ENVIRONMENTAL ENGINEERING
ASSOCIATION OF THAILAND

THAI ENVIRONMENTAL ENGINEERING JOURNAL

Vol. 37 No. 2 May – August 2023
ISSN (PRINT) : 1686 - 2961
ISSN (ONLINE) : 2673 - 0359

Thai Environmental Engineering Journal

Owner
Environmental Engineering Association of Thailand

Thai Environmental Engineering Journal

Vol. 37 No. 2 May – August 2023

ISSN (PRINT) : 1686 - 2961
ISSN (ONLINE) : 2673 - 0359

Thai Environmental Engineering Journal Vol. 37 No. 2 (2023) : 1-10
www.eeat.or.th

From Waste to Resource: An Economic Analysis of Landfill Mining for Refuse-Derived Fuel Production in Five Thai Landfills

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Abstract

Using the data from a prior investigation into the amount and quality of refuse-derived fuel extracted from five landfills, this study aimed to assess the economic viability of landfill mining across all landfills. The cost-benefit analysis involves the assessment of net present value, benefit-cost ratio, and economic internal rate of return to identify cost-effectiveness. The cost-benefit analysis results were related to the amount of refuse-derived fuel fractions in scenarios of processing both new and old waste. Nonthaburi active landfill site has the highest net present value (NPV) and benefit cost ratio (B/C ratio) which are 379,174,807.37 THB and 2.04, respectively. Followed by Nakhon Sawan active site which has NPV and B/C ratio of 187,649,865.46 THB and 2.12, respectively. In contrast, in the combined scenario (new and old waste), we found that, in addition to refuse-derived fuel quantity, refuse-derived fuel quality (in terms of calorific value) has an important effect on net present value; for example, soil cover and land recovery were essential benefits. The vital cost factors for old and new waste were refuse-derived fuel transportation and operating costs. Moreover, the refuse-derived fuel fraction was the primary factor influencing investment decisions. refuse-derived fuel price and transportation costs were the next-most significant factors in the absence of government support. The waste-separation process for mined waste should be improved in Thai landfills to increase refuse-derived fuel quantity. In addition, government policies are needed to secure landfill mining funding for projects that require additional support.

Keywords : Cost-Benefit Analysis; Waste Management; Refuse-Derived Fuel (RDF); Waste to Energy; Alternative Fuel

Introduction

Population and economic expansion in low-middle-income countries influence poverty and energy demand and increase waste generation [1]. The concept of the circular economy has been implemented in various nations to promote the efficient utilization of resources, safeguard the environment, boost economic growth, and shape policy [2, 3]. Two persistent issues are the escalation of waste generation and the application of waste reduction, reuse, recycling, and recovery strategies per the waste hierarchy [1, 3, 4]. Another aspect that aligns with the circular economy concept is the practice of energy recovery from waste through landfill mining. This approach complements other waste management strategies such as waste-to-energy, waste-to-land, and waste-to-materials approaches [5-8].

Thailand uses three main waste disposal methods: composting, combustion, and disposal on land. Waste disposal on land is the primary practice in Thailand and includes open dumping and landfill disposal [9]. Organic waste is degraded with aerobic degradation for open dumping and anaerobic degradation for landfilling. These two reactions influence the spatial variation of biodegradation at disposal sites. In addition, combustible and incombustible waste is mixed in disposal sites, making it difficult to correctly specify where landfill mining should take place. However, mined waste will be separated using machines. The quantity of combustible waste that is available for use as refuse-derived fuel (RDF) is impacted by the efficiency of the machinery and the amount of rejected materials, including soil-like materials unsuitable for RDF [10]. In addition to waste quantity, the heating value and moisture content of waste play a crucial role in determining the price of RDF. These factors are affected by the amount of time since the waste was disposed of since the share of RDF derived and its heating value increase with time. Biodegradation of organic waste produces leachate and influences organic fraction reduction. Over time, the leachate collection system decreases the amount of leachate, resulting in increased fractions of RDF, reduced moisture content, and increased heating value [11-14]. As a result, in the past, businesses in landfill mining usually processed waste in closed landfills with old waste [15, 16]. More recently, geophysical technologies and invasive methods have been applied to investigate disposed waste to evaluate the potential of RDF production in final disposal sites [17-20].

Because of the high investment required and the low price of RDF, landfill mining has not been economically viable, making it an unpopular business in developing countries [21]. The main investment costs for RDF production are related to the mining process, separation machinery, and transportation [22]. In addition to assessing the feasibility of landfill mining businesses, numerous studies have utilized cost-benefit analysis (CBA) to determine the investment required for landfill mining businesses. This analysis often incorporates metrics such as net present value (NPV), benefit-to-cost (B/C) ratio, and the economic internal rate of return (EIRR), all of which are contingent on the project period [21, 23, 8, 24]. In Thailand, landfill mining has been an unpopular option for some projects due to high investment costs, occasional low RDF prices, and high transportation expenses – this is especially the case if the project is located far from cement plants [25]. Previous studies have analyzed the quantity and quality of RDF in Thailand [17, 19, 20, 26]. However, there has, to date, been no CBA analysis of Thai landfill mining. This study's objective is to assess the economic value of the landfill mining business using geophysical and photogrammetry technologies to ascertain the quantity and quality of RDF at each study site. Additionally, the study offers practical guidelines for the landfill mining business based on realistic analysis.

Materials and Methods

This research evaluates the economic feasibility of the landfill mining business using data on RDF quantity obtained from the National Research Council of Thailand (2021). The five sites studied are the Nonthaburi, Nakhon Sawan, Chanthaburi, Buriram, and Yasothon landfills. A previous study collected aerial image data using unmanned aerial vehicles and produced photogrammetric maps using the Agisoft

PhotoScan Ver 1.4.4 (Agisoft, Russia), including a digital elevation model (DEM). The DEM was used to evaluate waste volume. Electrical resistivity tomography (ERT) was applied to estimate the quantity of RDF in the landfill by correlating the resistivity values with the RDF fractions. The ERT data was collected by conducting two to four ERT survey lines per area, with an electrode spacing of 2–3 meters, and employing the Schlumberger array [17, 18]. The correlation between RDF fractions and resistivity values using linear regression analysis with soil-cover criteria are shown in equations (1) for Nakhon Sawan old waste, Buriram old and new waste, and Yasothon old waste and (2) for Nonthaburi, Nakhon Sawan new waste, Chanthaburi, and Yasothon new waste [27]. Based on the waste density of 1.19 ton per m^3.

$$\% RDF = 0.0631RS + 48.866 \qquad (1)$$
$$\% RDF = 0.1917RS + 41.753, \qquad (2)$$

where %RDF is the percentage of RDF in landfill obtained from the resistivity survey, consisting of plastic bags, high-density plastics, foam, leather, rubber, and textiles, and RS is the resistivity value in ohm-m.

Based on the above equation, the weight percentage of RDF fractions ranges from approximately 52.42% to 64.70% for old waste and 46.75% to 53.62% for new waste. As already noted, the waste extracted through mining was blended with incombustible waste and soil-like materials. Muttarid et al. [10] estimate the efficiency of the separation machine used to sort RDF fractions as ranging from 51.66% to 56.89% by weight. Therefore, this study assumed a conservative estimate of 50% by weight for RDF fractions following the separation process. Table 1 displays the quantity of extracted waste, the RDF fractions, and their corresponding percentages.

CBA analysis was conducted to assess the potential for RDF production from landfills under three different scenarios: closed (i.e., old waste which waste age more than five years), still operating (i.e., new waste which waste age less than five years), and combined (i.e., old and new waste); the analysis included the costs of investment, operations, and maintenance. The direct and indirect benefits of RDF production were measured through NPV, B/C ratio, and EIRR, using a discount rate of 10% per year. It was also necessary to take into account the transportation of RDF from landfills to a cement kiln located in the Kaeng Khoi district of Saraburi province. The CBA is presented below.

Table 1 The amount of mined waste, RDF fractions, and percentage of RDF fractions

Landfill (nomenclature)	The amount of mined waste (ton)	RDF fractions (ton)	Percentage of RDF fractions (%by weight)
Nanthaburi inactive (NI)	204,164	53,511	26.21%
Nonthaburi active (NA)	1,451,491	367,590	25.33%
Nakhon Sawan inactive (NSI)	81,408	21,838	26.83%
Nakhon Sawan active (NSA)	618,123	144,486	23.38%
Chanthaburi inactive (CI)	531,899	157,123	29.54%
Chanthaburi active (CA)	142,453	34,730	24.38%
Burirum inactive (BI)	225,835	59,214	26.22%
Burirum active (BA)	320,234	85,855	26.81%
Yasothon inactive (YI)	180,767	58,478	32.35%
Yasothon active (YA)	110,190	28,462	25.83%

Cost-benefit analysis

1. Cost analysis

The financial costs of RDF production consist of investment, RDF transportation, electricity, and maintenance costs. The cost of equipment, construction, transportation, and electricity is adjusted to economic cost using conversion factors of 0.84, 0.88, 0.87, and 0.90, respectively [28].

2. Benefit analysis

The direct benefit of mining old waste is the proceeds of the sale of RDF, which amounts to 99,200 tons per year. This estimate is based on a productivity rate of 40 tons per hour, 8 hours of work per day, and 310 working days per year. The price of RDF is determined by its heating value, estimated at 0.2 THB per mega-calorie. The heating value used in this study was obtained from the National Research Council of Thailand (2021). Table 2 sets out the costs of transportation from the landfill to the cement kiln. The indirect benefits consist of a reduction of approximately 30% in the volume of soil-cover material, which has a density of 300 kg per m^3 and a value of 280 THB per m^3 [17, 29-31]. Additionally, land recovery is expected to reach 99,200 tons per year, with a disposal fee of 250 THB per ton. In the case of new waste, the direct benefits are derived from the sale of RDF and the disposal fee. The indirect benefit comes from the reduction of soil-cover materials.

Cost-Benefit analysis

In the CBA we compared costs and benefits over the project period to determine its feasibility and era. The future values of costs and benefits were converted into the present value with an annual discount rate of 10%. The feasibility and merit of the project were calculated as set out below.

1. NPV was used to determine the project's profitability at a defined discount rate; an NPV exceeding zero is an indicator of economic feasibility and is calculated using equation (3).

$$NPV = \sum_{t=0}^{n} \left(\frac{B_t - C_t}{\left(1+r\right)^t} \right), \tag{3}$$

where B_t is the benefit at year t, C_t is the cost value at year t, r is the discount rate, and t is project time measured in years from 0 to n.

2. B/C ratio was used to identify the cost management efficiency of the project at a defined discount rate. A B/C ratio greater than 1 indicates that the project is economically feasible and can be calculated using equation (4).

$$B/C = \frac{PVB}{PVC}, \tag{4}$$

where PVB is the present value benefit, and PVC is the present value cost.

3. EIRR is representative of the actual rate of return. If the EIRR is greater than the opportunity cost, the project is economically optimal, as demonstrated in equation (5).

$$NPV = \frac{\sum_{t=0}^{n} \left(B_t - C_t\right)}{\left(1+EIRR\right)^t} = 0 \tag{5}$$

Table 2 Transportation cost, heating value, and RDF price

Landfill	Transportation cost (THB/ton)	Heating value (kcal/kg)		RDF price (THB/ton)	
		New waste	Old waste	New waste	Old waste
Nonthaburi	380.87	2991.00	2628.00	598.20	525.60
Nakhon Sawan	375.65	4154.00	2011.00	830.80	402.20
Buriram	495.65	2845.00	2842.00	569.00	568.40
Yasothon	580.16	2606.00	2850.00	521.20	570.00
Chanthaburi	425.22	2557.00	2730.00	511.40	546.00

4. Sensitivity analysis was conducted to evaluate the impact on the project of unexpected changes. In the first four scenarios, the benefits were reduced by 10%, 20%, 30%, and 40%, and in the remaining four scenarios the costs were increased by 5%, 10%, 15%, and 20% while keeping other factors constant.

Results and Discussion

Cost-benefit analysis

The study results indicate that most of the landfills studied are economically suitable for waste mining, except for NSI and YA (see nomenclature in Table 1). This can be attributed to the two areas having the least amount of mined waste. In the case of combined operations, all sites are economically optimum, as shown in Figure 1(a). Of the sites, NA has the highest NPV of 379,174,807.37 THB and a B/C ratio of 2.04, followed by NSA with an NPV of 187,649,865.46 THB and a B/C ratio of 2.12. This is explained by the fact that the two areas have the highest RDF fractions. Additionally, NSA has the highest heating value, resulting in the highest RDF price. Figure 1(b) shows that NSA has a higher B/C ratio than NA due to the higher RDF price. In some cases, the EIRR could not be evaluated, as the net benefit of each year did not meet the criteria of having one negative and one positive value.

Comprehensive analysis of cost and benefit value

The costs and benefits of the most economically impactful factors were assessed. The study found that old waste was sensitive to soil-cover material reduction and land recovery, which were related to RDF fractions, in agreement with Zhou et al. (2015). Greater RDF recovery resulted in the recovery of soil-cover materials (waste-to-material) and land, leading to a higher B/C ratio, as shown in Figure 1(b). Transportation costs were sensitive to investment and operational costs, with the amount of RDF transported having a significant impact. The distance between the landfill and the cement plant was also a relevant factor, as evidenced by the high transportation costs recorded for the Yasothon landfill.

New waste was found to be sensitive to the soil-cover material reduction price and land recovery; this result is similar to that for old waste. In addition, the benefits attached to mining new waste were sensitive to operational costs since its heating value was lower than that of old waste, resulting in a lower RDF price. However, the operating costs were equivalent. This implies that for RDF production to be feasible in the case of new waste, separation and production processes should be improved to minimize costs, and waste treatment methods advanced to enhance biodegradation.

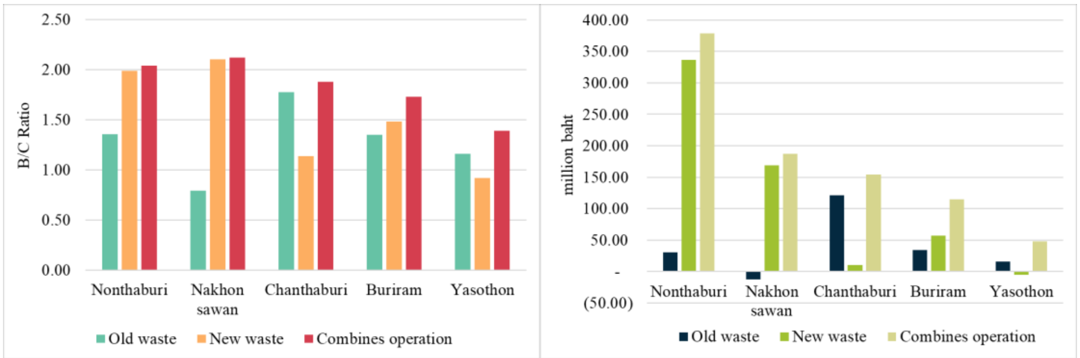

Figure 1 (a) NPV and (b) B/C ratio results for five sites

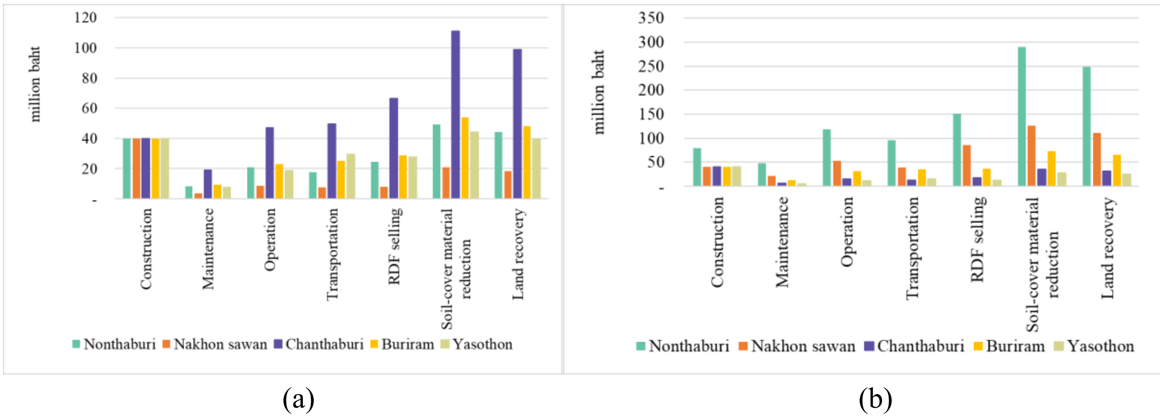

Figure 2 Sharing of investment and operating costs (maintenance, operations and transportation) and benefits (RDF selling, soil-cover recovery, and land recovery) of (a) old waste and (b) new waste

Sensitivity analysis

The results of the sensitivity analysis are presented in Table 3. This analysis is an evaluation of the project's cost-benefit position under unexpected conditions. The variables included operations, maintenance, and transportation costs, and the benefits were captured by the RDF selling price, soil-cover reduction, and land recovery. The analysis found that CI was economically feasible with a decrease in benefits, whereas CI and YI were not suitable with a decrease in benefits of more than 10% and 20%, respectively. NSI and CI were not suitable sites when benefits decreased by more than 30%. Regarding new waste, NA and NSA were suitable, while YA, CA, and BA were not suitable when benefits decreased by more than 10%, 20%, and 40%, respectively. When the costs were increased, most of the landfills were suitable, except for NSI and YA. In the case of combined operations, all landfills were suitable. This suggests that the RDF produced negatively correlates with the B/C ratio. Therefore, a decrease in RDF would be more impacted by increased costs and decreased benefits rather than changing transportation cost and RDF price.

Investment cost analysis

Figure 3 represents an investment cost in the case of private investment. Six scenarios were identified: without government support (scenario 1), with government support of the RDF price at 50 (scenario 2), 100 (scenario 3), 150 (scenario 4), 200 (scenario 5), and 250 (scenario 6) THB per ton, under the condition of a discount rate of 10%, and only in respect of direct benefits (the RDF selling price). The results show that mining these five landfills was not economically feasible without government support. Three sites, Nakhon Sawan, Nonthaburi, and Chanthaburi, would have been suitable sites with government support for RDF selling prices above 50, 100, and 200 THB per ton, respectively; Buriram and Yasothon landfills required government support of more than 250 THB per ton to be suitable. As noted in Table 1, the amount of waste mined was highest for Nonthaburi, followed by Nakhon Sawan, Chanthaburi, Buriram, and Yasothon, respectively. The RDF fractions of Nonthaburi were the highest, followed by Chanthaburi, Nakhon Sawan, Buriram, and Yasothon, respectively. As shown in Figure 3, the amount of waste at the Nakhon Sawan landfill was relatively high and had the highest RDF price, resulting in a high and increasing NPV. The RDF fraction of the Nakhon 7 landfill was lower than that of Chanthaburi but required less RDF price support because of relatively low transportation cost. In addition, Buriram and Yasothon landfills had very little RDF fraction and had high transportation costs influenced by higher levels of government support. The payback period with only construction costs included was the longest for Buriram, followed by Nonthaburi, Chanthaburi, Yasothon, and Nakhon Sawan. The construction cost of Nonthaburi was twice that of other landfills, and with the highest RDF fractions had a shorter payback period. While the Burirum landfill had very little RDF fraction and a relatively high transportation cost. Moreover, Nakhon Sawan had the lowest payback period due to a relatively high RDF fraction, the highest RDF price, and the lowest transportation cost. The payback period, including construction, investment, and maintenance costs, was positively correlated with the RDF fraction; the exception was the Burirum landfill, which had a lower RDF fraction than Nakhon Sawan but a higher payback period due to lower costs and higher benefit values.

