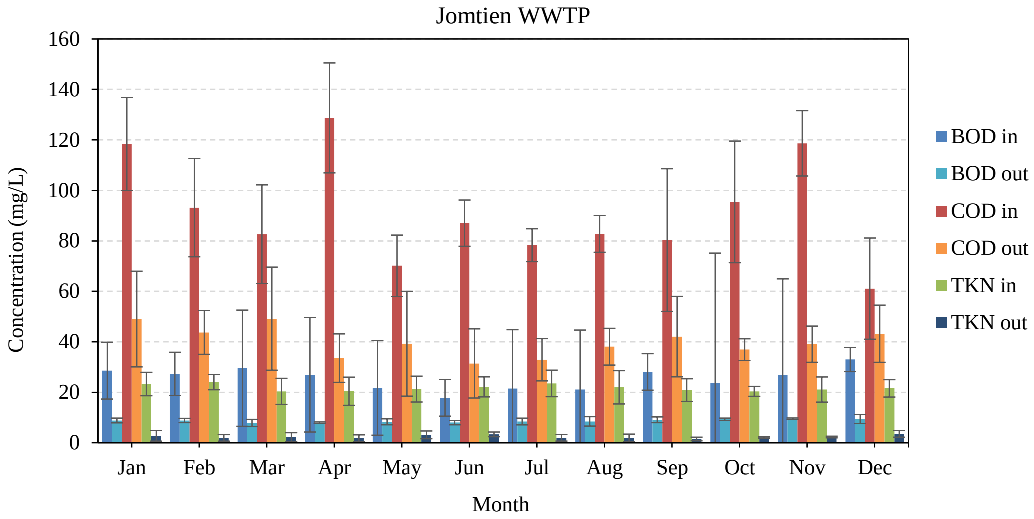


Figure 3. Wastewater loading and the properties of wastewater before and after treatment (cont.)

3.2 GHG footprint and carbon intensity from WWTP

3.2.1 GHG footprint from WWTP

Figure 4 shows the GHG emissions from the wastewater collection system and treatment plant. It was observed that the GHG footprint from Pattaya City WWTP was higher than that from Jomtien WWTP for all activities due to the higher volume of incoming wastewater.

The GHG emission from Pattaya City WWTP was 4,568.45±168.08 tCO_2eq/year, with scopes 1, 2, and 3 accounting for 55.44%, 44.18%, and 0.38%, respectively. The highest GHG emission of scope 1 was due to GHG release from the wastewater treatment process by microorganisms. A high volume of wastewater releases more GHG. The GHG footprint from Pattaya City WWTP was 4.22 times higher than that from Jomtien WWTP due to higher influent wastewater flow rate. This contributes to high energy consumption for the wastewater collection system and the aeration process, as well as for high GHG emissions from the activated sludge process. The Jomtien WWTP recorded GHG emissions of 1,204.92±65.78 tCO_2eq/year, calculated from scopes 1, 2, and 3, accounting for 60.59%, 36.52%, and 2.89%, respectively. The main carbon footprint comes from scopes 1 and 2, which are GHG emissions from wastewater treatment processes and electricity consumption.

The GHG footprints of Pattaya City and Jomtien WWTPs from the wastewater treatment plant were 1.4-2.2 and 3.9-4.5 times, respectively, higher than that of the wastewater collection system. Electricity consumption contributed the largest share of indirect GHG emissions (36.52-44.18%) and GHG emissions from the wastewater collection system (96.10-98.57%).