Table 3 Sensitivity analysis

Landfill		Nonthaburi		Nakhon Sawan		Chanthaburi		Buriram		Yasothon	
Sensitivity analysis		NPV (million THB)	B/C ratio	NPV (million THB)	B/C ratio	NPV (million THB)	B/C ratio	NPV (million THB)	B/C ratio	NPV (million THB)	B/C ratio
Decreased benefit											
10%	O	19.10	1.22	−17.28	0.71	93.24	1.60	20.77	1.21	4.44	1.05
	N	268.87	1.79	136.48	1.89	1.79	1.02	39.58	1.33	−21.29	0.71
	O+N	327.42	1.90	162.04	1.97	123.81	1.71	93.33	1.59	8.90	1.07
20%	O	7.31	1.08	−22.00	0.63	65.58	1.42	7.67	1.08	−6.70	0.93
	N	201.05	1.59	104.34	1.68	−6.63	0.91	22.02	1.19	−27.20	0.63
	O+N	275.67	1.75	136.44	1.82	93.24	1.53	71.97	1.46	−4.81	0.96
30%	O	−4.47	0.95	−26.72	0.55	37.92	1.24	−5.43	0.94	−17.84	0.81
	N	133.24	1.39	72.20	1.47	−15.05	0.80	4.47	1.04	−33.12	0.56
	O+N	223.91	1.61	110.83	1.66	62.67	1.36	50.60	1.32	−18.53	0.86
40%	O	−16.26	0.81	−31.44	0.47	10.26	1.07	−18.52	0.81	−28.97	0.70
	N	65.42	1.19	40.06	1.26	−23.47	0.68	−13.09	0.89	−39.03	0.48
	O+N	172.16	1.47	85.22	1.51	32.09	1.18	29.24	1.19	−32.24	0.75
Increased cost											
5%	O	28.54	1.26	−13.55	0.78	115.11	1.71	31.01	1.31	12.78	1.13
	N	323.62	1.91	162.98	2.03	8.51	1.11	53.22	1.43	−17.10	0.78
	O+N	364.92	1.96	181.29	2.04	147.61	1.81	108.85	1.67	18.11	1.13
10%	O	26.19	1.17	−14.53	0.76	109.33	1.65	28.16	1.27	9.99	1.10
	N	310.54	1.84	157.35	1.96	6.81	1.09	49.29	1.39	−18.82	0.76
	O+N	350.66	1.89	174.93	1.97	140.84	1.74	103.00	1.61	13.60	1.10
15%	O	23.84	1.09	−15.52	0.75	103.54	1.60	25.30	1.24	7.20	1.07
	N	297.47	1.78	151.71	1.89	5.11	1.06	45.37	1.35	−20.55	0.74
	O+N	336.40	1.82	168.57	1.90	134.06	1.68	97.15	1.56	9.09	1.06
20%	O	21.49	1.02	−16.51	0.74	97.76	1.55	22.45	1.21	4.42	1.04
	N	284.39	1.72	146.07	1.83	3.41	1.04	41.45	1.31	−22.28	0.73
	O+N	322.15	1.76	162.21	1.84	127.29	1.63	91.30	1.51	4.58	1.03

Note: N: New waste, O: Old waste, and O+N: Old and new waste

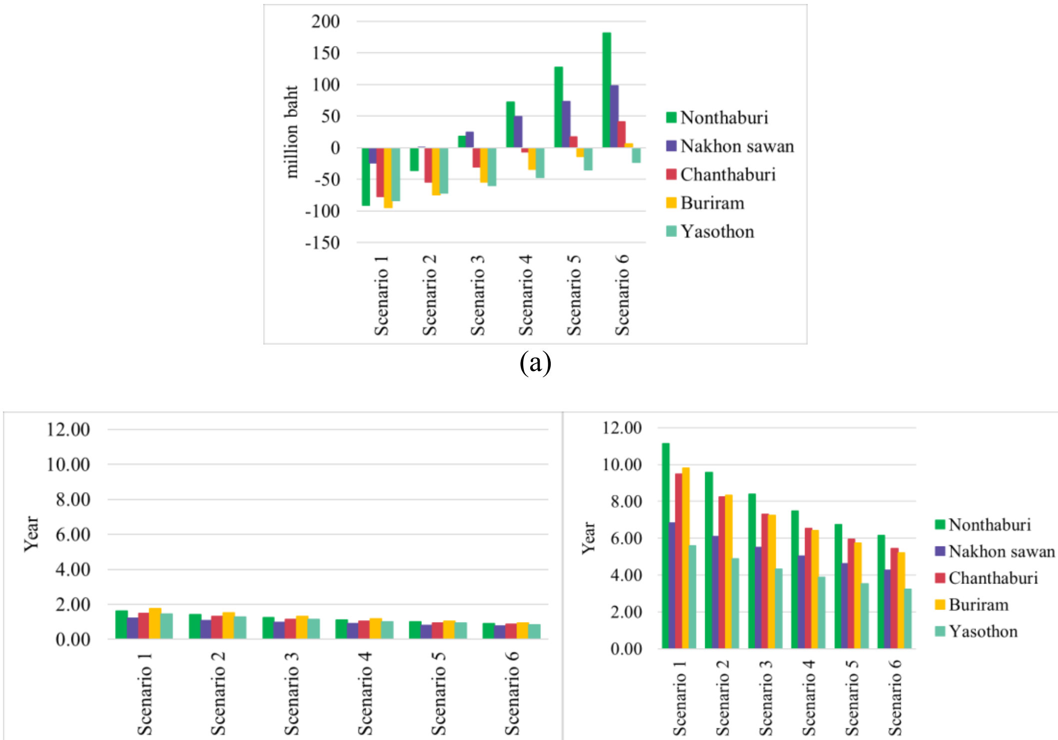

Figure 3 Private sector investment cost by (a) NPV, (b) payback period with only construction costs, (c) payback period with operations and maintenance costs

Conclusion

The CBA of the landfill mining business, based on the old and new waste criteria, revealed that the results of the CBA for the landfill mining business for old and new waste were based on the amount of RDF fractions. When the amount of RDF fraction is very low, as observed in NSI and YA, it results in a lack of economic viability. In cases where there is a combined operation, the quality of RDF in terms of heating value and the quantity of RDF fraction impacts economic value. The analysis of factors impacting NPV showed that it was affected by the amount of waste mined and the RDF fraction. The benefits related to soil cover and land recovery, while the costs were RDF transportation and operating costs for old and new waste, respectively. This is because the RDF quality is better for old waste than for new waste, resulting in a higher RDF price, while the operating costs are the same. The analysis of investing in the landfill mining business shows that the amount of RDF fraction is the primary factor in the decision to invest in the business, followed by RDF price and transportation cost, in the absence of government support. This suggests that the development of landfill mining businesses in Thailand should focus on improving the waste treatment process to enhance RDF from new waste to match that of old waste, for example, by using biodry processes or thin-layer landfills. Additionally, policies should encourage the use of RDF in the energy sector to reduce transportation costs by sending RDF to closed RDF power plants or cement plants. Furthermore, RDF production processes should be developed to improve mining and separation efficiency and reduce government support in cases of minimal waste.

Acknowledgments

The research team is sincerely grateful for financial support from the National Research Council of Thailand (NRCT), the Joint Graduate School of Energy and

Environment (JGSEE), the King Mongkut's University of Technology Thonburi (KMUTT) and the Center of Excellence on Energy Technology and Environment(CEE), Ministry of Higher Education, Science, Research and Innovation. The researcher team thank the Department of Earth Science, Faculty of Science, Kasetsart University and Faculty of Physical Education, Srinakharinwirot University, for supporting our instrument and economic analysis.

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Thai Environmental Engineering Journal Vol. 37 No. 2 (2023) : 11-22
www.eeat.or.th

Assessment on Health and Ecosystem Impacts and Costs of Ozone Formation from Passenger Transport in Bangkok Metropolitan Region

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Abstract

Using life cycle assessment framework, this research aimed to estimate and compare the emission inventories, health and ecosystem impacts, and costs of ozone formation from passenger road, rail, and water transport in the Bangkok Metropolitan Region (BMR) in 2022 and in 2027. The study considered passenger cars, public buses, and motorcycles in the road transport; electric trains and rail cars in the public rail transport; and cross river ferries, Chao Phraya boats and Saen Saep canal boats in the public water transport. The ReCiPe 2016 method and Thai Spatially Differentiated Life Cycle Impact Assessment (ThaiSD) method were applied in the impact assessment taking into account health and ecosystem impacts from two ozone precursors - NO_x and NMVOCs. Thai-specific factors were applied for assessing impacts from exhaust emissions in Thailand, while global average factors were applied for assessing impacts from the energy production. In 2022, total NO_x emissions, NMVOCs emissions, health impacts, ecosystem impacts and costs from the passenger transport in BMR were 5.05E+04 tonnes, 2.61E+04 tonnes, 1.21E+03 DALY, 4.95E+00 species·yr and 1.94E+03 million Baht, respectively. In 2027, total NO_x emissions, NMVOCs emissions, health impacts, ecosystem impacts and costs from the passenger transport in BMR will be 5.37E+04 tonnes, 2.91E+04 tonnes, 1.40E+03 DALY, 5.42E+00 species·yr and 2.32E+03 million Baht, respectively. The scenario analysis on the modal shifts from the business-as-usual situations of BMR in 2022 and 2027 to the public transport systems (buses, electric trains and water transport) was performed. Although the modal shifts to the public buses increased NOx emission, they could reduce NMVOCs emissions, health impacts, ecosystem impacts and costs. The modal shifts to the electric trains helped reduce NO_x emissions, NMVOCs emissions, health impacts, ecosystem impacts and costs. The modal shifts to the water transport resulted in increasing the emissions, impacts and costs. This study suggests the promotion of public buses and electric trains and addresses the need to improve public water transport with low emission technologies in the future.

Keywords : Ozone formation; health impact; ecosystem impacts; public transport; modal shift; life cycle assessment

Introduction

The effects of ozone on ecosystem includes the loss of species diversity, the alterations in the habitat quality of plants and animals, and the alterations in the water and nutrient cycles [1]. Since the industrial revolution, ozone has caused the reduction in the tree photosynthesis (11%) and the tree productivity (7%) [2]. In addition, ozone has adverse health effects. In 2019, the long-term ozone exposure caused an estimated 365,000 deaths; globally 1 out of every 9 deaths were from Chronic Obstructive Pulmonary Disease (COPD) [3]. Ozone has been linked to COPD for children, particularly those under the age of 5. It increases their vulnerability to lower respiratory tract infections, which accounted for 28% and 17% of air pollution-related mortality in Thailand in 2019 [3]. According to the 2019 report on air pollution and noise issues in Thailand, the ozone concentrations of Bangkok Metropolitan Region (BMR) exceeded the 1-hour ambient air quality standard from 2009 to 2019 [4]. The photochemical reaction between volatile organic compounds (VOCs) and nitrogen oxides (NO_x) produces ozone [5]. Additionally, 77% of NMVOCs emissions and 78% of NO_x emissions in BMR are attributed to road transport [6]. The Ministry of Transport (MOT) is now attempting to improve public transport, particularly in BMR, by reducing traffic congestion and minimizing transport-related pollution by modal shifting from private automobiles to public transit and modifying the modes of transport [7].

Life cycle assessment (LCA) is a tool for determining which of the compared alternative products has the lowest environmental impacts [8], as information for policymakers to determine the project priorities and budget allocations. In this investigation, LCA framework has been used as a health impact and ecosystem impact assessment tool. There are many studies related to the health impact and cost of $PM_{2.5}$ emissions from road, rail, and water transport in BMR [9-10]. However, data related to the health and ecosystem impacts and the cost of ozone formation is lacking. In this study, we develop and analyze the emission inventory of ozone formation from road, rail, and water transport. We also estimate and compare the health impacts, ecosystem impacts and costs of ozone formation originating from road, rail, and water transport to saturate the air pollution content in Thailand. The effectiveness of public transport management of BMR in mitigating the impacts and costs of ozone formation on human health and ecosystems as the result of modal shift in transportation were also assessed.

Methodology

Goal and scope definition

The scope of this study is to assess the health and ecosystem impacts and costs of ozone formation originating from road, rail, and water transport in BMR including 6 provinces - Bangkok, Samut Prakan, Nonthaburi, Pathum Thani, Nakhon Pathom and Samut Sakhon [11]. The air emissions in this study can be divided into two parts: emissions from the vehicle use phase and emissions from the energy production phase. Two functional units have been defined in this study: 1 passenger-kilometer (1 pkm) - the unit of measurement representing the transport of one passenger by a defined mode of transport over the distance of 1 km; and annual passenger transport services in BMR in 2022 and 2027.

This study includes road, rail, and water transport: passenger cars≤7 seats, passenger cars >7 seats, buses, motorcycles, electric trains (including BTS Skytrain which is an elevated electric train system and MRT (Mass Rapid Transit) which has both underground and elevated electric trains), rail cars (SRT; State Railway of Thailand), cross river ferries, Chao Phraya boats and Saen Saep canal boats. Engine types, technology ages and fuel types were used for road transport calculation. The fuel varieties included gasoline, B7 biodiesel, B20 biodiesel, liquefied petroleum gas (LPG), and Compressed Natural Gas (CNG). The emission inventory for vehicle transport is based on Tier 2 methodology of EMEP/EEA 2019 [12]. The framework used in this study is shown in **Figure 1** and the specific data used in this study are shown in **Table A-1 and A-2**.

Ozone precursors inventory phase

The road transport emissions were calculated in this study as:

Emission (kg/pkm) = Emission factor (kg/vkm) x 1/Occupancy rate (passenger/vehicle) (1)

The ozone precursors considered in this study are NO_x and NMVOCs. The NO_x, NMVOCs emissions were calculated using equation (1). For rail transport (rail car and electric trains), the emissions calculations were based on the EMEP/EEA 2019 [10]. Specific data for rail transport emissions are shown in **Tables A-3 and Tables A-4**. The rail car emission equation used in this study is:

Emission (kg/pkm) = Emission factor (kg/tonnes) x Fuel consumption (tonnes/pkm) (2)

The electric trains emission equation used in this study is:

Emission (kg/pkm) = Emission factor (kg/kWh) x Electricity consumption (kWh/pkm) (3)

Water transport emissions were calculated based on [13] as shown in equations (4-6) and the specific data on the water transport are shown in **Table A-5**.

Water transport emissions = Cruising emission + Idling emission (4)

Cruising emission (kg/pkm) = Travelling time trip (hr/trip) x Load factor (unitless) x Avg. power (hp/p) x Cruising factor (kg/hp-hr) x 1/Avg. distance (km/trip) (5)

Idling emission (kg/pkm) = Idling factor x Cruising emission (kg/pkm) (6)

The emissions were calculated for the health and ecosystem impact assessment for the functional units of all passengers in BMR in 2022 and 2027 as shown in equation 7.

Emission (kg/year) = Number of pkm (pkm/year) x Emission (kg/pkm) (7)

Ozone formation impact assessment phase

The methods applied for assessing health and ecosystem impacts from ozone formation in this study are the ReCiPe 2016 method [14, 15] and Thai Spatially Differentiated Life Cycle Impact Assessment (ThaiSD) method [16] considering two ozone precursors - NO_x and NMVOCs. Ozone could be inhaled by humans or absorbed by plants. Ingestion of ozone causes an increase in mortality, and the resulting harm to human health is measured in Disability-Adjusted Life Years (DALY). It could also cause the disappearance of plant species. Terminal damage to terrestrial ecosystems were evaluated and reported in the unit species·yr [14-16]. The emission factors for the emissions from the energy production were collected from the ecoinvent Database version 8.3.0 [17]. The characterization factors were obtained from the ReCiPe 2016 method [14] and the Thai SD Method version 1.0 report [16] as shown in **Table A-6**.

This study combined the health impacts of NO_x and NMVOCs to determine the total health impacts. Likewise, the ecosystem impacts of NO_x and NMVOCs were combined to determine the total ecosystem impacts. In this investigation, the equation used for health and ecosystem impact assessment is:

IS = CF x m (8)

where CF = Characterization Factor (DALY/$kg_{emitted}$, species·yr/$kg_{emitted}$)
m = the emission mass per functional unit (in unit $kg_{emitted}$/pkm, $kg_{emitted}$/year)

In this study, the equation used for the economic assessment of the health impacts is as follows:

Cost of health impact = Health impact x MCF_{Health} (9)

MCF is a monetary conversion factor for the valuation of damage to health quality and ecosystem quality in Thailand, based on the budget constraint method [18]:

Future Value of $DALY_{2011}$ in 2022 = Value of $DALY_{2011}$ x $(1+r)^{2022-2011}$ (10)

where r = the average inflation rate of Thailand from 2021 to 2022

In this study the equations used for assessing the costs of the ecosystem impacts are as follows:

Cost of ecosystem impact = Ecosystem impact x $MCF_{Ecosystem}$ (11)

Future Value of $BAHY_{2011}$ in 2022 = Value of $BAHY_{2011}$ x $(1+r)^{2022-2011}$ (12)

$MCF_{Ecosystem}$ (Baht/(PDFm^2.yr)) = ($MCF_{Ecosystem}$ (Baht/BAHY))/10000 (13)

where $MCF_{Ecosystem}$ = Monetary conversion factors for the damage to ecosystem quality

BAHY = Biodiversity-adjusted hectare year

Interpretation phase

The interpretation phase includes the comparison of ozone precursor emissions, ozone-related health and ecosystem impacts and costs from the applications of different modes of transport and different transport scenarios. This phase also covers discussion, recommendations, and conclusions based on the obtained results.

There are eight scenarios in this study as shown in **Table 1**.

The data used for the public transport scenarios in this study are from the three-year operational plan (2020-2022) of Department of Land Transport. In addition, the Pollution Control Department (PCD) and the Office of Transport and Traffic Policy and Planning (OTP) operational plan for 2023-2027 includes the scenarios for 2027. This study considered 7,751 electric buses based on the white paper, "$PM_{2.5}$ and health impact reduction options for road transport in Bangkok Metropolitan Region" [19].

Results and Discussion

The health impacts and costs of ozone formation from various modes of transport in the BMR region (in the functional unit of pkm)

The horizontal axis of **Figure 2** depicts the modes of transport in BMR in 2022. The vertical axis represents the total health impacts in µDALY/pkm and the total health costs in Baht/pkm.

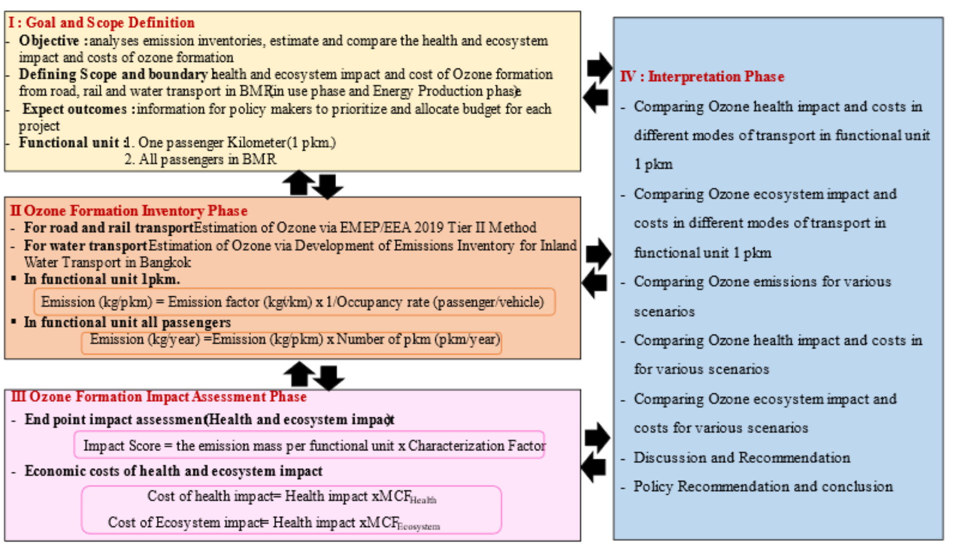

Figure 1 Research Framework of this study

Table 1 Scenarios analyzed in this study

Scenarios	
S1 2022 (BAU)	All modes of passenger road, rail and water transport in BMR in 2022
S2 2022	30% of all modes of transport shift to public buses in 2022
S3 2022	30% of all modes of transport shift to public water transport in 2022
S4 2022	30% of all modes of transport shift to electric trains in 2022
S1 2027	All modes of passenger road, rail and water transport in BMR in 2027
S2 2027	30% of all modes of transport shift to public buses in 2027
S3 2027	30% of all modes of transport shift to public water transport in 2027
S4 2027	30% of all modes of transport shift to electric trains in 2027

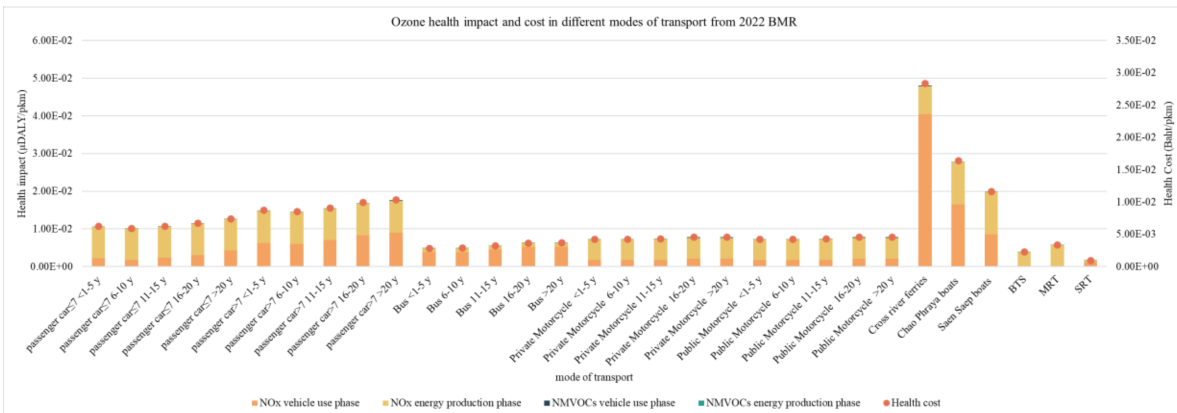

Figure 2 Total health impacts and costs from different modes of transport in BMR in 2022

In BMR, passenger cars ≤ 7 seats are mostly gasoline, followed by diesel, CNG, and LPG. The health impacts and costs ranged from 1.00E-02 to 1.25E-02 µDALY/pkm, and 5.96E-03 to 7.44E-03 Baht/pkm. Passenger cars with seven or more seats mostly used diesel fuel, followed by CNG, gasoline, and LPG. The health impacts and costs ranged from 1.44E-02 to 1.75E-02 µDALY/pkm and 8.53E-03 to 1.04E-02 Baht/pkm. The bus used CNG as the primary fuel, followed by diesel, LPG, and gasoline. The health impacts and costs ranged from 4.83E-03 to 6.28E-03 µDALY/pkm and 2.86E-03 to 3.72E-03 Baht/pkm. The health impacts and costs of private and public motorcycles, ranged from 7.21E-03 to 7.74E-03 µDALY/pkm and 4.28E-03 to 4.59E-03 Baht/pkm. The health impacts and costs of cross river vessels, Chao Phraya boats, and Saen Saep boats ranged from 1.97E-02 to 4.79E-02 µDALY/pkm and 1.17E-02 to 2.84E-02 Baht/pkm. The health impacts and costs of electric trains ranged from 3.84E-03 to 5.65E-03 µDALY/pkm, and 2.28E-03 to 3.35E-03 Baht/pkm. The rail car (SRT) results in negative impacts on health (1.59E-03 µDALY/pkm) and cost (9.43E-04 Baht/pkm).

The results indicate that NO_x had the greatest impacts on all modes of transport (greater than 90 percent). Thermal NO_x (Zeldovich Mechanism) is a chemical reaction between oxygen and nitrogen that forms combustion at high temperatures. The Fenimore Mechanism (Immediate NO_x) is a chemical reaction between a hydrocarbon compound and nitrogen in the air, influenced by several variables including fuel-air ratio, temperature, and pressure [20-22]. Thermal and immediate NO_x significantly emits during the vehicle use phase from the old water transport engines technology (pre-EURO) and old engine model years. The engine model years of cross river ferries, Chao Phraya boats and Saen Saep canal boats are all older than 20 years [13].

Consequently, the river crossing ferries had the greatest emissions, health impacts, and costs. In contrast, the rail cars (SRT) had the lowest health impact and expenditures due to their low fuel consumption and high occupancy rate. The passenger cars ≤7 seats, passenger cars >7 seats, buses, and motorcycles resulted in higher health impacts and costs due to their older age and inferior technology. LPG had the highest health impacts during the energy production phase, whereas CNG had the lowest health impacts. LPG and CNG engines were modified from gasoline engines and required a pressure-reducing device for complete combustion. In addition, LPG and CNG combustion temperatures were lower than gasoline and diesel [23-26]. As a result of advancements in road transport's engine technology, the health impacts and costs of road transport per pkm in 2027 were lower than in 2022. The health impacts and costs were ranked similarly.

The ecosystem impacts and costs of ozone formation from various modes of transport in the BMR region (in the functional unit of pkm)

The horizontal axis of **Figure 3** depicts the modes of passenger transport in BMR in 2022. The vertical axis displays the total ecosystem impacts in species·yr/pkm and the total ecosystem costs in Baht/pkm.