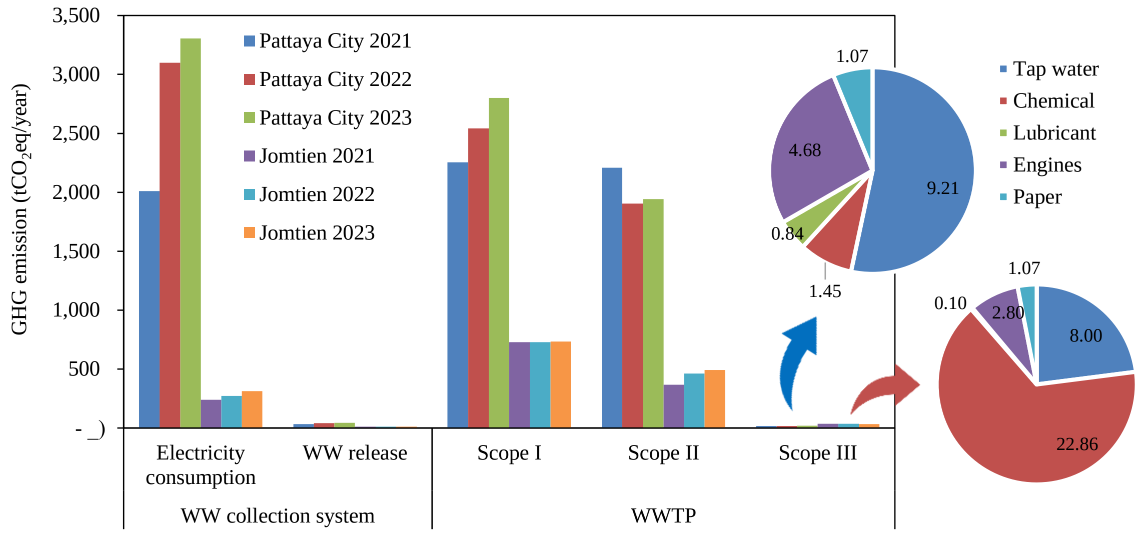


Figure 4. GHG footprint from wastewater collection system and WWTP during 2021-2023

3.2.2 Carbon intensity from WWTP

The GHG emission intensities of Pattaya City and Jomtien WWTPs were 0.237 and 0.218 kg CO_2eq/m^3, respectively (Table 1). In comparing with 4 WWTPs of Chonburi Province, these carbon intensities were 2.9-3.1, 1.2-1.4, and 1.2-1.3 times higher than those of Bangsaray Municipality, Sriracha Town Municipality, and Saen Suk Tai WWTPS, respectively, but were 1.3-1.4 times lower than that of Saen Suk Nuea WWTP (Phoolsap, 2020). The type of wastewater treatment system and the amount of wastewater loading contributed to the different carbon intensities of WWTPs in Chonburi province. That is, Bangsaray Municipality WWTP uses an aerated pond and has a flow rate of only 3,924.92 m^3/day. Meanwhile, Sriracha Town Municipality, Saensuk Tai, and Saensuk Nuea WWTPs use an oxidation ditch and have the flow rates of 9,779, 5,522.45, and 10,353 m^3/day, respectively.

In addition, Pattaya City and Jomtien WWTPs release 8-9 times less GHG than 7 WWTPs in Bangkok (Songpratheep and Jarusutthirak, 2018), 6.9-7.6 times less than a municipal WWTP in Iran (1.65 kg CO_2eq/m^3) (Aghabalaei et al., 2023), but 1.9-2.1 times more than 109 WWTPs in Spain (0.11 kg CO_2eq/m^3) (Maziotis and Molinos-Senante, 2023). It was due to the fact that each type of wastewater treatment system had different operating processes and operations, resulting in different GHG emissions.

Based on COD loading, the GHG emissions from the Pattaya City and Jomtien WWTPs were 2.99±1.39 kg CO_2eq/kg COD and 2.44±0.25 kg CO_2eq/kg COD, respectively. This was about the same as the Leachate WWTP, which had 2.61 kg CO_2eq/kg COD (Chanmit and Khemkhao, 2024).

Table 1. Carbon intensity of domestic WWTP from Thailand

Domestic WWTP	Carbon intensity (kg CO_2eq/m^3)	Reference
Chonburi Province		
Saen Suk Nuea	0.3127	Phoolsap (2020)
Saen Suk Tai	0.1869	
Sriracha Town Municipality	0.1747	
Bangsaray Municipality	0.0754	
Pattaya City, Chonburi	0.237±0.020	This study
Jomtien, Chonburi	0.218±0.011	
Bangkok Metropolitan Administration		
Rattanakosin, Si Phraya, Chong Nonsi, Chatuchak, Din Daeng, Nongkhaem, Thungkru	1.50-2.69	Songpratheep and Jarusutthirak (2018)

The average GHG emissions associated with the electricity consumption of Pattaya City and Jomtien WWTPs were 1.36±0.13 and 1.66±0.17 kg CO_2eq/kWh, respectively, close to China's 1.17 kg CO_2eq/kWh. In contrast, WWTPs in the USA, South Africa, and Germany released less GHG emission per kWh (0.72, 0.99, and 0.68 kg CO_2eq/kWh, respectively) (Wang et al., 2016).

According to data updated on October 31, 2024, the registered population in Pattaya City counts 116,654, and the non-registered population is 4 times higher. In addition, there are 1,000,000 tourists per month. Therefore, for all activities associated with wastewater generation during 2021-2023, the GHG footprint based on people ranged from 0.628-0.770 kg CO_2eq/person equivalent.

3.2.3 Key emission hotspots from WWTP

In Pattaya City, Thailand, there are three key emission hotspots associated with domestic wastewater treatment (Figure 4). The first hotspot is the wastewater collection system, where the pumps consume 30.80-40.75% of Pattaya City's total energy consumption, while Jomtien's WWTPs consume 17.33-19.74%. The second hotspot involves treating wastewater under aerobic conditions, which releases GHG when microorganisms remove BOD (27.58 kg CO_2eq/kg BOD) and TKN (178.27 kg CO_2eq/kg TN) from wastewater.

The aeration system, mixing, pumping, separation, and sludge treatment primarily cause the plant's electricity consumption, which accounts for 44.18% of the GHG footprint in Pattaya City and 60.59% in Jomtien WWTP. Gu et al. (2017) reported that aeration and additional sludge treatment are energy-intensive processes in WWTPs.

However, specific electrical consumption for units of the wastewater process in Pattaya City and Jomtien WWTPs were 0.18±0.03 and 0.13±0.02 kWh/m^3, respectively, lower than that from some other countries. For example, the energy input in a conventional AS system was 0.33-0.60 kWh/m^3 in USA (Wang et al., 2016; Bodik and Kubaska, 2013), 0.46 kWh/m^3 in Australia (Bodik and Kubaska, 2013), 0.40-0.43 kWh/m^3 in Germany (Wang et al., 2016), 0.42 kWh/m^3 in Sweden (Olsson, 2012), 0.52 kWh/m^3 in Switzerland (Hernández-Sancho et al., 2011), 0.53 kWh/m^3 in Spain (Hernández-Sancho et al., 2011), 0.269-0.31 kWh/m^3 in China (Wang et al., 2016; Bodik and Kubaska, 2013), 0.243 kWh/m^3 in Korea (Chae and Kang, 2013), and 0.304-1.89 kWh/m^3 in Japan (Yang et al., 2010; Bodik and Kubaska, 2013). Specific energy demand in WWTPs decreases with increasing inflow. However, the specific energy demand increases as the concentrations of pollutants in the influent, such as COD, BOD5, and nitrogen increase (Gu et al., 2017).

3.2.4 Operational cost

The cost of electricity and tap water usage gradually increased the operational cost of both wastewater treatment plants (Table 2). The operational cost of Pattaya City accounted for 1,386,212-1,864,155 USD/year and was 3.93-4.71 times higher than that of Jomtien WWTP. The operational cost per wastewater volume was 0.007 USD/m^3 for Pattaya City WWTP and 0.006 USD/m^3 for Jomtien WWTP.