The ecosystem impacts of passenger car ≤7 seats ranged from 3.16E-11 to 5.37E-11 species·yr/pkm, and the costs ranged from 7.81E-03 to 1.33E-02 Baht/pkm. The ecosystem impacts of passenger car > 7 seats ranged from 6.39E-11 to 8.81E-11 species·yr/pkm, and the costs ranged from 1.58E-02 to 2.18E-02 Baht/pkm. The ecosystem impacts of bus ranged from 3.17E-11 to 4.20E-11 species·yr /pkm, and the costs ranged from 7.83E-03 to 1.04E-02 Baht/pkm. The ecosystem impacts and costs of private motorcycles and public motorcycles ranged from 3.08E-11 to 7.14E-11 species·yr/pkm, and 7.61E-03 to 1.76E-02 Baht/pkm. The motorcycles (more than 16 years) had highest NMVOCs emissions during the use phase. The motorcycles have two-stroke engines using the pre-mixing of oil and fuel and have a higher fuel consumption [25, 27, 28]. The ecosystem impacts and costs of Cross river ferries, Chao Phraya boats and Saen Saep boats ranged from 8.97E-11 to 3.26E-10 species·yr/pkm, and 2.22E-02 to 8.06E-02 Baht/pkm. The ecosystem impacts and costs of electric trains ranged from 7.43E-12 to 1.09E-11 species·yr/pkm, and 1.84E-03 to 2.70E-03 Baht/pkm. The ecosystem impacts and costs of rail car (SRT) were 1.00E-11 species·yr/pkm and 2.48E-03 Baht/pkm.

More than 90% of the impacts of NO_x on ecosystem was attributed to all modes of transport, as indicated by the results. Older water transport engine technology (pre-EURO) and older engine model year in the cross-river transport systems resulted in the highest ecosystem impacts and costs. The elevated electric trains (BTS) have no emissions from vehicle use phase, the lowest electricity consumption, and a high occupancy rate resulting in the lowest costs and impacts on the ecosystem. Passenger cars ≤ 7 seats, passenger cars > 7 seats, buses, and motorcycles had high ecological impacts and costs due to their advanced age and limited emission control technology. The vehicle use phase and energy production phase of NO_x, and NMVOCs energy production phase had higher ecosystem impacts than NMVOCs vehicle use phase by 5, 9, and 3 times, respectively. The vehicle use phase and energy production phase of NO_x, and NMVOCs energy production phase had a greater impact on human health by 187, 1,306, and 3 times, respectively. Consequently, the ranking of ecosystem impacts was different from that of health impacts. As a result of advancements in road transport engine technology, the ecosystem impacts and costs of road transport per pkm in 2027 were less than in 2022. The ecosystem impacts and costs were ranked similarly.

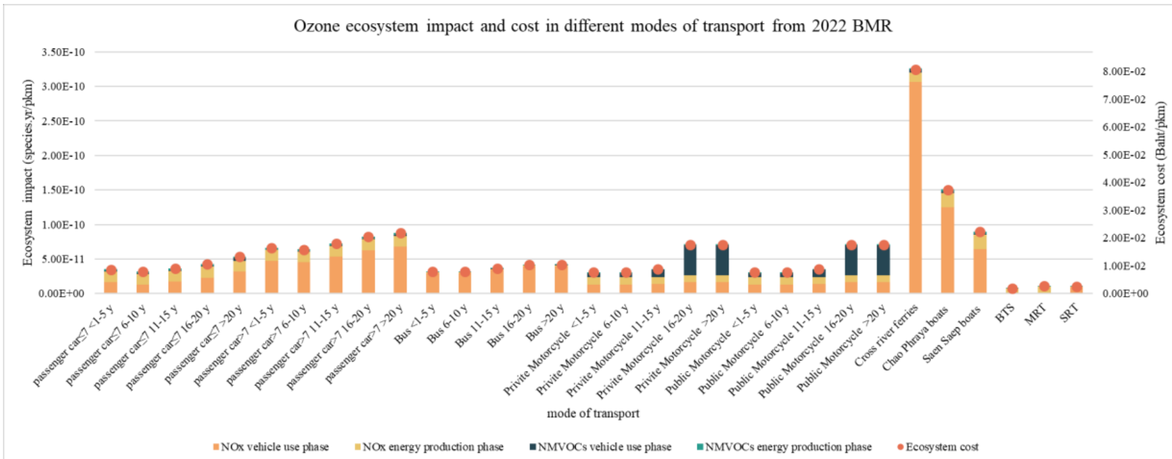

Figure 3 Total ecosystem impacts and costs in different modes of transport in BMR in 2022

Total BMR emissions in 2022 and 2027 (in the functional unit of annual passenger transport services)

The horizontal axis in **Figure 4** displays the eight study scenarios. The vertical axis displays the total NO_x and NMVOC emissions in tonnes/year for all modes of transport in the functional unit of transport in 2022 and 2027 in BMR.

Under the S1 2022 (BAU) scenario, NO_x emissions were summed as 5.05E+04 tonnes per year. The annual emissions of NMVOCs were equal to 2.61E+04 tonnes. In 2022, the cumulative NO_x emissions for scenarios 2, 3, and 4 were 5.19E+04, 9.06E+04, and 3.92E+04 tonnes per year, respectively. In 2022, scenarios 2, 3, and 4, NMVOCs emissions were 2.31E+04, 2.61E+04, and 1.96E+04 tonnes per year, respectively. In the scenario 1 2027, total NO_x emissions were 5.37E+04 tonnes per year. The annual emissions of NMVOCs equals to 2.91E+04 tonnes. In 2027, the total NO_x emissions for scenarios 2, 3, and 4 were 5.07E+04, 1.05E+05, and 4.23E+04 tonnes per year, respectively. The emissions of NMVOCs in 2027 for scenarios 2, 3, and 4 were 2.56E+04, 2.97E+04, and 2.23E+04 tonnes per year, respectively.

Passenger cars ≤7 seats, passenger cars > 7 seats and buses had the highest effects on the total NO_x emissions. Similarly, private motorcycle, passenger car ≤ 7 seats and passenger car > 7 seats had the highest influence on total NMVOCs emissions. In scenario 2 2022, NO_x emission was 3% higher than scenario 1 2022, while NMVOCs emission was 11% lower. The shifts in modes of transport to electric buses with no vehicle use phase emission in 2027 resulted in the reduction in the NO_x emissions (6% lower than NO_x emissions from scenario 1 2027). In scenario 3 for 2022, NO_x emissions were 79% higher than scenario 1 2022 because all modes of transport were shifted to water transport by 30% (which had the maximum NO_x emission per pkm in 2022). Similarly, the NO_x emissions in scenario 3 for 2027 were 96% higher than scenario 1 for 2027, and the NO_x emissions for road transport were lower in 2027 than in 2022. In scenario 4 for 2022, the NO_x and NMVOCs emissions were 22% and 25%lower than scenario 1 for 2022, respectively. This is because all modes of transport shifted to electric trains, which had no vehicle use phase emissions. Scenario 4 2022 had a greater percentage reduction than Scenario S 2027, due to the increase of transport in 2027. The best alternative with the lowest NO_x and NMVOC emissions in this assessment is Scenario 4 2022.

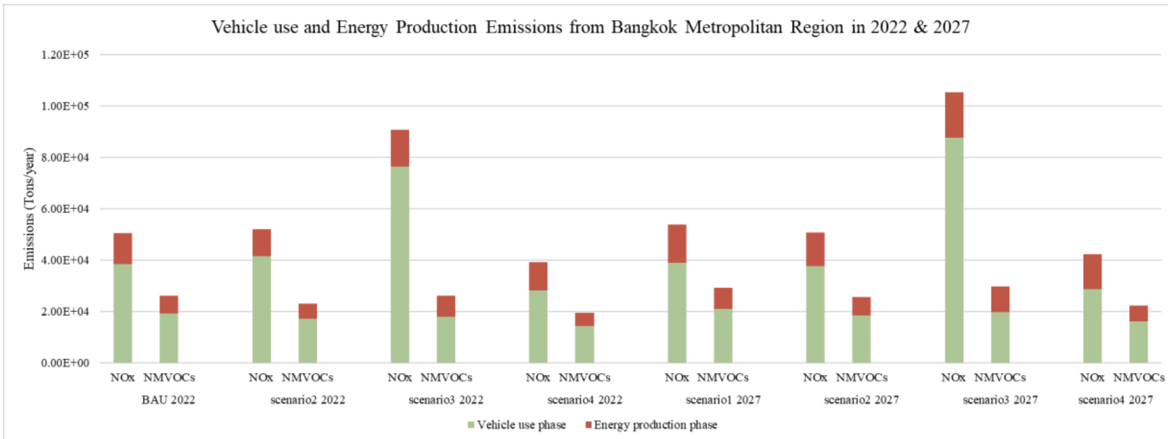

Figure 4 Total emissions in different 2022 and 2027 BMR scenarios

Total BMR ozone health impact and cost in 2022 and 2027 (in the functional unit of annual passenger transport services)

The horizontal axis of **Figure 5** depicts the eight scenarios examined in this study. The vertical axis displays the total health impacts in DALYs per year and the total health costs in Baht per year.

The total health impacts and costs under the BAU 2022 scenario was 1.21E+03 DALY/year and 7.17E+02 million baht/year. The total health impacts and costs for scenarios 2, 3, and 4 for 2022 were 1.14E+03, 1.75E+03, and 1.04E+03 DALY/year; and 6.73E+02, 1.04E+03, and 6.18E+02 million Baht/year (6.02%lower, 44.76%higher, and 13.70%lower than the BAU, respectively). The NO_x energy production phase had the greatest contribution on the total health impacts and costs of scenario 1 in 2027, which was 1.40E+03 DALY/year and 8.89E+02 million Baht/year. Scenarios 2, 3, and 4 2027 had total health impacts of 1.28E+03, 2.10E+03, and 1.23E+03 DALY/year, which were equivalent to the costs of 8.11E+02, 1.33E+03, and 7.78E+02 million Baht/year (8.78% less, 49.66% higher, and 12.52% less than scenario S1 2027).

The results indicate that the NO_x energy production phase had the greatest effect on the total health impacts (56.73 - 76.84% of the total health impacts). Scenario 2 for 2022 had the reduced health impacts from the NO_x energy production phase, NMVOCs vehicle use phase, and NMVOCs production phase by 12%, 12%, and 10% respectively, compared to scenario 1 for 2022. Scenario 2 for 2027 has the potential to lower the health impacts and costs than scenario 2 for 2022, due to the modal shift of transport to electric buses, which have no emission during the vehicle use phase. Scenario 3 for 2022 had the highest total health impacts from NO_x vehicle use phase and production phase, which were 98% and 20% higher, respectively, than the Scenario 1 for 2022. The health impacts and costs of Scenario 3 for 2027 were greater than those of Scenario 3 for 2022 as the result of the transition from road transport engines with more advanced technology in 2022 to water transport engines with older technology in 2027. Scenario 4 for 2022 had the lowest health impacts and costs because of the shift in all modes of transport to electric trains, which had nil vehicle use phase and low energy production phase emissions and health impacts per pkm. Scenario 4 for 2022 had a greater percentage reduction than Scenario 4 for 2027, due to the increase in transport in 2027 (similar to emissions).

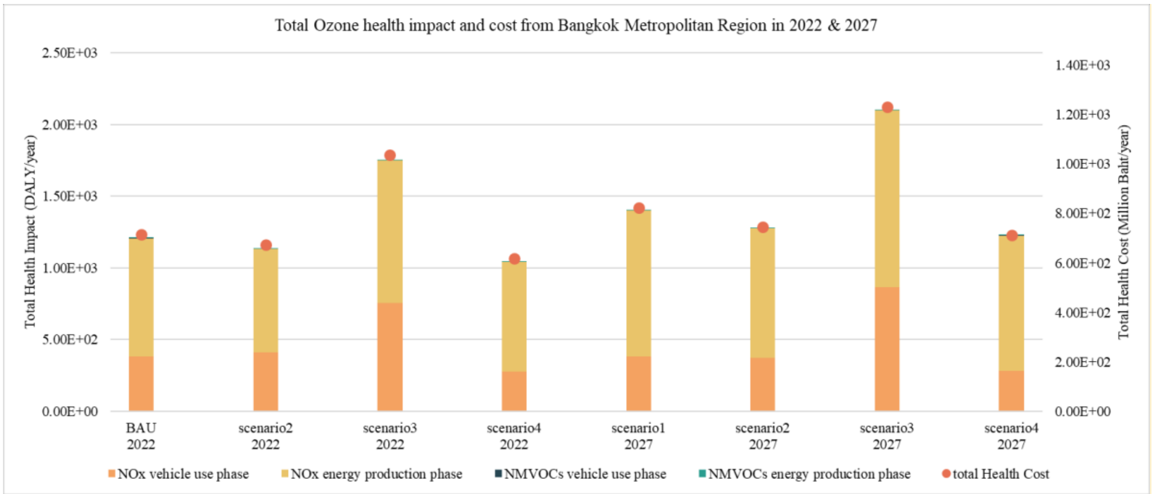

Figure 5 Total health impact and cost in different 2022 and 2027 BMR scenarios

Total ozone ecosystem impacts and costs in 2022 and 2027 (in the functional unit of annual passenger transport services)

The horizontal axis of **Figure 6** depicts the eight scenarios examined in this investigation. The vertical axis represents the entire ecosystem impact of a species·yr/year and total ecosystem cost expenditures in Baht/year.

The total ecosystem impacts and costs under the BAU 2022 scenario is 4.95E+00 species per year, or 1.22E+03 million Baht per year. The total ecosystem impacts for Scenarios 2, 3 and 4 2022 were 4.92E+00, 8.12E+00 and 3.93E+00 species·yr/year, respectively. This is equivalent to 1.21E+03, 2.01E+03 and 9.70E+02 million Baht/year, respectively (0.58% less, 64.07% higher and 20.61% less than the BAU 2022). The total ecosystem impact and cost of Scenario 1 for 2027 was 5.42E+00 species·yr per year, or 1.43E+03 million Baht per year. Scenario 2, 3 and 4 for 2027 had total ecosystem impacts and costs equal to 5.03E+00, 9.50E+00 and 4.34E+00 species·yr/year, or 1.33E+03, 2.51E+03 and 1.15E+03 million Baht/year, respectively (7.20% less, 75.30% higher and 19.83% less than Scenario 1 for 2027).

These results indicate that the NO_x vehicle use phase had the greatest influence on the total ecosystem impacts (49.19% to 70.37%). The NO_x energy production phase, the NMVOCs vehicle use phase, and the NMVOCs production phase had lower impact on the ecosystem in Scenario 2 2022 compared to Scenario 1 for 2022. Due to the modal transition of transport to electric buses, which have zero vehicle use phase emissions corresponding to Scenario 2's annual health impacts and emissions, Scenario 2 for 2027 could have a lesser impact on the ecosystem compared to Scenario 2 for 2022. The cumulative ecosystem impacts of Scenario 3 for 2022 from NO_x vehicle use phase and production phase were greater by 98% and 20% than Scenario 1 for 2022. Scenario 3 for 2027 had the highest ecosystem impacts and costs as the consequence of shifting all modes of transport from road transport engines with newer technology to water transport engines with older technology. As a result of shifting all modes of transport to electric trains, which has zero vehicle use phase emissions, low energy production phase emissions and ecosystem impacts per pkm, Scenario 4 for 2022 had the lowest ecosystem impacts and costs. Due to the increase in transportation in in 2027, the emissions and health impacts for Scenario 4 for 2027 was greater than Scenario 4 for 2022.

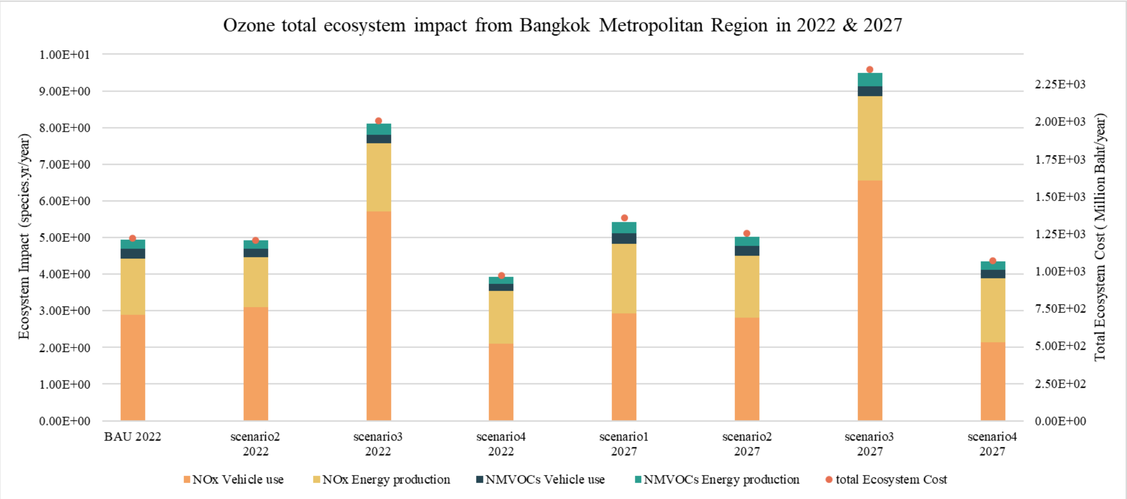

Figure 6 Total ecosystem impacts and costs in different 2022 and 2027 BMR scenarios

Conclusions

In BMR, the health impacts, ecosystem impacts and costs of ozone formation for various modes of transport were determined. BAU of transport in BMR has the greatest effect on the health and ecosystem impacts and costs compared to passenger cars ≤7 seats, passenger cars >7 seats, buses, and private motorcycles. 30% of all modes of transport in BMR were converted to buses in 2022. As a result, the NO_x emissions were 3% higher, while the NMVOC emissions, health impacts, and ecosystem impacts were 11%, 6.02%, and 0.5% lower than BAU transport in BMR, respectively. In addition, shifting all modes of transport to electric buses could reduce the NO_x and NMVOC emissions, health impacts, and ecosystem costs in 2027. 30% of transport in BMR shifted to water transport in 2022, which has the highest vehicle use phase emission per pkm and the highest health and ecosystem impacts per pkm. As a result, the NO_x emissions, health, and ecosystem impacts were 97%, 44%, and 64% higher than BAU transport in BMR. All modes of transport shifted to electric trains, which has zero vehicle use phase emissions and low energy production phase emissions and ecosystem impacts per pkm. As a result, the NO_x and NMVOCs emissions were 22% and 25% less than BAU transport in BMR, and health and ecosystem impacts were 13% and 20% less than BAU transport in BMR. Shifting all modes of transport to the electric trains resulted in the lowest emissions, heath, ecosystem impacts and costs. It is therefore essential that Thai government increases the main public transport system; electric trains should be covering the BMR area in the same way as feeder development, such as the use of EURO 4 and above for boats and buses or the use of electricity as fuel. In addition, the technology of private cars should be developed, such as the use of EURO 4 and above, including the use of electricity as fuel. This result corresponds to the 20-year transport system development strategies for Thailand [7], 5-year action plan (2023-2027) of the PCD [29] and MOT Transport Action Plan for 2022 [30]. This will help in developing environmentally friendly and safe modes of transport with focus on rail and electric buses and create connections between stations to facilitate travel. Moreover, this result is consistent with the Annual PCD Action Plan for 2022 [31]. BMR should concentrate on transport pollution solutions. For conducting more comprehensive scenario analysis in the further studies, electric cars (passenger cars≤7 seats, passenger cars>7 seats) should be considered, because there were 41,784 new registered electric cars in 2023 compared to the number of new registered cars between January and June in 2022 [32].

Appendix A. Supplementary data

Supplementary data to this article can be found online at
https://doi.org/10.17632/nrxcykdjrs.2

Acknowledgments

This research project is supported by the National Science and Technology Development Agency (NSTDA) through the Research Chair Grant 2559 on the project “Network for Research and Innovation for Trade and Production of Sustainable Food and Bioenergy” (RD&E Fund: FDA-CO-2559–3268-TH), the Worldwide Universities Network (WUN) through the Research Development Fund (RDF) 2022 on the project “Towards Net Zero and Sustainable Cities with Resource Optimization, Circular Economy and Research Network (NZS CITIES)” and National Research Council of Thailand (NRCT): grant number 395/2563.

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Thai Environmental Engineering Journal Vol. 37 No. 2 (2023) : 23-30
www.eeat.or.th

Housing and Environmental Development for the Low Income Elderly in Bangkok : a Case Study on Rental Housing of National Housing Authority, Bangkok, Thailand

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Abstract

Thailand Is becoming a super-aged society in 2031 which causes development of housing and environment for elderly is an important issue during urbanization. The National Housing Authority (NHA) has been set to provide subsidized housing for elderly with low-income, who face affordability and accessibility issues. The objective of this study was to suggest components of the development of the right adequate housing and environment for seniors. It was conducted by using a case study of rental housing development of NHA. This study is qualitative research using a housing safety checklist for older people with 3 NHA rental housing areas include Ramintha Rental Housing project, Huai Khwang Rental Housing project and Din Daeng Rental Housing project. The result of the study showed that all 3 rental housings scored less than 60 percent caused by unsafe bathrooms; a lack of handrails, elevators and proper ramp slopes. there are 3 senior housing and environment development guidelines: 1) Physical and environmental development, senior housing concept should be considered elderly basic needs, project should prepare suitable location; project plan and focus on positive space. 2) Emotional and social development. The project should prepare sufficient and reasonable spaces to senior group activities. And 3) Economic development. The project should prepare areas for senior service units.

Keywords : Elderly; City; Housing; Environment

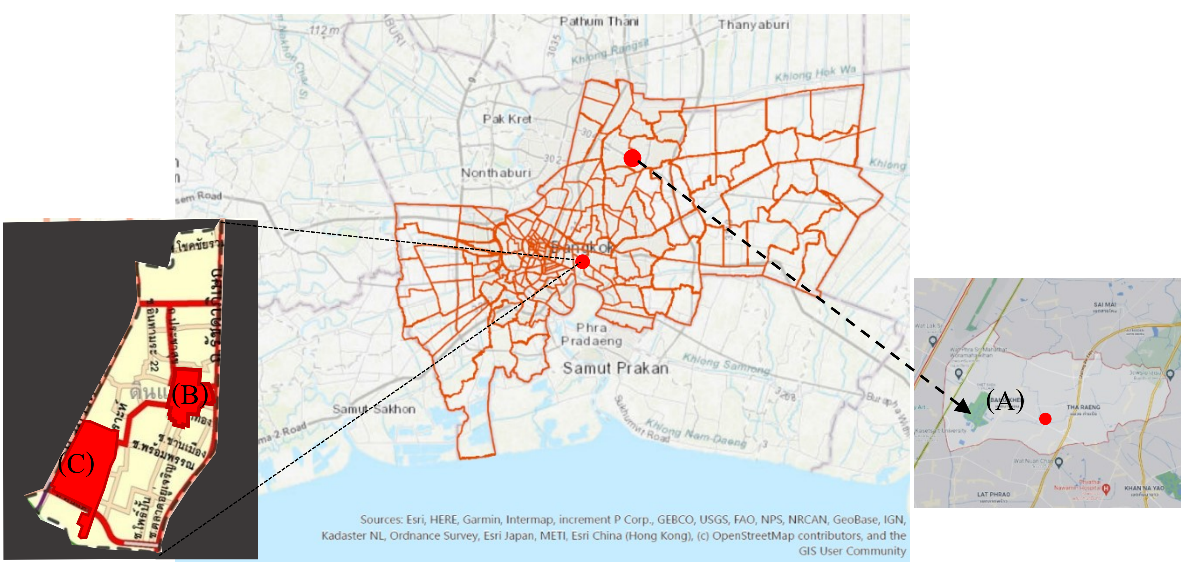
Introduction

Thailand has a total population of 66.5 million people, with 12 million elderly (aged over 60 years) approximately 18% of the total population. It has become "Completely Aged Society" in 2022 and will become a Super-Aged Society in 2031 with proportion of elderly more than 28 percent of the total population [1]. According to Goal 11: Sustainable cities and communities of Sustainable Development Goals (SDGs) [2], that aim to make cities and human settlements inclusive, safe, resilient and sustainable, outcome target 11.1, By 2030, ensure access for all to adequate, safe and affordable housing, and basic services and upgraded slums. Providing housing for low-income earners is an important mission of the National Housing Authority (NHA) [3], but the NHA's rental project is inappropriate for the elderly. Therefore, the researcher aims to prepare the guidelines for the housing development and environment suitable for the elderly in the rental building project of the NHA, with the following objectives: 1) to survey housing and the environment in the rental building project according to the rehabilitation plan to improve the quality of life (rental) in Ramintha, Huai Khwang, and Din Daeng Rental Housing project at Bangkok, and 2) to propose guidelines for the development of housing and environment in a suitable format for the elderly in low-income cities.

The Universal Design are not entirely about accessibility but about the appropriateness of design solutions to gender, to demographic group, and to social and economic setting. The Design for all principle consists of seven principles, 1) Equitable use, 2) Flexibility in use, 3) Simple and intuitive use, 4) Perceptive information, 5) Tolerance for error 6) Low physical effort; and 7) Size and space for approach and use [4]. Until the Accessibility of Housing has set criteria for housing suitable for the elderly and disabled, consisting of 7 topics, including entrances and halls, doors, corridors in buildings, ramps, elevators, stairs, and bathrooms [5]. Apart from creating designs that work for everyone, it's important to also consider what older people need. These needs can be put into two groups: basic needs that take care of their physical requirements, and more advanced needs that focus on their social well-being. These advanced needs include things like helping them live longer, keeping their bodies and minds active, and making sure they can hold onto the things they gained earlier in life, such as knowledge, expertise, wealth, prestige, and authority [6]. Consequently, the notion of managing accommodations for the elderly entails a consideration of both individual and societal needs. Elderly group are part of society [7], according to related research studies, it was found that, there were two types of changes in the elderly, 1) physical or body condition that directly affecting an environment management to be concern about the inside and outside living safety of residence [8-11], 2) social, psychological and economic changes, should be allocated for joint activities for all ages of people. It is a flexible area to use and the elderly can conveniently and safety to access. Including access to public health service system [12-15]. Especially that low-income elderly have access to housing. It is the first to establish the Guidelines for Affordable Housing for the Elderly by the World Health Organization Global Network for Age-friendly Cities and Communities [16].

Research Methodology

This research is conducted using a qualitative approach. It involves using a checklist to collect data and using questionnaires for community leaders in the National Housing Rental Building Project. Additionally, semi-structured interviews are used as research tools. The study also includes a literature review and gathers relevant information from three low-income housing development sites: Ramintha, Huai Khwang, and Din Daeng Rental Housing projects overseen by the National Housing Authority (NHA). See Figure 1.



Ramintha(A), Huai Khwang(B), and Din Daeng(C) Rental Housing project

Figure 1 The location of the case study of Rental Housing projects in Bangkok area in each district
Sources: https://bmagis.bangkok.go.th/

Selection of key informants

Key informants are divided into two parts.

1) Community leaders living in the National Housing Authority Rental Building Project, 5 persons per 1 community.

2) Qualified persons, experts and people with experience in developing housing and environment suitable for the elderly. By defining 3 representative groups, namely those who set the policy group of practitioners and a group of 6 academics to analyze success factors, problems, obstacles, methods of operation leading to application in accordance with the context of Thailand.

Key informants for this study were purposefully selected using a specific sampling method. These individuals were selected on purpose because they play important roles in the community and have experience in creating suitable housing and environments for the elderly. The criteria for their selection are outlined as follows:

1. Community leaders (5 people per community) 15 person
2. Assistant Governor of National Housing Authority 1 person
3. National Housing Architects level 8 2 person
4. Head of community center 3 communities 3 person

Research Instrument

1. Provide tools by creating preliminary questionnaires and surveys

On the issue of housing for the elderly that accordance with factors in the study. Including creating questionnaires for key informants and used checklist for a survey of a housing and environment for the elderly.

The researcher used a questionnaire to collect data for analysis as follows:

Part 1: Questionnaires about personal information, lifestyle, overall health, caregivers, body function problems, and the scene of the accident.

Part 2: Environmental and housing information interview, the characteristics of the current residence, residents, number of members, period of residence, problems encountered in housing, future housing needs, areas that need to be improvement.

Part 3: Elderly activities in the community data collection.

Part 4: Assessment Checklist for Elderly Housing and Environment: Identifying Current Conditions, Usage Issues, and Implementation Challenges. The checklist is structured around five distinct topics: 1) Environment and Community Facilities, 2) Corridor Accessibility (both internal and external), 3) Multilevel Travel Accessibility, 4) Bathroom and Toilet Facilities, and 5) Housing Units. (Table 1)

References for the Assessment Criteria from Legislation and Manuals:

1. **Ministerial Regulations on Building Facilities for the Disabled or Disabled and Elderly, A.D. 2005 (B.E. 2548)** [18].
2. **Building and Environmental Design Recommendations for All, A.D. 2014** by the Association of Siamese Architects under the Royal Patronage [19].
3. **Elderly Home Standard Guide A.D. 2020 (B.E. 2563)** by the Office of Promotion and Protection of the Elderly, Office of Welfare Promotion and Protection of Children, Youth, Opportunistic Persons, and Elderly, Ministry of Social Development and Human Security (MSDHS) [20].

Table 1 Scoring according to the housing and environment assessment form for the elderly

Specification	Full score	Scoring results	
		Mandatory criteria	**Criteria should be provided**
1. Environment and Community facilities	**6**	3	3
2. Corridor and foot part	**5**	3	2
3. Travel in different levels or between floors	**9**	9	-
4. Bathroom / Toilet	**9**	3	6
5. Housing unite	**3**	2	1
Total score	**32**	**(20)**	**(12)**

Standard level

- ☐ Excellent Level (Mandatory criteria = 20 points, should be provided = 11-12 points)
- ☐ Very Good (Mandatory criteria = 20 points, should be provided = 9-10 points)
- ☐ Good level (Mandatory criteria = 20 points, Should be provided = 7-8 points)
- ☐ Moderate level (more than 60% Mandatory criteria = 12 points or more, Should be provided more than 60% = 7 points or more)
- ☐ Should be improved level (Less than 60% Mandatory criteria = less than 11 points, Should be provided more than 60% = less than 7 points)

Using the scoring principle based on actual conditions. The total score must be more than 60% because it is a criterion related to the safety of the elderly. (Compulsory more than 60 percent = 12 points or more, should be provided more than 60 percent = 7 points or more)

2. Semi Structure Interview

This step was used for experts and people who have experience in developing housing and environment suitable for the elderly. The questions for interviewing experts are divided into 4 issues,

2.1 Development of housing and environment suitable for the elderly.

2.2 Related parties.

2.3 Areas or projects for the development of housing and environment suitable for the elderly.

2.4 Modern tools and innovations in housing development and environment suitable for the elderly.

Results and Discussion

1. Result of survey for residential buildings and environment of Ramintha, Huai Khwang, and Din Daeng Rental Housing project

Summary of survey for residential buildings and environment of Ramintha, Huai Khwang, and Din Daeng Rental Housing project by using checklist shown in Table 2 and Figure 2.

1.1 Results of housing and environment survey, in the rental building project according to the rehabilitation plan to enhance the quality of life (rental) in the Bangkok area, Ramintha, Huai Khwang, and Din Daeng Rental Housing project for environment and housing suitable for the elderly development. It found the residential building should be improved even though every project was more than 60 percent on the mandatory criteria. The Huai Khwang Community Housing Project has achieved the highest assessment score. However, it falls short of meeting certain mandatory criteria. Following this, the project lacks appropriate bathroom facilities, including steps between indoor and outdoor spaces, handrails, shower seats, doors narrower than 90 centimeters, and insufficient space (1.5 meters) for accommodating wheelchairs. In addition, there is a noticeable shortfall in vertical mobility, as there is no provision for an elevator or suitable equipment to facilitate movement between floors. Moreover, the ramps in the project are compromised by unsuitable steepness, inadequate width, and an absence of handrails.

Table 2 Result of Assessment of Housing and Environmental Conditions for the Elderly Across 3 Communities

Specification	Full score	Ramintha		Huai Khwang		Din Daeng	
		Mandatory criteria	Criteria should be provided	Mandatory criteria	Criteria should be provided	Mandatory criteria	Criteria should be provided
1. Environment and Community facilities	**6**	3	-	3	1	3	1
2. Corridor and foot part	**5**	2	-	3	-	2	-
3. Travel in different levels or between floors	**9**	5.5	-	5.5	-	4.5	-
4. Bathroom / Toilet	**9**	1	1	1	1	1	1
5. housing unite	**3**	2	-	2	-	2	-
Total score	32	13.5	1	14.5	2	12.5	2
Grand Total score		**14.5**		**16.5**		**14.5**	

Note: Full score of 32 (20 points for Compulsory score and 12 points Scores for should be provided partX

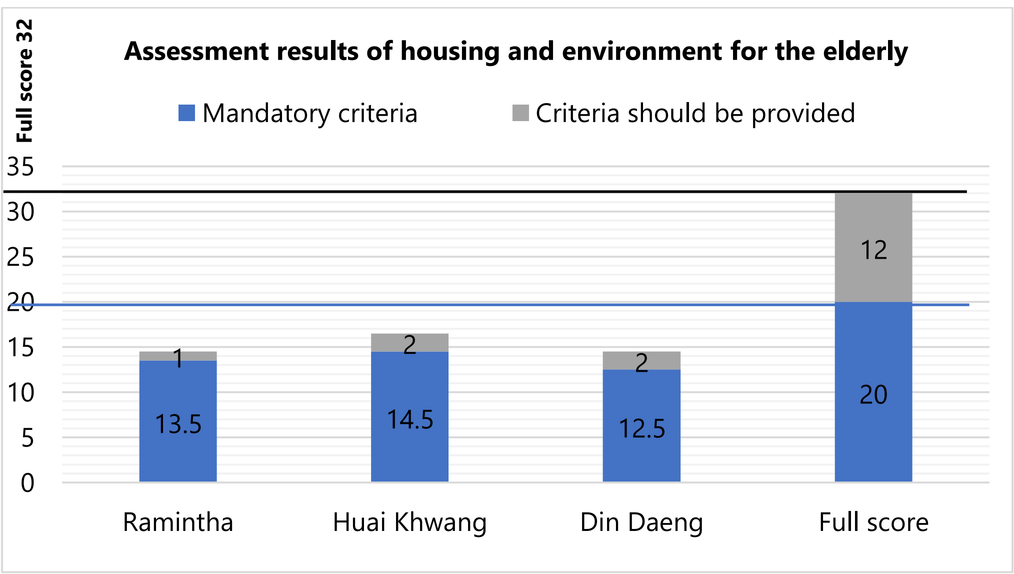


Figure 2 Results of the assessment of housing and environment for the elderly in 3 communities

1.2 Results of interviews with community leaders. It found most of elderly in the community could help themselves. Live with family about 3-5 persons per unit. The period of living in the project is more than 20 years. The problem found in the room is the bathroom due to the slippery and cramped spaces. Common area is a staircase due to its rough and dilapidated surface. The elderly people want to live in the same area with improvements to be appropriate.

1.3 Results of the experts interview. It can be concluded that the National Housing Authority has no plan to support for elderly housing. Because it is a project development in the main mission based on low-income earners housing. Currently, the National Housing Authority is prioritizing housing projects for the elderly. This follows the universal design principle set out in the 2005 Ministerial Regulations, which focuses on facilities for disabled individuals and the elderly. In rental buildings for low-income earners, 10% of the units are designed for the elderly and located on the first floor. For future development, it should be developed based on the needs of the actual residents in the area conjunction with network creation of responsible agencies to develop projects in line with government policies. The key innovation is the community cooperation system to sustainably innovation accessible management for low-income earners. Therefore, participation innovation should be promoted, for example, savings projects, borrowing-returning of necessary equipment for the elderly service, a time bank is an exchange of time in a volunteer manner with cooperation of related agencies.

2. Guidelines of housing and environment suitable for the elderly with low income

Results from surveys of current conditions of all 3 rental projects, interviews with community leaders and executives managers of the National Housing Authority. The guidelines for developing housing and the environment suitable for the elderly in low-income cities can be summarized as follows:

2.1 Physical Development and environment.

2.1.1 Basic needs of the elderly should be concerned, such as physical safety and health, privacy, social interaction and personal security.

2.1.2 The development of housing for the elderly should be planned from the location selection to project lay-out, such as concern about various service sources, not isolation, near public transportation.

2.1.3 Creating a positive environment requires attention to factors such as easy accessibility, physical safety, well-defined personal boundaries, and the ability to foster motivation.

2.2 Social Development. Housing development should be concerned about social needs and elderly groups integrated into create or enhance social activities by providing adequate and appropriate space for elderly activities.

2.3 Economic changes in the elderly population, including reduced income and increased healthcare costs, have an impact on economic development.

2.3.1 It's important to create suitable spaces that collaborate with relevant government agencies to provide services for the elderly. This ensures access to high-quality services that are tailored to their age group.

2.3.2 Design housing and environments for the elderly to encourage longer stays, reducing hospital or nursing home moves. Prioritize collaborative, user-friendly, safe, and cost-effective designs for sustained living.

Conclusions

Creating suitable housing and environments for the elderly within the context of developing low-income cities poses significant challenges due to limited space during urban development. This makes it more difficult to ensure a good quality of life for the elderly population. There is still a limitation on the low-income elderly economic status which housing for the elderly in this era to the near future must be able to create an age-friendly environment with the goal for social activities, support and help within the community. NHA has an additional mission to build good quality housing, near affordable and low cost. It should include in the housing development and people's quality of life policy. Even it is difficult and may not be attractive to investors in economic terms, but housing policy will be an important tool for improving the well-being of the elderly to accessible for good, affordable housing options can be created and provide supportive environments for the quality of life of the elderly.

Acknowledgment

This article was successfully completed. due to kindness and useful advice from all thesis examination committee members. I would like to thank to those who cooperated in answering the questionnaire. And thank you to the staff of the Institute of Metropolitan Development of Navamindradhiraj University for providing various assistance. Due to receiving kindness from the community leaders of 3 Community Housing Project worker Executives and experts of the National Housing Authority.

I would like to thank my father, mother, younger sister who have always been my inspiration in my studies, as well as all of friends and seniors in Institute of Metropolitan Development, Navamindradhiraj University for their help and help in completing this thesis.

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Thai Environmental Engineering Journal Vol. 37 No. 2 (2023) : 31-41
www.eeat.or.th

Improvement of Biogas Production Efficiency from Dairy Manure by Air-lift System Using Simple Simulation Program and Reactor Operation Approaches

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Abstract

Anaerobic process has been perceived as a sustainable method for treating and producing biogas from dairy farm. However, some operational problems have regularly been reported. This study was conducted in order to determine the suitable mixing scheme for the modified covered lagoon using air-lift systems to enhance the system efficiency and prevent the pipe clogging problem. Suitable biogas flowrate and installing position for the air-lift system were determined via the flow scheme simulation using ANSYS Student 2019 program. Both biogas flowrates and installation positions were found to significantly affect the mixing regimes and reactor performances. At the suitable biogas flowrate of 20 L/min, reactor contents were properly mixed both in the front and the reaction parts of the reactor. Results from the actual reactor operation using three 8 m^3-modified covered lagoons operated at the organic loading rate of 2.0 kg VS/m^3-d showed that anaerobic pond installed with the air-lift system in the front part provided better system stability, waste treatment and biogas production efficiencies compared to those obtained from the one with the air-lift system both in the front and the end parts and the control one without any mixing system.

Keywords : Anaerobic digestion; Biogas; Air-lift; Dairy manure

Introduction

Dairy farming contributes substantially to the growth of some agricultural countries. In Thailand, there are approximately 17,837 households associated with dairy farming in different parts of the country. The majority of these farms are small-scales (55%), which mostly employ family members (85%). Milk production amounted to 2,093,412 kg of milk daily in 2009 [1]. However, activities of dairy farms generate a significant amount of waste, especially dairy manure consisting of organics, solids and nutrients. This waste can pollute the environment if it is not appropriately managed. Dairy manure, on the other hand, can be a useful resource for renewable energy production in forms of biogas in anaerobic digestion [2]. Biogas can play an important role in dairy farm activities, e.g. as a fuel to boil milk, produce hot water for disinfection and can also be used to produce electricity for large farms having large amounts of waste [3]. One of the problems utilizing biogas reactors is the low efficiency or even system failure caused by the accumulation of solids in the pipe or openings in the system leading to clogging [4]. This problem is rather common when dairy manure is used as the feedstock as it can contain high amounts of biomass fiber and grits [5, 6]. Alleviation of clogging problems have been reported to be done by combining the mixing system with the biogas reactor as mixing helps to homogenize liquid phase and solids phase throughout the digester.

Many researchers discovered that mixing system rendered better performance for biogas reactor. Wang et al. analyzed the biogas digester fed with cow manure and operated under 3 modes, i.e., unmix, continuous mix (mixing for 15 minutes at 15 minutes interval) and intermediate mixing (mixing for 15 minutes at 45 minutes interval). Methane percentages in biogas obtained from digesters with continuous mixing was significantly higher than those from the unmixed and intermediate mixing [4]. Nandi et al. investigated effects of mixing on the performance of anaerobic reactor digesting cow manure under continuous mixing (mixing at 100 rpm for 5 min at 15 min interval) with propeller, and without mixing. The highest biogas production was also gained from reactor with mixing [7]. Jegede et al. also found that up to 40.6% higher of specific biogas production anaerobic were detected from the Chinese dome digesters treating cow manure and operated as the impeller mixed digesters (STRs) compared to those gained from the unmixed digesters (UMDs) [8]. Mixing patterns also affected reactor performance as Babaei and Shayegan reported that intermittent mixing (15 min on and 30 min off) could improve biogas production by 30–40% compared to continuous and minimal mixing (twice in a batch per day and 30 min each time) when municipal solid waste was used as the feedstock in anaerobic digesters [9]. From previous studies, majority of mixing method investigated in anaerobic digesters were conducted using the propeller. Though it is rather convenient to install, flexible to use and can generate enough mixing intensity for anaerobic digestion, propeller mixing could require high energy and maintenance cost. Moreover, it is not practical for the large-scale anaerobic digester as either numbers or sizes of propeller-driving motors can be the major constrain. Reactor mixing can effectively be done via the air-lift configuration. Air-lift operation is conducted through the installation of pipes below the water level in the reactor. The compressed air or, for anaerobic digesters, biogas produced inside the reactor is pumped through to the pipe at the lower end to push the water up to the height above the water level in reactor, generating particular flow pattern as a loop circulation [10]. The advantages of air-lift is good mixing, low energy requirements, low operation and maintenance cost, low contamination risk and no heat generation [11]. This study aimed to (1) utilize the simple simulation program to assess conditions for air-lift mixing and (2) investigate effects of biogas flow rates and installing positions for air-lift system on biogas production efficiencies of the full-scale modified covered lagoons (MCL) treating dairy manure.

Methodology

Substrate

Dairy manure used in this study was obtained from Darunee farm, Doi Lor District, Chiang Mai, Thailand. The fresh manure was stored in a storage tank at ambient temperatures before feeding. Concentrations of Chemical oxygen demand (COD), Total solids (TS) and Volatile solids (VS) were 64,959±3,913 mg/L, 57,863±7,395 mg/L and 48,875±6,919 mg/L, respectively. Temperatures of cow manure was 29.48±1.18 °C. Dairy manure characteristics are shown in Table 1.

Table 1 Dairy manure characteristics

Parameters	
pH	6.88±0.05
TS (mg/L)	57,863±7,395
VS (mg/L)	48,875±6,919
VFA (mg/LCH_3COOH)	13,528±901
Alkalinity (mg/L$CaCO_3$)	3,869±310
COD (mg/L)	64,959±3,913
Temperature (°C)	29.48±1.18

Experimental methods

The experiment was divided into 3 parts. In the first part, the specific methane yield of dairy manure was determined using the biochemical methane potential (BMP) test. The second part was conducted to find the suitable biogas flowrate and installing position for the air-lift system using ANSYS FLUENT (2019, Student Version). In the third part, effects of air-lift systems on the performance of three identical full-scale modified covered lagoon system (MCLs) were investigated. Details of each experiment are explained as follows:

1. BMP test

The specific methane yield of dairy manure was determined using the BMP test. This test has been used to characterize various substrates and is an important tool for determine methane potential, biodegradability and phase of digestion [12]. The obtained results were fitted with the modified Gompertz model [13] in order to gain the maximum methane production from this waste.

The BMP test was performed in 1,000 mL glass bottles with working volume of 400 mL under mesophilic conditions. The bottle was added with inoculum (120 mL) and dairy manure (9 mL) to have the inoculum to cow manure ratio of 2:1 by VS. Then distilled water was added to reach the working volume. Alkalinity was adjusted with sodium bicarbonate to reach the pH around 7.0. Each bottle was purged with nitrogen gas for 3 minutes to ensure anaerobic conditions and then sealed with a septum. The controlled experiment (blank) was also prepared using only inoculum. Temperature was maintained at 35±2 °C by keeping each bottle inside the water bath (Memmert WNB 45, Germany). All experiments including blank were done in 3 replicates for a period of 55 days

Biogas production was measured via gas pressure in the bottle using Digital Manometer (DM9200, Obereisesheim, Germany). Each bottle was manually shaken before pressure measurement. When pressure reached approximately 250 mbar, biogas compositions were measured using Multichannel Portable Gas Analyzer (Gas Data, GFM406, Coventry, U.K.). Conversion of bottle pressures into volumes of biogas at standard temperature and pressure was done using Equation (1) [14].

$$V_0^{tr} = \frac{V\,(P - P_w)\,T_0}{P_0\,T} \tag{1}$$

where V_0^{tr}, V, T_0, T, P_w, P_0 and P represent volume of dry gas at standard temperature and, volume of gas as read off (mL), pressure (mL) normal temperature (273 K), temperature of the fermentation gas or ambient space (K), vapor pressure of water as function of temperature of ambient space (hPa), normal pressure (1,013 hPa) and pressure of gas phase at the time of reading (hPa), respectively.