Table 2. Operational costs of WWTP during 2021-2023

Details	Pattaya City			Jomtien		
	2021	2022	2023	2021	2022	2023
Operational fees						
- Chemical cost	104,400	104,400	104,400	14,500	14,500	14,500
- Other expenses	457,309	457,309	457,309	202,887	202,887	202,887
Electricity cost						
- Wastewater treatment plant	396,190	377,202	451,249	76,120	98,964	108,865
- Wastewater pumping station	400,897	584,828	833,782	49,483	57,107	62,494
Tap water cost						
- Wastewater treatment plant	13,707	14,374	15,923	9,220	9,206	7,095
- Wastewater pumping station	548	551	1,493	110	90	159
Total (USD/year)	1,386,212	1,538,665	1,864,155	352,320	382,754	395,998

Note: 1 Baht=0.029 USD (November 9th, 2024)

3.3 Options for reducing GHG footprint from WWTP

Implementing energy efficiencies will help reduce energy consumption and lead to a reduction in GHG emissions from energy usage. These include improving process operations and installing energy-saving equipment (Maktabifard et al., 2018). The Pattaya WWTPs have replaced the large aerator with a small aerator and replaced it with a blower instead of a mechanical surface aerator. Automatic aeration control equipment has also been installed for the optimal operation of aeration systems and water pumps.

Based on the GHG footprint in Figure 4, the reduction of the carbon footprint should focus on Pattaya City WWTP. Installing 268 modules of 600-watt solar cells on the office building roof of Pattaya City WWTP could generate approximately 238,582.98 kWh annually. The performance of the solar cells was calculated and analyzed using the performance ratio (PR). The WWTP achieved a PR of 81.3%, resulting in a reduction of CO_2 emissions by 108.70 tCO_2eq/year and a reduction of electricity fees by 2,840 USD/month with a payback period 4.73 years, which is equivalent to a 2.38% reduction in the WWTP's GHG emissions. Installing solar cells on 1,408 modules in the WWTP would generate 1,253,450.15 kWh annually. This led to a reduction in GHG emissions of 571.06 tCO_2eq/year, or 12.50%, and a monthly reduction in electricity fees of 14,920.5 USD with a payback period 4.80 years.

Pattaya City WWTP is situated in elevated areas and necessitates pumps for the transportation of wastewater, leading to significantly elevated electricity expenses (Figure 5). This WWTP comprises 34 pumping stations for combined sewer collection from Pattaya and Naklua areas. In 2023, electricity based on pumping stations consumed 5,523,331 kWh, or 1,493 USD per year. Installing a WWTP at station PS12, which receives a flow rate of 59,679 m^3/day, or 716,148 m^3 of wastewater annually, would reduce the GHG footprint from the wastewater collection system by 1,219.44 tCO_2eq/year, or 35.13%, and can save 239,091.57 USD.