Results from BMP tests were used to create a model for the prediction of methane generated by fitting with the modified Gompertz model (Eq. 2) [13].

$$M = M_0 \times \exp\left\{-\exp\left(\frac{R_m \times e}{M_0}(\lambda - t) + 1\right)\right\} \tag{2}$$

where M, M_0, R_m, and λ represent the cumulative methane yield (mL CH_4/gVS) at a given time, methane production potential (mLCH_4/gVS), maximum methane production rate (mLCH_4/gVS-d), and lag phase (d), respectively.

2. Reactor mixing regime simulations

Reactor mixing regimes were analyzed by simulating the flow regime inside the 2D reaction tank using ANSYS FLUENT (2019, Student Version). The calculation was undertaken using the numerical method, i.e. the fractional step discretization of the time-dependent incompressible Navier-Stokes equations [15], to find the answer from the governing equations shown in Table 2. The program was set up to find the multiphase equation of each type of phase, i.e., liquid, solids and gas, in the reactor. This relied on the volume of fluid method for calculation and was simulated as the triangle unstructured mesh with approximately 400,000 elements. The set boundary condition of the experiment is shown in Figure 1 and dimensions of the reactor is presented in Figure 2.

Table 2 Numerical methods to find the answer from the Governing equations

	Governing equations
equations	Incompressible Navier-Stokes equations
Transient term	Second order implicit metho
Spatial derivatives term	Second order finite volume upwind method
Pressure-velocity coupling	Fractional step method
Pressure term	PRESTO

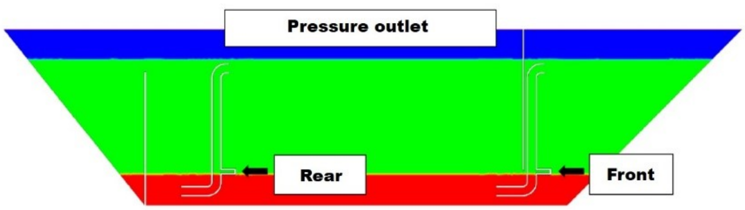


Figure 1 Boundary condition for simulation (green = liguid; red = solids; blue = gas)

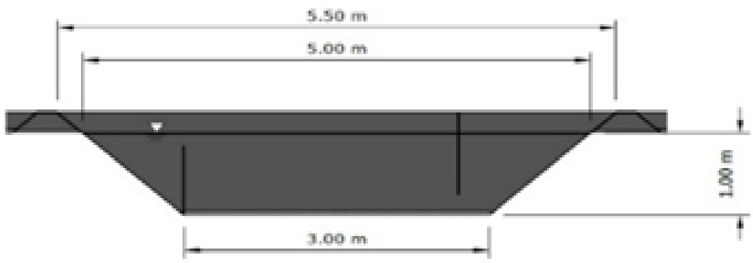


Figure 2 Dimensions of reactor

Three different biogas flowrates, i.e., 5, 10 and 20 L/min, were simulated when air-lift systems were operated both in the front and rear parts of the reactor (namely Case 1, 2 and 3, respectively). Also mixing pattern was investigated when the air-lift system was operated only in the front part at the biogas flow rate of 20 L/min (Case 4). The initial simulation condition is presented in Table 3.

3. Effects of air-lift systems on the performance of MCLs

Effects of air-lift systems on the performance of three identical full-scale MCLs (R1, R2 and R3) were investigated at Darunee farm, Doi Lo District, Chiang Mai, Thailand. Each MCL (Fig 3(a)) had the working volume of 8 m^3 and was fed via the feeding pipe located at the front end of the reactor while effluent was overflowed through the effluent pipe installed at the other end of the reactor1 and dimensions of the reactor is presented in Figure 4. The HDPE sheet was used to cover each reactor and biogas was collected via a gas pipe located at the rear part of the reactor. Before feeding, dairy manure was mixed with water at the ratio of 1:1.5 by wt. The reactor was manually fed 3 days/week with amount of dairy manure of 589.5 L. R1 was used as the controlled reactor and operated while the air-lift system was completely turned off (without mixing). R2 was operated with the air-lift system only in the front part was turned on, while in R3 air-lift systems both in the front and rear parts were on. At each location, two pipes were installed and the biogas flowrate was equally divided through these two pipes (Fig 3(b)). All reactors were fed with the real dairy waste under ambient temperatures and operated at the OLR of 2.0 kg VS/m^3-d for 112 d, which was equivalent to 3.5 times of the HRT. The air-lift system in R2 and R3 was on for 20 min every one hour [9] and operated at the biogas flowrate of 20 L/min. Dimensions of the reactor is presented in Figure 4.

To monitor the reactor performance, temperature, biogas volume (diaphragm meter; AMPY Gas Meter Model 750, ZETLAND, Australia), biogas composition (multichannel portable gas analyzer version GFM406, Gas Data, Coventry, U.K.) and pH (pH meter; TQC Sheen, WATERPROOF PHTESTR30, Netherlands) were measured at the site three times per week. Samples of effluent were taken on weekly basis and analyzed for chemical oxygen demand (COD), total solids (TS), volatile solids (VS), total suspended solids (TSS), volatile suspended solids (VSS), volatile fatty acids (VFA), and alkalinity (ALK) according to the Standard Methods [16].

4. Statistical Analysis

The experimental data of all studied reactors were investigated and compared using the one-way analysis of variance (ANOVA) at the confidence level of 95%.

Results and Discussions

Potential of biogas production from dairy manure

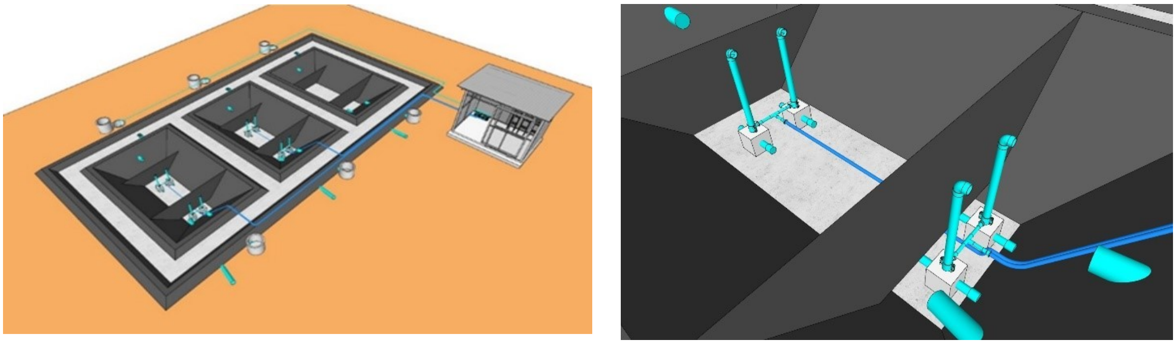
The specific methane production obtained from the modified BMP test was 196 L CH_4/kg VS in 55 days of experiment (Fig 5). Results fitted well with the modified Gompertz model (R^2 = 0.99) [13] and the total specific methane yield (P) obtained was 316.11 L CH_4/kg VS with the lag time (λ) of 3.50 d (Table 4). These values were in the same range as those reported to gain from dairy manure in previous studies [17].

Simulations of reactor mixing

Visual mixing images of different phases and velocity magnitudes and directions inside the reactor are shown in Fig 6. For Case 1, it was found that at the end of the simulation period (60 sec), majority of solids (especially at the middle part of the reactor) still settled at the bottom of the reactor which was corresponded with the small velocity magnitude and relatively larger dead zone area (Fig 6(a)). When biogas flowrate was increased to 10 L/min (Case 2), less solids were settled in the middle part of the reactor. However, small velocity magnitude, especially right at the area behind the first baffle wall, was still clearly observed (Fig 6(b)). Mixing at this particular area is crucial as the organic loading at the front of the reactor is high and thorough contact between microorganisms and substrates need to be achieved to avoid low pH profile and imbalance conditions among different microbial group at the latter parts of the reactor. At the biogas flowrate of 20 L/min (Case 3; Fig 6(c)), better mixing in the middle part of the reactor was visually observed. More importantly, velocity vectors behind the first baffle wall area were obviously present with much lesser dead zone area. When only the front part air-lift system was operated at the flowrate of 20 L/min (Case 4; Fig 6(d)), almost all solids were settled in the middle part of the reactor. Yet, thorough mixing was still attained at the front part and considerable velocity vectors are spotted behind the first baffle wall. From these aforementioned results, biogas flowrate of 20 L/min was chosen as the optimum condition for MCL mixing. Operation of the air-lift system at different locations in the reactor was then investigated using the pilot-scale MCLs.

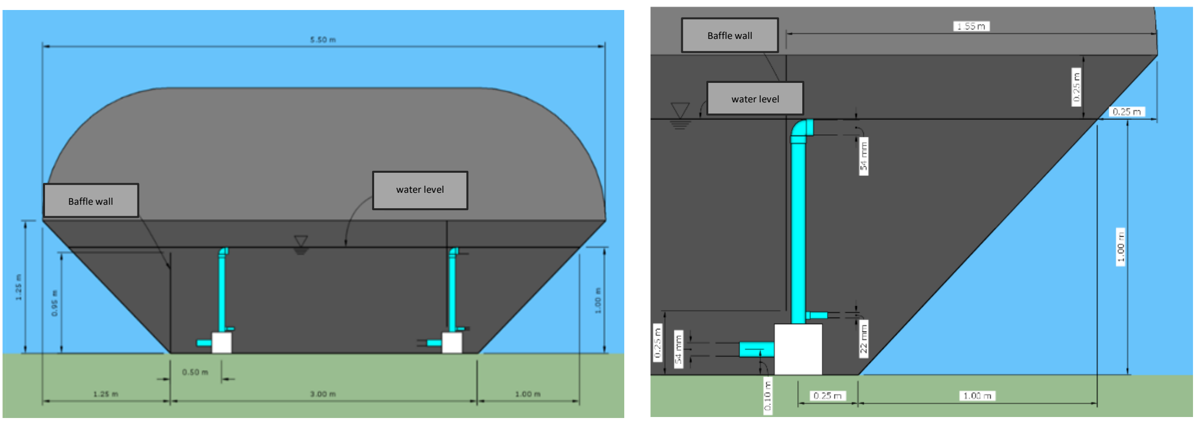
Table 3 Initial simulation conditions

Case	Gas flow rate (L/min)		Position of mixing
	Front	Rear	
1	5	5	front and rear
2	10	10	front and rear
3	20	20	front and rear
4	20	0	front



(a) (b)

Figure 3 Full-scale MCLs (a) and air- lift system in each MCL (b)



(a) (b)

Figure 4 Dimensions of MCL (a) and air lift system (b)

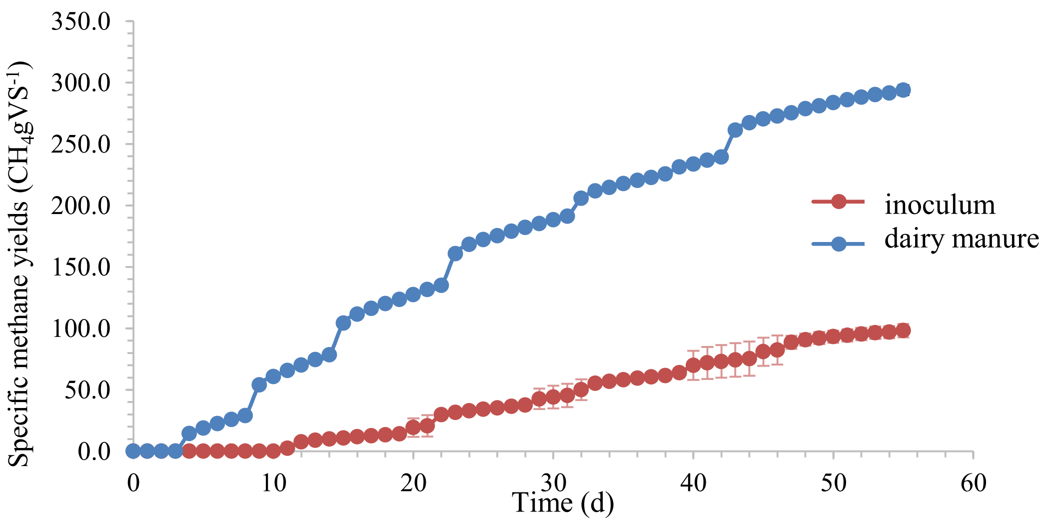
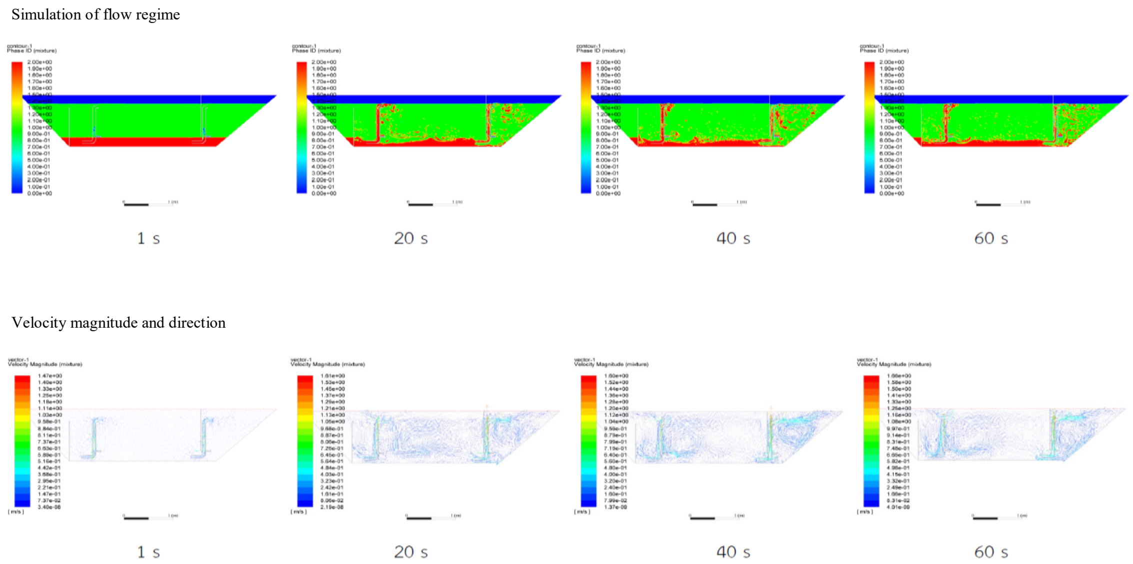


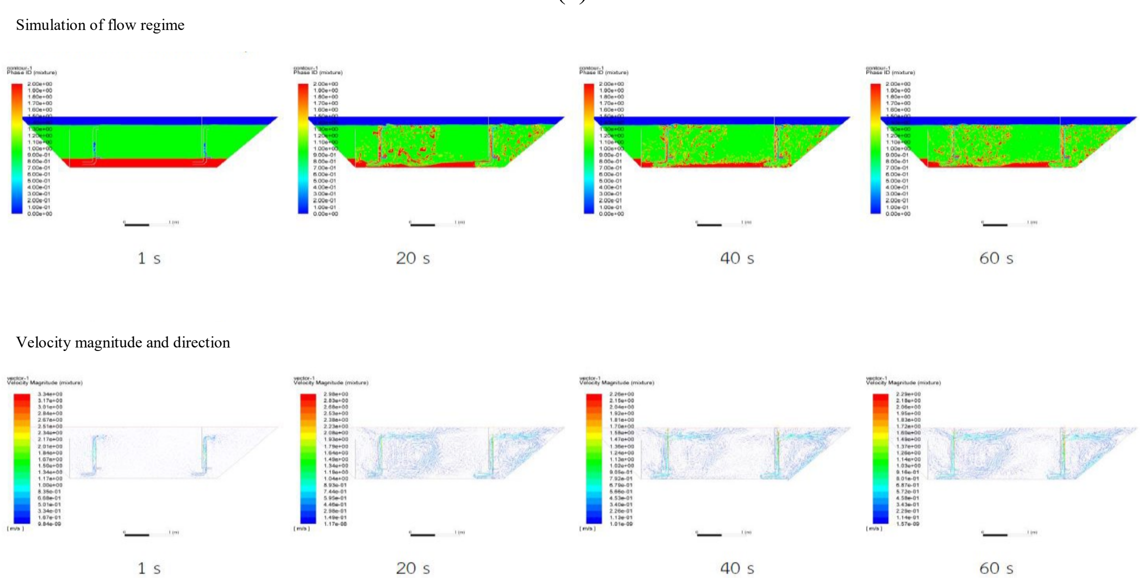
Figure 5 Results obtained from the BMP

Table 4 Results obtained from the modified Gompertz model

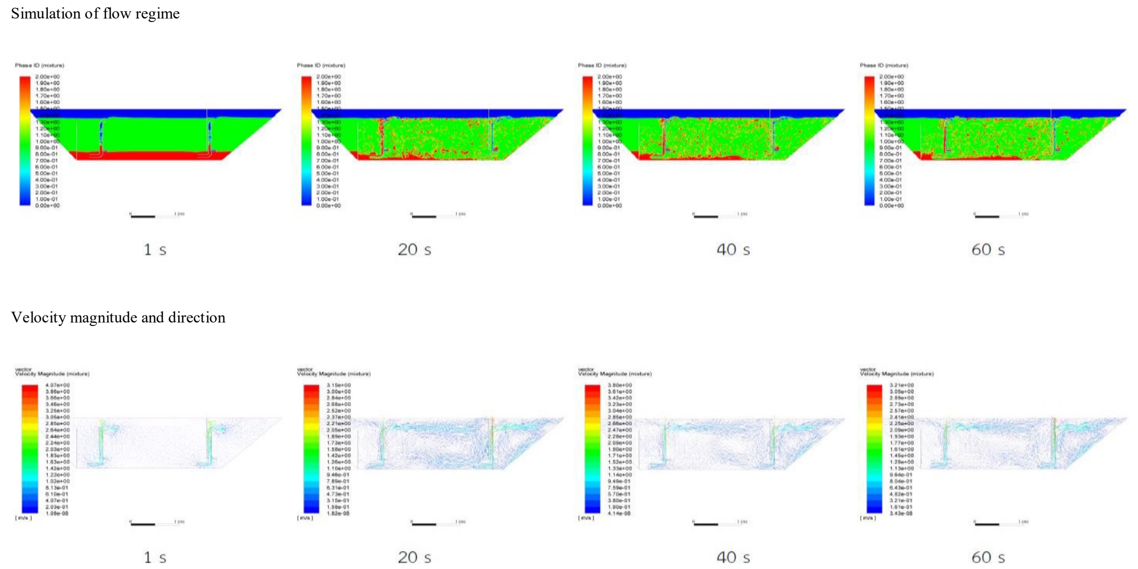
Sample	P (ml CH_4/g VS)	R_m	λ	R^2
Dairy manure	316.11	7.65	3.50	0.99



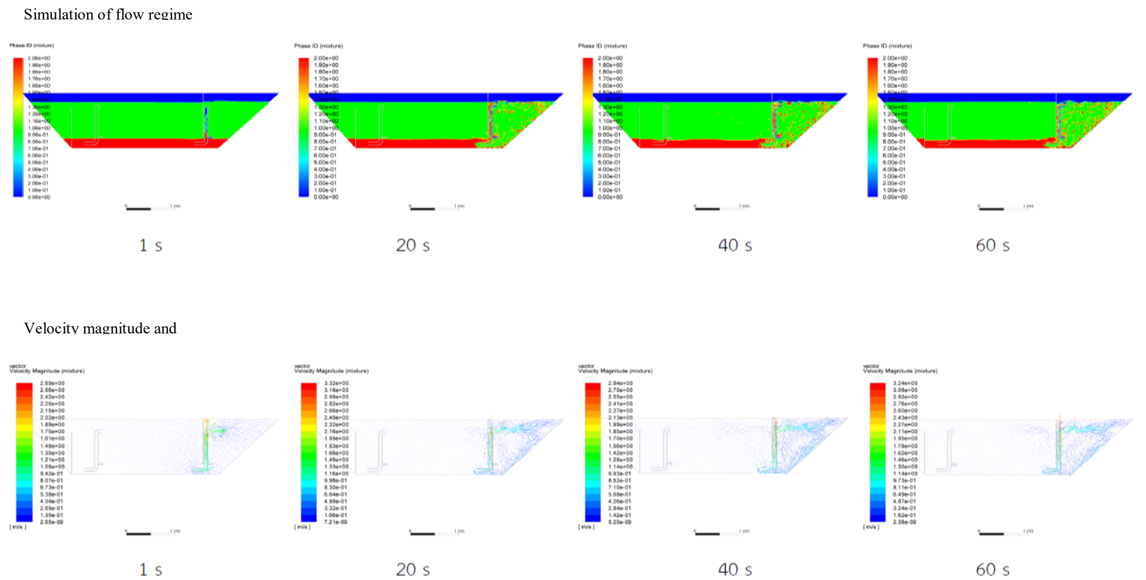
(a)



(b)



(c)



(d)

Figure 6 Simulations of reactor mixing at different biogas flowrates; (a) 5 L/min (Case 1), (b) 10 L/min (Case 2), (C) 20 L/min (Case 3) and (d) 20 L/min (Case 4; the air-lift system was operated only in the front part)

Effects of air-lift system operations on the performance of MCLs

Performance of all studied MCLs is presented in Table 4. Effluent pH values of R1, R2 and R3 were 7.31±0.04, 7.22±0.11 and 7.25±0.04, respectively, which were within the optimum range for suitable anaerobic digestion (6.8–7.2; [18]). All reactors were operated under the temperatures of 31.52±0.73, 31.64±0.79, 31.68±0.75 °C for R1, R2 and R3, respectively. These temperatures were in the optimum range of 30–39 °C [19], which was suitable for the growth and function of mesophiles.

Table 4 Performance of all studied MCLs

Parameter	Influent	Effluent		
		R1	R2	R3
pH	6.89±0.11	7.31±0.04	7.22±0.11	7.25±0.04
Temperature (°C)	29.48±1.18	31.52±0.73	31.64±0.79	31.68±0.75
COD (mg/L)	57,789±11,420	24,487±4,675	27,396±8,055	31,355±8.899
TS (mg/L)	57,548±10,276	30,073±6,318	29,685±8,986	35,017±7,089
VS (mg/L)	48,873±8,744	23,244±5,365	23,850±7,631	27,403±5,522
Alk (mg/L$CaCO_3$)		2,915±0.11	2,422±631	2,522±333
VFA (mg/LCH_3COOH)		1,419±127	970±222	998±132
VFA/Alk		0.49±0.04	0.41±0.04	0.40±0.05
CH_4(%)		54.7±9.1	51.6±11.4	57.3±4.6
Biogas production (L/day)		2,084±356	3,304±938	1,684±412
Specific methane yield (L CH_4/kg VS_{added})		100±19	156±51	81±19
Removal efficiency of COD (%)		56±13	51±16	43±20
Removal efficiency of TS (%)		47±12	48±15	37±19
Removal efficiency of VS (%)		52±12	51±15	42±17

*Notes: Data is shown as Mean ± Standard deviation; confidence level significantly was 95%.

Effluent VFA concentrations of the unmixed R1 (1,419±127 mg/L) was significantly higher (p = 0.000) than those of R2 and R3. Also, the VFA/Alk ratio of R1 was found to be the highest among all studied reactors. High VFA level is the result of microbial interaction being failed to convert organic matters into suitable types of VFA for biogas production [20]. Accumulation of VFA have negative effects on the system as high VFA concentrations cause the inhibition of methanogenesis leading to the process failure [21]. That R2 and R3 could maintain effluent VFA concentrations in low levels (< 1,000 mg/L) suggested that mixing was crucial for the well-balanced microbial interactions of anaerobic digestion of dairy manure. In terms of COD and VS removal, comparable removal efficiencies were obtained from R1 and R2 while significantly lower efficiencies were detected from R3. This inferiority of R3 could partly be the results of excessive mixing and sludge wash out from the reactor.

Interestingly, both biogas production and specific methane yield obtained from R2 (3,304±938 L /d and 156±51 L CH4/kg VS) were significantly higher (p = 0.000) those of R1 (2,084±356 L/d and 100±19 L CH_4/kg VS) and R3 (1,684±412 L/d and 81±19 L CH_4/kg VS). Moreover, R3 was found to produce the lowest biogas and provide the least specific methane yield, even when compared to those of the unmixed R1. These results indicated that for a particular type of anaerobic reactor, both the mixing intensity and position of mixing device were crucial and needed to be specifically determined. For the MCLs studied in this current work, installation of air-lift systems both in the front and rear parts (R3) which rendered the most complete mixing resulted in methane production efficiencies being the lowest. Deterioration of R3 efficiencies could be caused by the sludge wash out as effluent TS and VS of R3 were significantly higher than those of R1 and R2 (p = 0.006 and 0.013, respectively). Results clearly showed that provision of the mixing system only in the front part (as in R2) was the most suitable arrangement for the treatment and biogas production from dairy waste. Under this installation, the reactor could reasonably remove VS, produce methane (which was accounted for 79.6% of the maximum specific methane yield gained from the BMP test) and provide the conditions suited for maintaining process stability.

Conclusion

Both biogas flowrates and installation positions were found to significantly affect the mixing regimes and reactor performances. The suitable biogas flowrate was 20 L/min, which provided the best MCLs performance when installed only at the front part of the reactor. This work also suggested that the simple simulation program could be effectively used to assist in the determination of suitable mixing conditions for the anaerobic bioreactor.

Acknowledgement

Authors would like to thank Darunee farm, Doi Lo District, Chiang Mai, Thailand for the area and manure provided during the experiment. All simulations were done by Assoc. Prof. Dr. Watchapon Rojanaratanangkule and Jiratrakul Tunkeaw, Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University. The author (Pornpawee) acknowledged the Faculty of Engineering, Chiang Mai University, for financial support under a Research Assistant scholarship (RA).

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Thai Environmental Engineering Journal Vol. 37 No. 2 (2023) : 43-51
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Measurement of Aerosol Size Distribution in an Urban Park; a Case Study of Chulalongkorn Centenary Park in Bangkok, Thailand

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Abstract

This study investigated the particle size distribution (PSD) in the Chulalongkorn University Centenary Park, an urban park in Bangkok. Two continuous 7-day measurements were conducted during February to March 2023 by employing the Scanning Mobility Particle Sizer (SMPS) and the Optical Particle Sizer (OPS) to measure in the range of 10 – 10,000 nm. Observed $PM_{2.5}$ concentrations and local meteorological parameters were gathered for analysis. Ultrafine-mode concentrations exhibit diurnal pattern correlating with the traffic rush hours in the morning and in the evening. The statistics of geometric mean diameter also indicate minimum values twice daily in the morning and evening rush hours indicating the behavior of freshly emitted particles and subsequent growth. The number concentrations were significantly lower during the daytime than at nighttime highlighting the nighttime meteorological influence. The lumped number concentrations of particles larger than 80 nm (N80) correlates well with $PM_{2.5}$ data. Comparing between the two-measurement period, higher humidity is related to overall larger sizes that could be indicative of hygroscopic growth. Size distributions at chosen periods are presented to highlight the various influences of primary particle emission and microphysical processes. This work provides new information of the level of ultrafine particles that urban dwellers are exposed to in an urban park.

Keywords : size distribution; number concentration; particulate matter; urban park; meteorological parameter

Introduction

Poor urban air quality continues as major environmental issues that face contemporary society including Thailand. Over the past decade, the capital of Thailand has consistently experienced seasonal high $PM_{2.5}$ episodes with no obvious aim for abatement. Bangkok typically has severe $PM_{2.5}$ air pollution events from November to March due to a variety of factors including traffic, street vendors, transportation sectors, open burning, and industries [1]. Urban parks are currently one of the essential components of urban planning, and studies on air quality use them to give a background concentration of pollutants to offer the communities a variety of services and advantages [2-4]. The particle number concentration (PN), surface area concentration (PS), and mass concentration (PM), where PM is directly related to the particle volume concentration (PV), are commonly used to indicate the concentration of atmospheric particles [5]. Accumulating particles contribute significantly to the PS and PV while ultrafine particles typically dominate the PN [5]. Additionally, the recent studies [6, 7] descried the complex dynamic processes including meteorological data, emission sources, and atmospheric processes like nucleation, condensation, coagulation, and deposition contribute the concentration variability of ultrafine particle number size distribution (UFP-PNSD). Modes of four sizes used to describe the particle number size distribution (PNSDs) are nucleation (<25 nm), Aitken (25–100 nm), accumulation (100–1000 nm) [5], and coarse mode (<10000 nm) [8].

Suspended particulate matter has an adverse effect on the environment and human health. The PM_{10} and $PM_{2.5}$ fractions of particulate matter may pass through conductive airways and have a negative impact on the respiratory system and cause increased rates of cardiopulmonary mortality, shortened longevity, respiratory and cardiovascular disorders, as well as other adverse effects on human health [6, 9]. Recent epidemiological studies have shown a direct link between respiratory tract and cardiovascular diseases to airborne PM in urban environment [10]. Despite the chronic $PM_{2.5}$ problem, parallel efforts should be dedicated to advance our knowledge of ultrafine particles and aerosol number concentrations in line with the updated Air Quality Guidelines from WHO.

Several studies [11, 12] stated that the amount of pollution in the park majorly come from the sources in the surrounding area of this park. Moreover, the studies [2, 13] argued that the park in an urban area decreased turbulence of wind speed caused by the presence of its vegetation causing the increased pollutant concentration. Many air pollution studies focused on the case study of emission sources, measurement, simulation, and health risk assessment of particulate matter with the lack of particulate matter concentration and size distribution in urban parks in Thailand.

The objective of this study was to explore the aerosol number size distribution in an urban park locating in the Bangkok central business district. The measurement data will be analyzed together with $PM_{2.5}$, PM_{10}, and meteorological data measured at the park during the same period to provide further insights about the dynamics of the size distribution and level of ultrafine particles in the park.

Methodology

Case Study Area

The aerosol size distribution measurement was conducted in the Chulalongkorn University (CU) Centenary Park (13°44′22″ N, 100°31′25″ E), located in the central business district of Bangkok, Thailand. The site is at an elevation of 2 m above mean sea level and with a total area of 4.48 ha (0.048 square kilometers). The measurement work was conducted with the two measuring periods in the measurement spot (13°44'20.5"N, 100°31'26.1"E). The Park is located adjacent to the Chulalongkorn campus bordering with commercial and community areas. Right next to the park is an ongoing construction site and a community mall with restaurants and markets. Moreover, surrounded road network includes an expressway (West 270 m. away – annual average daily traffic (AADT) 319,180 veh/day), Banthat Thong rd. (adjacent West– AADT 27,500 veh/day), Rama IV rd. (South 375 m. away – AADT 110,397 veh/day), Phaya Thai rd. (East 465 m. away – AADT 61,600 veh/day) and Rama I rd. (North 765 m. away – AADT 46,582 veh/day). The park is open to the public for recreational uses between 5AM – 10PM. Often there are public venues and activities.

Measurements and Data Analysis

The continuous measurements of particle size distributions (PSD) were measured with the Scanning Mobility Particle Sizer (SMPS) model TSI 3910 in conjunction with the Optical Particle Sizer (OPS) model TSI 3330. The SMPS measures the particles covering the sizes of 10–420 nm while the OPS covers the range of 300–10,000 nm. The instruments measure aerosol number concentrations in various size bins and the mass and surface concentrations can be reported using an assigned particle density under a spherical shape assumption. The PSD samples were obtained at 1-minute time resolution. The measurements were carried out in two 7-day continuous periods from 20 February 2023 to 27 February 2023 and to 3 March 2023 to 10 March 2023. The measured PSD from the two instruments were merged using the Multi-instrument Manager (MIM) software and further analyzed and visualized using Microsoft Excel. Meteorological parameters and mass concentration of particles with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) measured by sensors installed at the CU Centenary Park are gathered for statistical analysis [14]. The sensor data which has native time resolution a scale of seconds was temporally averaged to 1-minute average data.

Results and Discussions

Particle size distributions

Figure 1 shows the aerosol number size distributions, dN/dlogDp, in unit of cm^{-3} with respect to sample timestamps. The 1-minute resolution data is displayed as color contour. The average particle number concentrations of 1st and 2nd period were 14,325 cm^{-3} and

11,961 cm^{-3} respectively. Overall, it can be observed that PSD from both measurement periods exhibit similar diurnal pattern. Typical PSD has a dominant mode at around 100 nm with repetitive occurrences of the peaking mode down to 30–50 nm sizes. We will discuss this diurnal pattern further in the next subsection.

Analysis of lumped number concentrations, $PM_{2.5}$, and meteorological factors

To allow comparative analysis of number concentrations in conjunction with other measurement data, the PSD is converted to lumped number concentrations, namely, N10, N40, N80, and N150, which mean total number concentrations of particles with diameter larger than 10 nm, 40 nm, 80 nm, and 150 nm, respectively, in a similar manner to [15]. Time-series of lumped number concentrations are depicted in Figure 2 a) – b) in comparison with the measured $PM_{2.5}$. It is visible that $PM_{2.5}$ correlates well with N80 because accumulation mode particles (Dp 100–1000 nm) overwhelmingly contribute to mass concentrations more than Aitken- and ultrafine-mode particles on the same particle number basis. We also presented the modal number concentrations obtained from the differences between the two lumped number concentrations. For example, N10-40 is the difference between N10 and N40 which highlight the ultrafine-mode concentrations. Figure 2 c) – d) are the plots for N10-40, N40-80, and N80-150. N10-40 displays diurnal cycles peaking twice at around 8AM and 7PM and hit the minimum twice at around 3AM and 2PM. We hypothesize these diurnal peaks to coincide with the traffic rush hour patterns in the morning and the evening and minimum to be associated with coagulation scavenging. Past studies identified the size of particles from traffic emission to center at 15 nm [16].

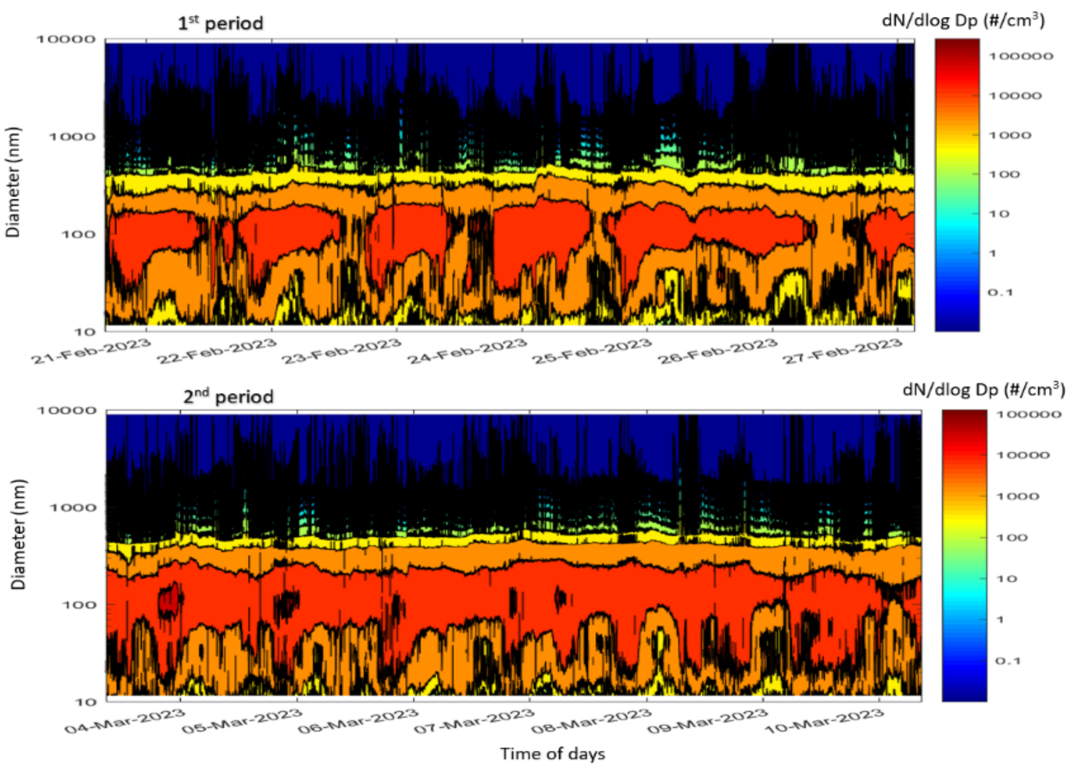

Figure 1 Time-series contour plots of aerosol number size distributions (dN/dlogDp) for the two measurement periods

We gather meteorological parameters measured at the park at the same as the PSD measurement. Temperatures during both measurement periods covered similar ranges of 23 to 39° Celsius and 26 to 38° Celsius. Relative humidity was slightly higher in the second period. Temperature, pressure, and relative humidity display diurnal cycle that closely linked to solar radiation levels. The plots indicate a general negative correlation between temperature and particle number concentrations and likewise with solar radiation. This can be explained with the higher chance of turbulence and atmospheric instability during the daytime that promote dilution of aerosol concentrations.

In addition, relative humidity usually reaches the maximum value of 75% in 1st period and 85% in 2nd period in this study. According to research [17], wet and dry deposition can induce fine particulate matter to coalesce, and several studies [18-20] stated that the high relative humidity may encourage gas-to-particle conversion, increasing the smaller PM fractions [21]. Past studies presented cases of nucleation events with high ultrafine concentrations persisting on the scale of hours followed by subsequent growth [22]. However, we only observe high ultrafine particles in 1-minute burst followed by a rapid growth to larger diameters. Thus, evidence seems to suggest we did not encounter new particle formation event which is probably understandable given the lack of conditions with low preexisting particles. The effect of higher relative humidity in the 2nd period can contribute to the overall larger diameters of the PSD compared to the 1st period this is because water vapor can condense onto hygroscopic particles and grow their sizes.

As mentioned above that solar radiation negatively correlates with lumped number concentrations. However, there are some incidences of high lumped number concentration during the daytime, for example, 21 February 2023 14:15. Locally emitted particles may be the reason but further investigation and data will be needed to shed more light on such event. During both the daytime and nighttime, wind speed has a significant impact on the particle number concentration. The wind speed was found with the highest speed of 4 m/s in 1st period and 2.9 m/s in 2nd period in the daytime, respectively. The wind speed in the measurement is generally higher in the daytime than the nighttime due to the solar radiation. Moreover, the reduction of number concentration in N10, N40, N80 and N150 was observed in both periods of measurement when the wind speed is very high in the daytime. However, a significant increasing in the magnitude of N10, N40, N80 and N150 was observed at nighttime when the wind speed is weak due to the lack of solar radiation. In this case, the evident case was found that the higher wind speeds can also increase the dispersion of particulate matters and other precursor gases. As such the wind direction is another important factor that affects the particle number concentration and size distribution in the atmosphere during both daytime and nighttime [23]. By showing Figure 2 m) – n) for wind direction, the average wind direction was found with the degree value of 348.75 - 11.25 degrees (north direction being 0 degree) in both periods of measurement. There is no clear correlating pattern of wind directions and number concentration because the aerosol concentrations involve various factors, such as the source strength, meteorological conditions, and other topography of the measurement area.

In Figure 1, the highest nucleation-mode particles concentration was significantly dispreading at night as compared to daytime. The fraction with Dp <100 nm showed higher particle number concen-trations (dN/dlog Dp) during daytime and nighttime in both periods often above 105 particles/cm^3. Then, particulate matter with diameters ranging from 10 nm to 10 μm portray similar particle number concentration values throughout the sampling periods. Figure 3 illustrates the diurnal distributions of geometric mean diameters (GMDs) of particles, with an average range spanning from 70 nm to 110 nm during both measurement periods. Furthermore, it is noteworthy that there exists no significant disparity between the highest GMD values observed during the daytime and nighttime in both periods. The traffic emission can influence low GMD every day around 8am and 7pm in the traffic rush hours. The average geometric mean diameters (GMD) in daytime and nighttime were observed to be 83.5 nm and 86.2 nm in the 1st period and 84.4 nm and 95.6 nm in the 2nd period, respectively. This suggests no particular contrast of particle number situations between the two sampling periods. The average geometric mean of nighttime is slightly greater than the daytime average value suggesting that nighttime humidity can contribute to condensational growth. In addition, the average geometric mean values for morning traffic rush hours (7-9AM),

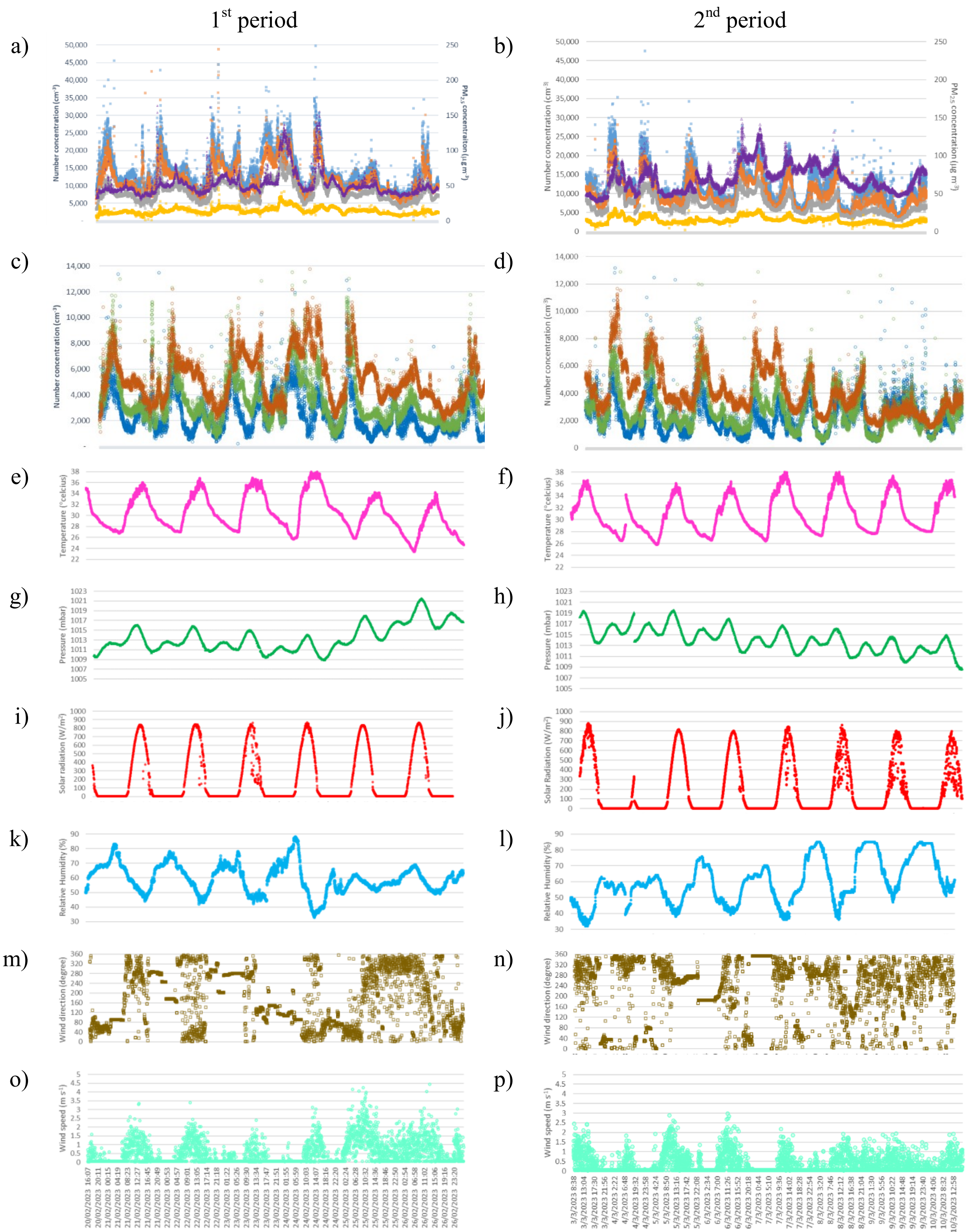

Figure 2 Time-series plots of lumped number concentrations, $PM_{2.5}$ concentrations, modal number concentrations, and meteorological parameters in both measurement periods; a)-b) N10, N40, N80 and N150 and $PM_{2.5}$, c)-d) N10-40, N40-80, and N80-150; e)-f) temperature; g)-h) air pressure, i)-j) solar radiation; k)-l) relative humidity; m)-n) wind direction; o)-p) wind speed.