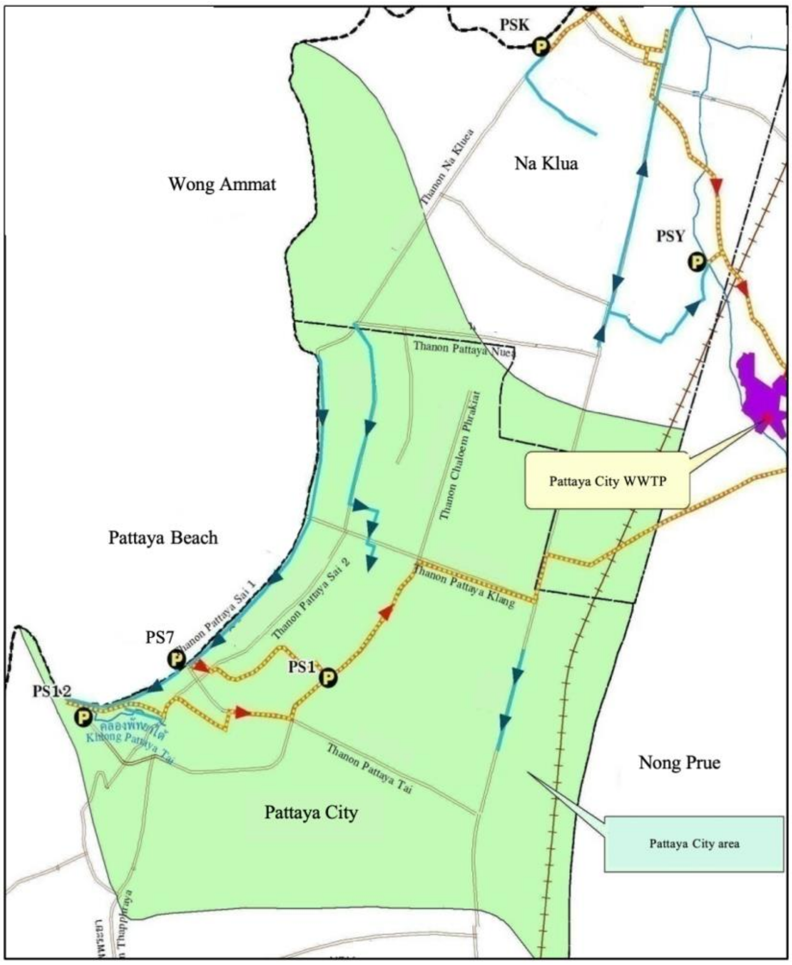


Figure 5. Wastewater collection system for Pattaya City WWTP

4. CONCLUSION

The total CF footprint from both Pattaya City and Jomtien WWTPs was estimated to be 5,610.61-6,020.18 tCO_2eq/year and the carbon intensity ranged between 0.628-0.770 kg CO_2eq/PE, 0.45-0.47 kg CO_2eq/m^3, 4.43-6.99 kg CO_2eq/kg COD, and 2.99-3.06 kg CO_2eq/kWh. The operational cost per wastewater volume was 0.013 USD/m^3. The results revealed the main sources of emissions: the wastewater collection system accounting for 34.47-44.61%, the activated sludge process counting for 43.02-45.74%, and electricity consumption counting for 30.02-39.48%. Optimal costs and GHG emissions from operating WWTPs depend on the quantity of BOD, TKN, and SS removed from wastewater. Therefore, different methods for reducing operational costs and GHG emissions should be defined by the regulator for WWTPs.

This study suggested three options for GHG reduction.

1. Installing solar cells on the office building roof produced electricity of 238,582.25 kWh/year, which could reduce GHG emissions by 108.70 tCO_2eq/year (a 2.38% reduction from total GHG emissions in WWTP) and save 32,825.73 USD.

2. Installing solar cells in the plant would generate 1,253,450.15 kWh annually, resulting in a reduction in GHG emissions of 571.06 tCO_2eq/year, or 12.50%, and a saving of 170,095.12 USD.

3. Installing a WWTP at station PS12 with a capacity of 59,679 m^3/day would reduce the GHG footprint from the wastewater collection system by 1,219.44 tCO_2eq/year, or 36.41%, and result in a savings of 239,091.57 USD.

The WWTP should maintain a balance of effluent quality, energy efficiency, and GHG emissions. Therefore, if the municipal wastewater treatment plants have a goal for carbon neutrality and energy sustainability, the approaches for resource recovery, nutrient recycling, water reuse, and energy production on site with combined heat and power (CHP) from biogas should be investigated in the future.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Kiatsak Sriwongchai, Deputy Permanent Secretary of Pattaya City, Acting Permanent Secretary of Pattaya City; Mr.Nattapong Santaveesuk, Director of Prevention and Drainage Management System Division; and the staff of the Pattaya City and Jomtien WWTPs, Pattaya City, for sharing the routine operational data during 2021-2023. Special thanks to Dr. Elvin J. Moore, Foreign Lecturer, Department of Mathematics, King Mongkut's University of Bangkok for checking English grammar.

AUTHOR CONTRIBUTION

Conceptualization, W.P., A.P. and M.K.; Methodology, W.P.; Software, W.P. and M.K.; Validation, W.P., A.P. and M.K.; Formal Analysis, W.P. and M.K.; Investigation, W.P. and M.K.; Resources, W.P.; Data Curation, W.P. and M.K.; Writing - Original Draft Preparation, W.P. and M.K.; Writing - Review and Editing, A.P. and M.K; Visualization, W.P. and M.K.; Supervision, A.P. and M.K.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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