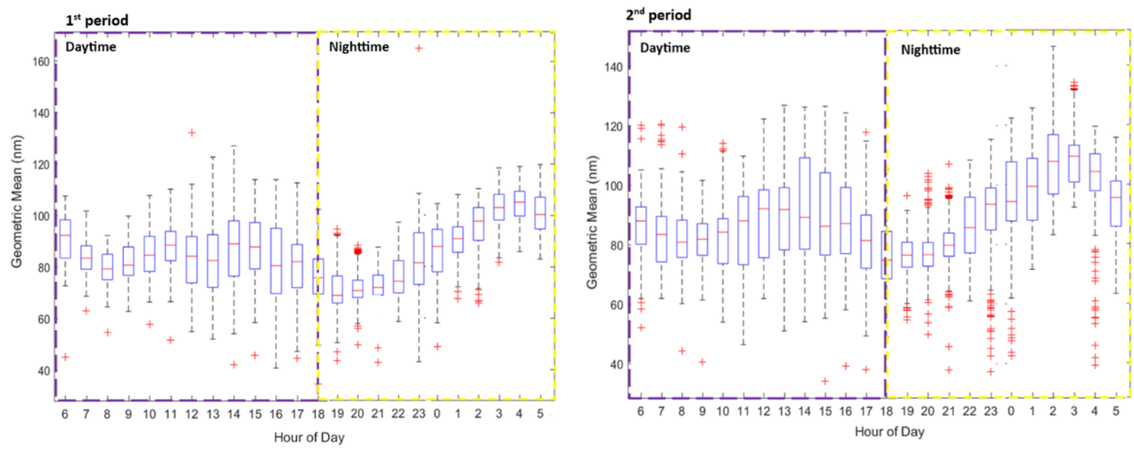

Figure 3 Box plots of geometric mean diameters of PSD in the two measurement periods

mid-day (9AM-6PM), evening rush hours (6-8PM), and nighttime (8PM-7AM) are 81.1 nm, 83.9 nm, 70.9 nm, 87.8 nm, respectively, for the 1st period and 81.8 nm, 84.9 nm, 76.7 nm, and 97.5 nm, respectively, for the 2nd period. The contrast of rush hours and non-rush hours is more notable with the smaller rush hours GMD. This is in accord with the published influence of fresh emission at 15 nanometers. Then after the rush hours, lower traffic means there is fewer supply of freshly-emitted particles and the existing particles grow through coagulation and condensation.

Figure 4 shows the particle size distribution over several selected timestamps in the first period and the second period respectively. In Figure 4a), the typical number concentrations at midday tend to be like PSD of 21 February 2023 12:55 centering at 80 nm and the higher ultrafine concentrations, PSD show bimodal feature with high peak centering around 50 nm and a lower peak at 15 nm such as that on 21 February 2023 17:20. The presence of 15 nm peak may suggest the influence of traffic emission and the second peak may be a result of growing via coagulation. Nighttime size distribution, such as that of 21 February 2023 21:07, peaking at 100 nm could be a result of ultrafine particles emitted during the evening rush hour. It is worth noting that the 2nd period coincided with particularly high $PM_{2.5}$ on multiple days. Apart from the typical shape of PSD centering at the 80 – 90 nm like that in Figure 4b), there is some instance of bimodal distribution with high peak at 30 nm and a lower peak at 150 nm on 4 March 2023 21:28. These insights underscore the complexity of aerosol microphysical dynamics, shaped by multifaceted factors. While the current analysis provides valuable data, it also prompts considerations for further investigation. Future studies may delve into the intricate interplay of meteorological conditions, geographical influences, and seasonal variations on particle size distribution. Additionally, comparing these findings with existing research could enrich our understanding of regional aerosol dynamics.

According to good practices statement of WHO air quality guideline 2021, control of ultrafine particle sources shall be prioritized by the levels of UFPs being low PNC (<1,000 particle/cm^3 (24-hour mean)) or high PNC (>10,000 particle/cm^3 (24-hour mean) or >20,000 particle/cm^3 (1-hour mean)) [24] Figure 5 displays the mean values of total particle number concentrations (all with diameters larger than 10 nm). The results indicate high number concentrations in term of 24-hour mean values throughout both measurement periods. However, high 1-hour mean PNC occasionally occur in the evening and consistently more frequently during the first period. This finding should prompt more attention dedicated to monitor number concentration on a regular basis.

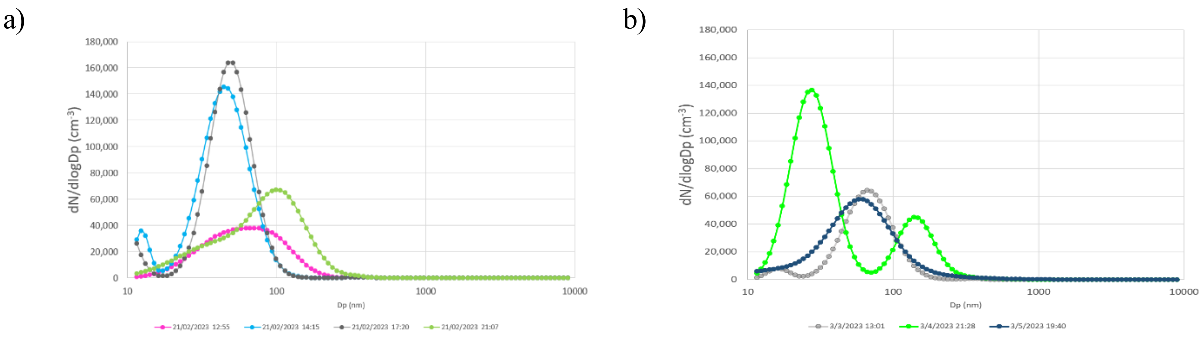

Figure 4 Size distribution of selected times for a) first period and b) second period

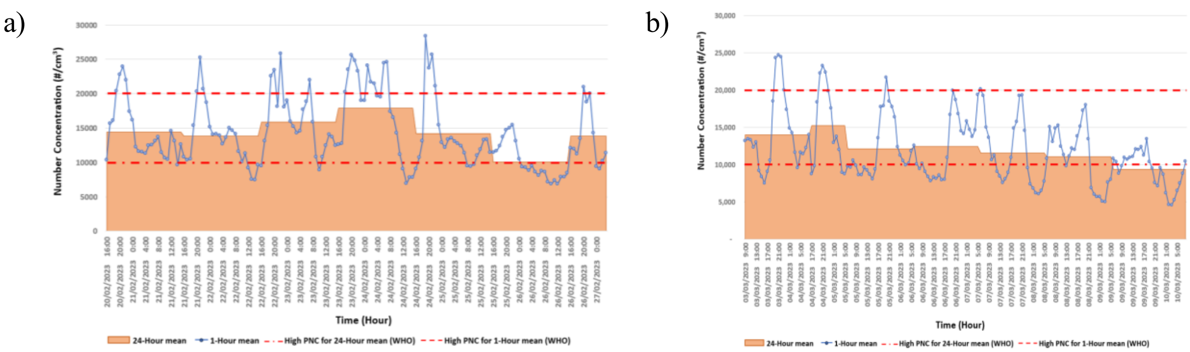

Figure 5 Total number concentrations for a) 1st measurement period and b) 2nd measurement period. The blue line symbols display 1-hour mean and the orange area shows 24-hour mean values. The red continuous broken line marks the WHO recommended high PNC for 1-hour mean and the red dash dot line marks the high PNC for 24-hour mean

Conclusion

Number size distributions were measured in Chulalongkorn University Centenary Park in Bangkok for two continuous 7-day periods in February and March 2023. The results suggested that meteorological conditions had some influence on the particle. Local traffic emissions and adjacent construction site were also anticipated to contribute to ultrafine particle concentrations in the park. Ultrafine particles concentration demonstrated peak patterns in agreement with the morning and evening rush hours. Nighttime increase of concentrations was consistently observed. The statistics of particle geometric mean diameters also exhibit the diurnal pattern of minimum at morning and evening rush hours indicating the influence of fresh emission (low GMD) and subsequent growth (higher GMD). The study also analyzed the lumped number concentration of particles (N10, N40, N80 and N150) and found good correlation of N80 with PM2.5. N80 variability patterns do not show clear correlation with diurnal solar cycle or road traffic activities because the involvement of long-range transport that brought $PM_{2.5}$ into the study area. Also, it was found that higher relative humidity may be the reason for overall larger particles due to hygroscopic growth in the 2nd period. In reference to the recommended benchmarks outlined in the 2021 WHO guideline, the 24-hour mean particle value featured in this investigation surpassed the threshold of 10,000/cm^3, thereby indicating exclusively high PNCs. Additionally, the analysis revealed occasional exceedances the 1-hour mean value of 20,000/cm^3 especially at night. Finally, this study was concluded that meteorological conditions greatly influence the particle concentrations and local traffic emissions plays an important role in the ultrafine concentrations. Aerosol microphysics is a complex process that is essential to consider in the context of understanding and managing ultrafine particles pollution. This work provides new information and good practices of the level of ultrafine particles that urban dwellers are exposed to in an urban park.

Acknowledgements

This research study is supported by Chulalongkorn University Ratchadapiseksompotch Fund for new lecturers (year 1) contract no. DNS 65_036_21_006_1. The SMPS and OPS instru-ments belong to the Scientific and Technological Research Equipment Center, Chulalongkorn University. We acknowledge Thailand Network Center on Air Quality Management (TAQM) and EnvGIT for their support of CUSense monitoring data. We would like to specially thank Assoc. Prof. Dr. Sirima Panyametheekul and Assoc. Prof. Dr. Sanphet Chunithipaisan for their kind support of sensor data. We are grateful to staffs of CU Centenary Park and PMCU (Property Management Chulalongkorn University) for the approval and supporting of measurement in CU Centenary Park.

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Thai Environmental Engineering Journal Vol. 37 No. 2 (2023) : 53-64
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Local Perception on the Invasion of Plecos (*Glyptoperichthys gibbiceps*) and Ecosystem-based Management in Tempe Lake, South Sulawesi, Indonesia

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Abstract

Tempe Lake in South Sulawesi, Indonesia, is encountering a global threat on biodiversity and people well-being: the invasive alien species. The invasion of plecos (*Glyptoperichthys gibbiceps*) deteriorates ecosystem conditions at Tempe Lake, including bank erosion and changes in lake ecosystem function. Local communities in Wajo, a district located adjacent to Tempe Lake, implemented several approaches to reduce pleco population e.g., direct killing, sun-drying, and pleco-based food processing. However, these efforts failed due to the lack of economic incentives and social acceptance of the food made from plecos. Local perception towards the pleco invasion and management alternatives needs to be understood. This study examined local perception on the pleco invasion, villager knowledge about the plecos, and ecosystem-based management. A survey-based study was conducted in 17 villages adjacent to Tempe Lake in Wajo during August to November 2022. A semi-administered questionnaire was employed to collect data i.e., household socioeconomics, villager perception and knowledge, and management alternatives. In total, 200 household representatives participated in the questionnaire of which 53.5% are fishermen. Local fishermen recognized drastic declines in their catch due to increasing pleco population, which directly affected fish consumers because they needed to pay for more expensive fish. The fishermen group expressed strongly that the pleco invasion needs to be controlled now. They perceived that current management was ineffective, especially direct killing of the plecos. Local communities expressed an ecosystem-based management with economic incentives for local community participation is the key. Furthermore, a cost-benefit analysis of proposed projects is essential for effective implementation. Local communities, both villagers and local administration, need clear and sufficient information to help them see potential gains and losses from their actions whether they decide to "do no nothing" or "do something about it."

Keywords : invasive alien species; plecos; Tempe Lake; ecosystem-based management

Introduction

The International Union for Conservation of Nature (IUCN) defines invasive alien species as "*species introduced into places outside their natural range that have negative impacts on native biodiversity.*" There are several vectors for invasive species to colonize in certain environments. Scientists classify these vectors into two groups. The first group is transportation-related vectors, representing economic or social activities when moving from one place to another. Examples of species known to be transported from their native habitats to other places are *Styela clava* and *Botrylloides violaceus* (invasive ascidians) and macroalgae e.g., *Sargassum muticum*, hulled on recreational boats [1]. Secondly, trade and consumption activities [2], including dam construction, sport fishing and aquaculture [3], agricultural expansion, natural resource exploitation, and urbanization [4] are also key vectors of alien species distribution and invasion. Invasive species affect a biomass balance in certain habitats [5], alter ecosystem functions and cause economic losses [6]. Large-scale tree mortalities were caused by gypsy moths (*Lymantria dispar*), hemlock woolly adelgids (*Adelges tsugae*), beech scales (*Cryptococcus fagisuga*), and emerald ash borers (*Agrilus planipennis*) [7]. Moreover, alien species spread over time as global logistic transport grows. Sea or marine-based logistic transport accounts for nearly 90% of global transportation, allowing a large number of species to travel outside their native habitats. The world's emerging shipping network could yield a 3-to-20-fold increase in global invasion risk of alien species by 2050 [8].

Fish have been introduced outside their native habitats throughout the world. For example, the armored catfish or plecos (Loricaridae), native to freshwater habitats of the South and Central America, are recorded outside their native range, including Central America, southern states of the USA, the Pacific Ocean, East and Southeast Asia, since the second half of the 20th century [9]. Plecos spread due to bad practices in aquarium trade and hobbies [10]. Sometimes, they escaped by accidents due to floods. Plecos have demonstrated posing threats to non-native ecosystems because they outcompete native species, alter species composition and induce erosion and siltation [10-13]. They potentially lead to native species reduction or even extinction [14-15].

Tempe Lake is one of the largest freshwater wetlands in South Sulawesi, Indonesia. It is home to great biodiversity, including at least 19 fish species, 21 species of aquatic plants, three species of reptiles, and five migratory bird species [12, 13]. In addition, two fish species are classified as endemic to Tempe Lake, namely the binishi (*Oryzias celebensis*) and the Celebes rainbow (*Telmatherina ladigesi*). Tempe Lake greatly contributes to local livelihoods, including agriculture, aquaculture, transportation, fishery, and water supply [16, 17]. However, Tempe Lake is experiencing substantial changes that alter lake ecosystem conditions such as water pollution, sedimentation, decreases in native fish populations, and invasion of alien species, specifically the plecos (*Glyptoperichthys gibbiceps*, Loricaridae, Figure 1). In 2014, the Indonesian Ministry of Marine Affairs and Fisheries (Regulation Number 41) listed the plecos as an invasive alien species due to wide propagation and aggressive competition with native fish, which led to population declines and damaged local fishery [18]. The pleco invasion deteriorates ecosystem conditions at Tempe Lake, including bank erosion and changes in lake ecosystem function, especially from species composition and interaction alteration [19, 20].

Local communities in Wajo, a district located adjacent to Tempe Lake, had implemented several approaches to reduce pleco population such as direct killing, sun-drying and pleco-based food processing. However, these efforts failed due to the lack of economic incentives and social acceptance of the food made from plecos [18]. Villagers were unfamiliar with the taste so hesitated to eat it. A survey conducted in 2021 revealed that management alternatives need to be affordable and practical at a household-scale for local communities to get involved [19].

Figure 1 A picture of plecos caught by a local fisherman from Tempe Lake.
(The photograph was taken by the researcher in 2022)

Given potential threats from the pleco invasion to Tempe Lake, effective management with community participation is needed more urgently than ever. Local perception towards the pleco invasion and management alternatives needs to be understood. This study examined local perception on the pleco invasion in Tempe Lake, villager knowledge on the plecos and their habitats, and ecosystem-based management. Local community participation is one of the key factors necessary for effective management [13], and it depends on villager perception and expectation of benefits accrued from investing their time, labor or money in management activities [21, 22]. Many ecosystem management projects failed due to low community participation [23]. For instance, rural communities in the Kat River valley, located between small agricultural towns of Seymour and Fort Beaufort, South Africa, positively viewed that an increasing number of invasive cacti (*Opuntia ficus-indica*) were beneficial. Villagers could earn additional income from selling the cactus fruit, although scientists and ecosystem managers were trying to eradicate these invaders to protect the native species [18]. Another example is the Yellowstone Cutthroat (*Oncorhynchus clarkii bouvieri*), a native species being threatened due to angler preferences of a native fish over invasive species e.g., predatory lake trout (*Salvelinus namaycush*). To protect native populations from overfishing, while helping reduce invasive species population, Yellowstone lake's managers need to change angler's perception so they can shift from catching only native fish to invasive species [24]. These different perspectives between the locals and project managers resulted in low participation hindering effective management.

Methodology

The study took place in 17 villages, located adjacent to Tempe Lake in Wajo district, South Sulawesi, Indonesia (Figure 2). A semi-administered questionnaire was conducted in August to November 2022 to collect data, including household socioeconomic conditions, villager perception on the lake and pleco invasion, knowledge on the plecos and their habitats, and management alternatives. A sample size was determined using the Taro Yamane's formula [25] with 7% of error. Household representatives from each of the 17 villages were asked if they would be willing to participate in the survey. If they agreed, they would be personally interviewed according to a series of questionnaire questions. Basically, the questions on local perception were structured based on a Likert's scale scoring from 1 to 5 (1 = strongly disagree to 5 = strongly agree). In addition, village leader interviews and onsite observation were conducted to cross check data from the questionnaire. Data analyses were based on descriptive statistics, t-test, and the Chi-square test of Independence. We hypothesized that key household socioeconomic conditions e.g., occupation: fishermen vs non-fishermen, educational levels, age and household income, are likely to influence the samples' perception and willingness to participate in the pleco invasion ecosystem-based management.

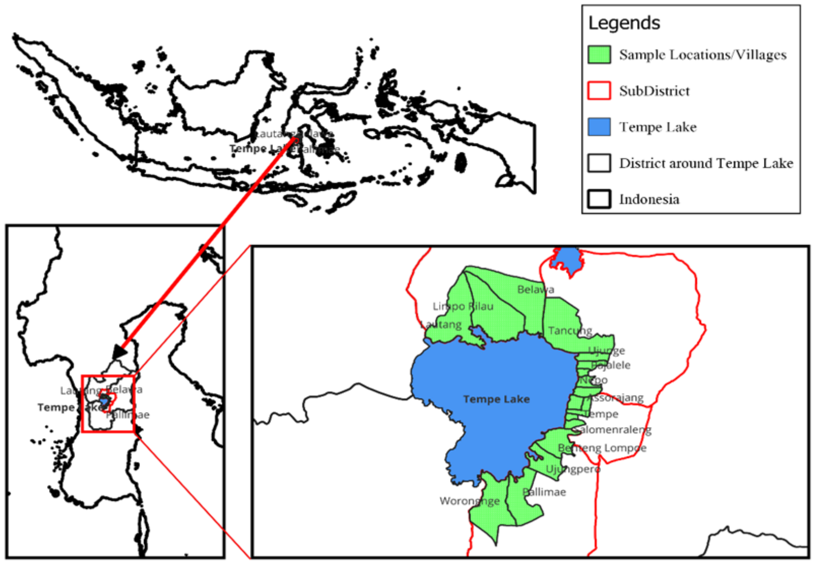

Figure 2 The study site: Tempe Lake and the 17 villages located adjacent to the Lake in Wajo district, South Sulawesi, Indonesia

Results and Discussion

Household socioeconomics

In total, 200 household representatives participated in the questionnaire survey of which 53.5% are fishermen. The rest is a non-fishermen group, consisting of civil servants, business owners, contract employees and farmers. The majority of samples (97.5%) aged between 25-60 years with about 2.5% considered as elderly. The average age is 37 years old, indicating active labors responded to the questionnaire. Basic education within the fishermen group is elementary school (48.6%); some obtained no education (6.5%) and none earned higher education. In contrast, the non-fishermen group mostly obtained high school and higher education (46.2% and 31.8%, respectively). They generally work as civil servants in local government agencies e.g., Wajo local administration, public school, and hospital.

The majority of respondents, especially fishermen, earned income on average of US$90.93 per month, slightly below a national standard for civil servant salary i.e., US$101 up to US$196 monthly (Indonesian Government Declaration Number 15, 2019). Meanwhile, about one fourth of the non-fishermen group were considered as a middle to higher income family, obtaining a monthly salary above US$101. Generally, one household consists of two and four members for the fishermen and non-fishermen groups, respectively. Approximately, 65.5% of the family members are considered active labors, responsible for household income generation. Figure 3 summarizes key socioeconomic conditions of the sampled households.

Local livelihoods and connections between the Wajo people and Tempe Lake

The majority of Wajo residents are the Buginese, the biggest native group of South Sulawesi. Their livelihoods directly depend on Tempe Lake, especially subsistence fishery and seasonal cultivation due to regular flooding in areas near the lake. From May to September, a rainy season, floods usually occur, turning large amounts of land into a shallow lake (Figure 4). Throughout the year, the majority of villagers earn their income from fishery and farming. But during the flooding season, they earn income only from fishery and sometimes wait for the government aid. Crops such as vegetables and rice are usually cultivated in the dry season from October to April when floods recede. During the survey, villagers said that this year they encountered the most severe flooding in the past decade. Floods lasted for nearly three months and water levels reached up to 4 m.

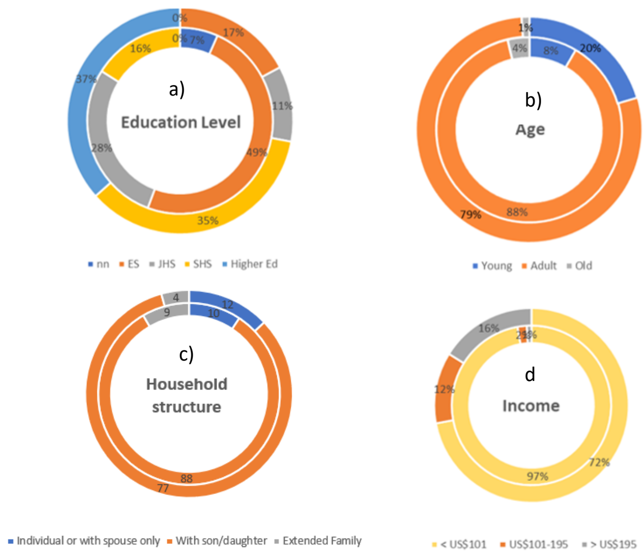

Figure 3 The sampled households' socioeconomic conditions: a) education levels, b) age classes, c) household structure, and d) income levels. Note: The inner doughnut charts depict fishermen's information, while the outer depicts non-fishermen

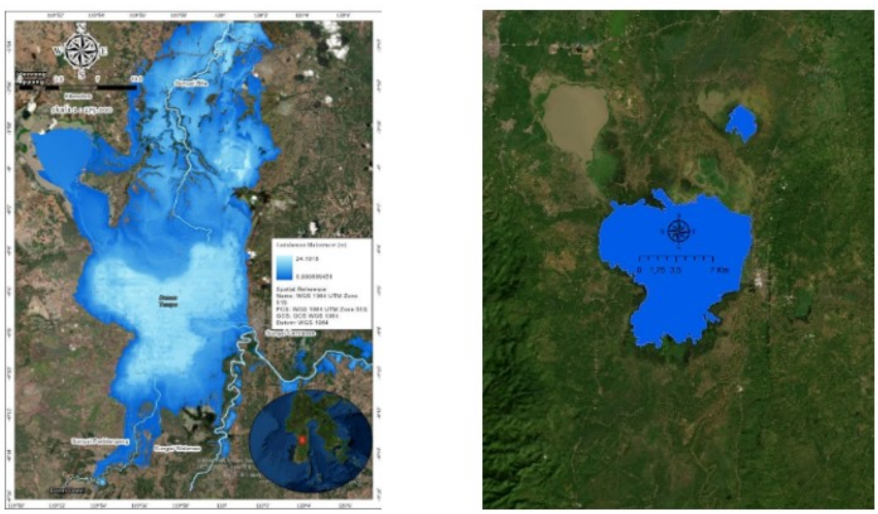

Figure 4 Areas in/around Tempe Lake during: the flooding season (left) and the dry season (right)

The Wajo people adapt to flooding conditions. Nearly all households owned boat(s) either for fishing or commuting during the flood season. The government provided some households, especially those with low income, with a boat so they can use during the flooding (Figure 5). In addition, some families built a floating house on the lake, particularly in villages located at the southern side of Tempe Lake e.g., Tempe and Laelo. This traditional housing style is common among subsistence fishermen families since they can move around following a fishing ground. However, a number of floating houses declined due to changes in lake conditions, land use regulation and socioeconomic development.

Figure 5 Different boat styles provided by the government to some local households since floods occurred regularly: a. big-sized boat, b. small-sized boat and c. square-type boat

Key ecosystem changes at Tempe Lake

Table 1 summarizes key changes at Tempe Lake observed by local villagers. The fishermen group clearly stated that water quality was polluted, followed by more frequent flooding and biodiversity decline. Meanwhile, the non-fishermen group expressed half and half opinions. The majority of them agreed that floods occurred more often, but they were less aware of water quality change and biodiversity loss, including the pleco invasion. Moreover, 18 respondents from the non-fishermen group (~20%) clearly stated "there are no problems" at all. Perhaps, the non-fishermen group did not directly interact with the lake when compared to those fishermen who go out fishing every day. The fishermen observed lake conditions during their fishing trips and recognized changes. They can act as a real-time monitor; thus, their perception and participation are essential for effective management.

Furthermore, local perception of the lake conditions related to village locations. Figure 6 depicts geographic locations of the samples who agreed (red) and disagreed (green) with the given issues as described in Table 1. Basically, those who agreed that flooding and biodiversity loss problems existed lived in villages located north of the Tempe Lake but downstream of the "Bendungan Gerak" Dam. The dam was constructed in 2013 for flood control and water resource management purposes. Areas closer to the dam experienced less flooding because dam operation conveys flood water to flow out of the village zones. Meanwhile, the majority of samples who expressed concerns on lake water quality distributed throughout the study villages. Finally, none of the samples recognized land use conflict in their village area.

Table 1 Key changes observed by local villagers living in/around the Tempe Lake

Items	Fishermen		Non-fishermen	
	A	D	A	D
1. Water quality is polluted.	107	0	45	48
2. Floods occurred more frequently, affecting local people.	76	31	50	43
3. Biodiversity decreased.	74	33	36	57
4. There are land use conflicts in your area.	0	107	0	93
5. The Pleco population increased.	107	0	34	59

Note: A = agreed, D = disagreed. Numeric data represent a number of samples responded to the statements.

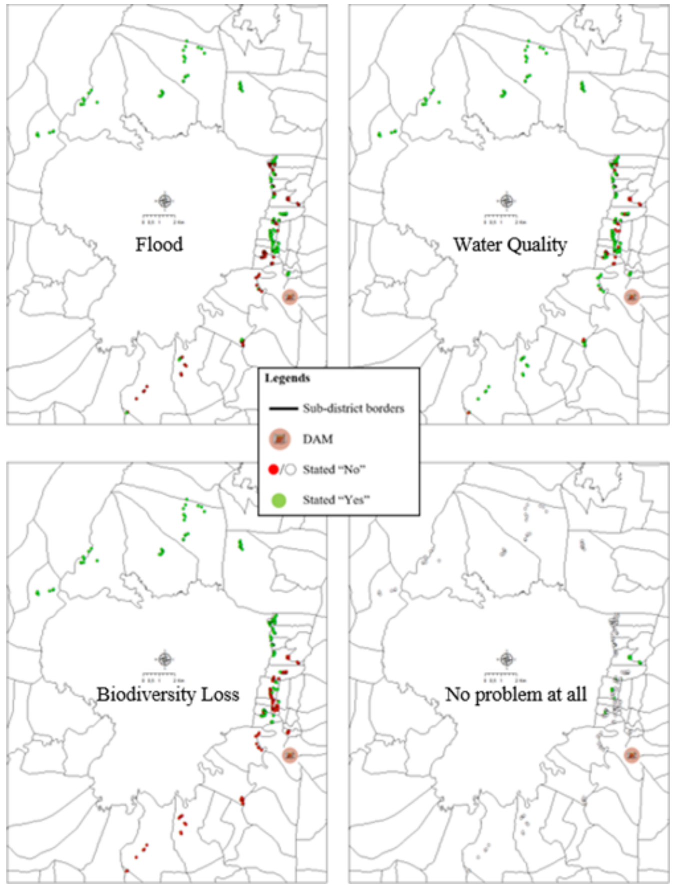

Figure 6 Geographic distribution of the sample responses: Red = agreed that problems existed, and Green = disagreed with such the problems

Local perception and knowledge on the pleco invasion and current management

Local fishermen recognized a drastic decline in their catch due to the increasing pleco population. The pleco invasion caused other fish prices to rise due to decreased amounts of catch, which directly affected fish consumers because they needed to pay for more expensive fish. The fishermen group expressed strongly that the pleco invasion needs to be controlled in a timely manner (Table 2). They disagreed that current management was effective, especially direct killing of the plecos, whereas the non-fishermen group agreed otherwise. Local fishermen reflected that economic incentives are the key. Since the plecos now obtain no market value, nobody wants to invest anything because they cannot see any benefit returns. However, when the two groups were asked if they would like to eat food made from plecos, they gave a neutral response. This is considered a positive signal since they did not reject the idea of turning plecos to human food – the pleco-based food processing. Villagers wanted to try if the project showed them potential profits from doing so. Particularly, the fishermen group would like to give it a try because they want to get rid of plecos.

Moreover, the respondents agreed that they observed decreasing connections between people and the lake, especially among young generations. This poses a great challenge for effective management since youth power and their participation is one of the keys to determine our future toward sustainability [26]. Urbanization brings convenience but also departs people from nature, especially the young because they basically grow up in the more urbanized environment. With loose connections, they may not realize how important Tempe Lake is to their livelihoods. Some of the interviewed fishermen leaders said that their kids were not interested in fishing due to hard-working perception, high costs but low returns. Many parents actually encouraged their children to go work in cities since better income jobs can be expected. Subsistence fisheries can hardly support household economies. The pleco invasion even worsens this situation. It does not only deteriorate the lake and biodiversity but also shatter the community structure and culture.

Obviously, local people recognized the pleco invasion and its impacts on the lake and livelihoods, especially within the fishermen group. Despite knowing about the invasion, we asked how villagers knew about the plecos, including physical appearance and habitat. All the fishermen could tell what the pleco fish looks like and where its habitat is. In contrast, the non-fishermen group received an average score of 1.63, significantly lower than the mean score of the fishermen group (Table 3). They might recognize or hear some of the invasion problems, but do not pay attention to the fish since their livelihoods depend on other activities rather than fishery.

Community willingness to participate in ecosystem-based management of the plecos

The pleco invasion needs action now, and it needs to be ecosystem-based management where ecological, social, and economic aspects are taken into considerations [27]. We asked what the villagers at Wajo thought about ecosystem-based management to deal with the pleco invasion at Tempe Lake. In doing so, we proposed a project named "the pleco-based Black Soldier Fly (BSF) feedstock production" where plecos will be used to make the BSF feedstock. This will help reduce the pleco population – an *ecological aspect*. Meanwhile, villagers who participate in the project will be able to make additional income from catching the plecos and/or processing the BSF feedstock – an *economic aspect*. Furthermore, this pleco-based BSF feedstock production will add value to fishery and create a new local business, so helps attract villagers to stay in their village instead of moving out – a *social aspect*.

Table 2 Local perceptions on the pleco invasion and current management approaches

Items	Fishermen		Non-fishermen	
	Mean (SD)	A-level	Mean (SD)	A-level
1. Knowing the term "invasive species"*	4.11 (0.57)	SA	2.44 (0.93)	NS
2. Observed plecos in the lake in the past decade*	5.00 (.00)	SA	1.94 (.88)	D
3. The pleco invasion drives up other fish prices*	4.92 (0.27)	SA	2.53 (1.17)	NS
4. Plecos dug holes for nesting caused bank erosion*	3.71 (.96)	A	1.58 (.65)	D
5. Current management is effective*	1.37 (0.78)	D	2.41 (1.13)	NS
6. Direct killing is the most effective method*	1.00 (0.00)	D	3.04 (0.98)	A
7. Will eat pleco-based food	2.54 (1.51)	NS	2.25 (1.33)	NS
8. Less connections between youth and the lake*	4.92 (0.27)	SA	3.94 (0.75)	A

Note: A-level = agreement level, SA = strongly agreed, A = agreed, D = disagreed and NS = not sure. * Indicates a significant difference (t-test, p-value < 0.05) of mean between the fishermen and non-fishermen groups.

Table 3 Villager knowledge about the pleco fish characteristics and habitat

Items	**Fishermen**	**Non-fishermen**
1. Pleco mouth position	1.00(0.00)	0.43(0.50)
2. Scale hardness	1.00(0.00)	0.53(0.51)
3. Moving habit	1.00(0.00)	0.40(0.49)
4. Habitat position	1.00(0.00)	0.28(0.45)
Average total score	4.00(0.00)	1.63(0.49)

Note: a full score is 4.00 where the samples with score 0.00 = very limited knowledge, 1.00-3.00 = obtained some knowledge and 4.00 = well recognized of the pleco. * Indicates a significant difference (t-test, p-value < 0.05) of mean between the fishermen and non-fishermen groups

Approximately, 68.5% of respondents expressed their willingness to participate in the proposed management project, especially the fishermen group, due to the alarming situation of the pleco invasion. All of the interviewed fishermen said “yes” that they would catch and sell plecos to the BSF feedstock production. For the non-fishermen group, we received quite a positive response of their participation (approximately one third of the non-fishermen group said “yes”). However, the majority of respondents who said “yes” stated their confidence level of participating below 50% for the non-fishermen group but between 51-75% for the fishermen group (Table 4). This is considered a big hurdle to cross for management planning and proposal when putting it into practice. Villagers may not see clearly what actions they will take; whether or not they will be able to really get involved even though they might agree with such a proposal. Uncertainty of outcomes and benefit returns lessens villagers' confidence to participate. And it becomes a big challenge for project managers to put the plan into clear and real outcomes to be expected by villagers. Meanwhile, the respondents who said “no” to the proposed project indicated three main reasons for not willing to get involved, including time constraint, infeasible implementation, and ineffective outcome expectation.

Table 4 Villager willingness to participate in the proposed ecosystem-based management of plecos: the BSF feedstock production

Item	Fishermen group (%)	Non-fishermen group (%)
1. Willing to participate in the project		
● Yes	100	32.26
● No	0	67.74
2. A confidence level of participating		
● <50%	4.67	73.33
● =50%	18.69	3.33
● 51-75%	42.06	16.67
● >75%	34.57	6.67
3. Reasons of not willing to participate		
● No time to participate	0	71.42
● Didn’t think it’s feasible to implement the project	0	26.98
● Didn’t expect effective outcome from the project	0	1.58
4. If you said “yes”, what activity you would likely to participate		
● Catch and sell plecos to the BSF feedstock production	33.64	46.67
● Process plecos into the BSF feed	42.06	26.67
● Both activities: catch, sell and process plecos	24.3	26.66

Conclusions

Tempe Lake in South Sulawesi, Indonesia is encountering one of the global threats on biodiversity and people well-being – the invasive alien species. The invasion of plecos reduced native fish populations, caused erosion, and changed the lake ecosystem functions – *ecological impacts*. Subsequently, decreases in native fish affected fishery production; amounts of catch dropped and lowered fishermen income – *economic effects*. Moreover, fishery is perceived as a hard-working job with low economic returns, especially among young people. A mindset towards other jobs drives them away from fishery and/or other labor-based jobs. Particularly, a civil service position is projected as a job with high respect, stable and secure income even after retirement. It is a way out of poverty. As a result, young people usually look for jobs outside fishery, migrate to big cities, but often end up with daily wage-labor work. This workforce migration leads to changes in family structure from extended to a single-family type, disconnection among family members and slum settlement in big cities – *social impacts* (Figure 7).

Local communities expressed an ecosystem-based management with economic incentives for local community participation is needed in a timely manner. The pleco-based BSF feedstock production is proposed since it offers the alternative to deal with economic, social, and ecological aspects of the problem, especially from the lack of economic incentives that result in no investment and/or low participation. However, the project's implementation directly depends on local perception and their willingness to participate. We received quite positive responses from the local communities in Wajo, especially the fishermen group with the degree of confidence to participate in the management project greater than 50%; but educating the public to recognize problems or impacts from the pleco invasion is still needed to gain people participation. Furthermore, a cost-benefit analysis of the proposed project is essential for effective implementation. Local communities, both villagers and local administration, need clear and sufficient information to help them see potential gains and losses from their actions whether they decide to "do no nothing" or "do something about it."

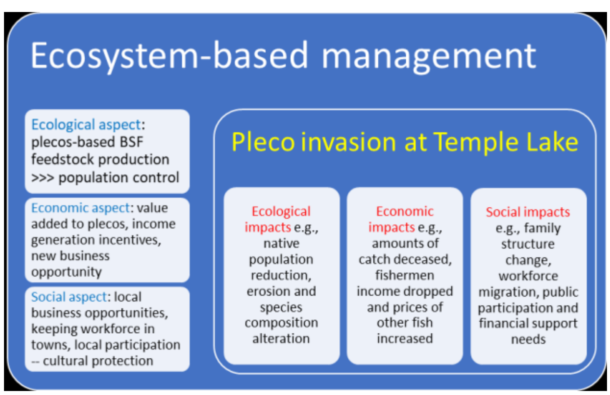

Figure 7 Ecological, economic, social, and public impacts from the pleco invasion

Acknowledgement

Firstly, this research is financially supported by the Faculty of Science, Khon Kaen University research fund through GMSKKU scholarship. We appreciate academic inputs from the Integrated Land and Water Resource Management Research and Development Center in Northeast Thailand, Khon Kaen University, Thailand. Our great gratitude goes to the Wajo administration officials for facilitating our access to the field and helping coordinate with village leaders. Finally, we are very thankful for all the villagers in Wajo who participated in the study.

Their time and responses are greatly appreciated. Lastly, we thank our enumerator, Ms. Desti, Ms. Emi, Mrs. Sulfiana, and Mr. Yasin to help us gather data and communicate with the locals.

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Thai Environmental Engineering Journal Vol. 37 No. 2 (2023) : 65-76
www.eeat.or.th

The Water Footprint of Pa La-U Durian

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Abstract

The study's objectives of this research were to assess the water footprint of Pa La-U Durian in Huai Sat Yai, Hua Hin, Prachuap Khiri Khan Province. By collecting primary data from interviews with farmers and related secondary data which were calculated by CROPWAT 8.0 program, the water footprint of Pa La-U Durian had an average of 2,284.67 m^3/rai (2.79 m^3/kg), divided into the amount of rainwater used (Green water), which was equal to 1,008.46 m^3/rai (1.23 m^3/kg), irrigation water consumption (Blue water), which was equal to 692.36 m^3/rai (0.85 m^3/kg), and the amount of water used in pollution treatment (Grey water) which was equal to 583.91 m^3/rai (0.71 m^3/kg). According to the study's findings, which took into account each growth period, the branch growing period has the highest water footprint, measuring 745.39 m^3/rai (0.91 m^3/kg), because it contains the most green water and grey water in comparison to other growth periods. Grey water should be reduced, and farmers should be encouraged to use organic fertilizers, bio fertilizers, or microorganisms, as part of a strategy to reduce the water footprint of the production process. Due to the proportion of nitrogen in fertilizer in organic fertilizers being less than chemical fertilizers and leaching-runoff of organic fertilizers equal to 0.06 [1], while chemical fertilizers equal to 0.1 [2], resulting in a decrease in the grey water footprint from 583.91 m^3/rai (0.71 m^3/kg) to 24.81 m^3/rai (0.03 m^3/kg). As a result, the water footprint will be reduced to 1,725.59 m^3/rai (2.11 m^3/kg), which will not only lessen its negative effects on the environment but also encourage the growth of sustainable agriculture. In addition, the results of this research can be used for the monthly water footprint to plan the allocation of irrigation water to support the needs of Pala-U durian in each growth period.

Keywords : Pa La-U Durian; Water footprint

Introduction

At present, the shortage of water resources in Thailand is increasing, which causes water shortages for household consumption, agriculture and industry and economic damage. The shortage of agricultural water, which has caused serious damage to farmland and agricultural productivity. Therefore, modern farmers must optimize water resources management to adapt to the changing situation. Alternatives to water management such as agricultural technology development, effective sharing of land and water, choosing low moisture crops or high profit and efficient water retention crops. However, water footprint is also one of the tools to, directly and indirectly, evaluate water consumption, aiming at finding ways to improve water use efficiency and maximize its benefits.

Water resources are an important factor in agricultural products. Especially industrial crop that generate income for farmers and affect the growth of the country's income. One of them is durian. There are more than 200 varieties of durian cultivated in Thailand, but there are about 5 varieties that are popular for consumption and trade and have been promoted as follows: Chani, Mon Thong, Kan-yao, Kra-dum Thong and Phuang ma ni. Furthermore, 14 durian varieties that are known as geographical indication:GI from the Department of Intellectual Property [3] that represent products originating from specific locations, where products derive their unique quality and reputation [4]. Hence, it has a relatively high selling value because it is a premium-grade durian.

One of the important factors that can improve the quality and yield of GI durian is the availability of sufficient water resources for planting. One solution is irrigation projects and effective water management for farmers. From the above-mentioned statements, it causes interest in choosing Pa La-U Durian, registration number GI 57100062 from the Ministry of Intellectual Property0 the climate is characterized by high relative humidity and the temperature is low at night in the rainy season, there will be water flowing down from the mountain bringing nutrients to replenish the agricultural areas every year. The taste is less sweet, firm texture, and has no strong smell, which is different from other areas. Moreover, the value per unit is as high as 250-400 baht per kilogram and has become more and more popular until it's not enough to meet the needs of consumers. Due to water shortage, the planting area in Huai Sat Yai district is limited to 1,328.50 rai with an average is 0.817 tons/rai [5]. Therefore, Royal Irrigation Department has constructed the Ban Pa La-U Reservoir in Prachuap Khiri Khan Province to solve the problem of drought and water shortage for agriculture in the area of 5 villages of Huai Sat Yai district with reservoir storage of 10.46 million cubic meters [4]. Currently, it is under construction and is expected to be completed in 2024. When starting the water distribution system Pa La-U Durian production area will get enough water to make durians, with more quality and quantity. In addition, it can also increase the area for planting Pa La-U Durian as well.

At present, in Thailand, not only there is little data on calculating the water footprint of Pa La-U Durian but most of them are durians in Rayong, Chanthaburi and Trat province, as shown in Figure 3 but also the program automatically calculates the water use of plants for water allocation planning of the Royal Irrigation Department is CWR-RID and ROS, there is still a lack of data on Pa La-U Durian to be used in the calculation. Therefore, this study could bring information about the monthly water demand and crop coefficient (K_c) of Pa La-U Durian to be one of the plant databases. This could assess the water demand more consistent with the plants.

From the above-mentioned statements, the assessment water footprint of Pa La-U Durian from the beginning until the end of the production process. The total water footprint of the process of growing Pa La-U Durian is the sum of the green water footprint (The amount of water in the form of moisture in the soil due to rainwater used in the production), the blue water footprint (The amount of irrigation water that plants need to increase) and the grey water footprint (The amount of water used to dilute pollutants in water should reach the specified standard value of plants). The study of water footprint allows better understanding of water scarcity and water pollution level problems in the area and leads to proper efficient water management in the area to make water security along with economically sustainable. Furthermore, the results provide water use information for each growing stage and help farmers plan their crops which will make the production of products more efficient.

Materials and Methods

Data collection

Primary data is the data on planting, fertilizer usage and watering of Pa La-U Durian from an interview with the director of Huai Sat Yai Agricultural Cooperative, Pa La-U Durian plantation farmers and staff of Hua Hin Agricultural Extention Office. According to interviews with farmers in this area, it was reported that in the case of insufficient rainfall, farmers withdrew water from Palao brook, Pranburi river and groundwater, which results in higher production costs for farmers due to the cost of electricity used for pumping water.

Secondary data is the data gathered from various agencies to use for the water footprint assessment of Pa La-U Durian in the study area. The secondary data includes climate data, rainfall data and crop data. Details about the secondary data are as follows. Climate data provided average climate data in the past 30 years (1991-2020), minimum and maximum temperature, rainfall, wind speed, relative humidity and amount of light from the Meteorological Department, Hua Hin station. Water quality analysis of nitrate-nitrogen (NO_3-N) in 2018-2020 [6]. Crop data included information on crop coefficient (K_c) which can be classified into seven stages, maintenance of leaves, branches, and trunks of durian stage, induce flowering stage, flower development stage, produce fruit stage, young fruit development stage, fruit growth stage, and ripening stage [7].

CROPWAT 8.0 program calculation

Use CROPWAT 8.0 program to calculate Effective Rainfall (P_{eff}) and Reference Crop Evapotranspiration (ET_o) by using Hua Hin station climate data consisting of minimum and maximum temperature, humidity, wind speed, and amount of light. Rainfall data is the average twelve-month rainfall in the past 30 years (1991-2020).

Calculation of Crop Evapotranspiration (ET_c)

Crop Evapotranspiration (ET_c) can calculate by using data on Effective Rainfall (P_{eff}) and crop coefficient (K_c) in each of the growth stages.

$$ET_c = K_c x ET_o$$

Calculation of water footprint

This method is the assessment of water usage from the beginning until the end of the production process with the Water Footprint Assessment Manual [8]. Which is the calculation of the total amount of water used for all three types as follows:

1. Green water footprint (WF_{green}) is an indicator of the plant use of rainfall, the amount of water in the form of moisture in the soil due to rainwater. that was used in the production of Pa La-U Durian, which can be calculated from the ratio between the quantity of rainfall used by plants with the amount of yield per crop area

$$WF_{green} = \frac{CWU_{green}}{Y}$$

When WF_{green} is the green water footprint of plants [m^3/ton], Y is yield [tons/rai] and CWU_{green} is the quantity of rainfall used by plants [m^3/rai] which is calculated from comparison with ET_c and P_{eff} (calculated from CROPWAT 8.0 program by using Hua Hin station climate data consist of minimum and maximum temperature, humidity, wind speed, and amount of light. Rainfall data is the average twelve-month rainfall in the past 30 years (1991-2020)).

If $P_{eff} > ET_c$; $ET_{green} = ET_c$
If $P_{eff} < ET_c$; $ET_{green} = P_{eff}$

Then unit convert ET_{green} [mm.] to CWU_{green} [m^3/rai].

2. Blue water footprint (WF_{blue}) is an indicator of consumptive use of irrigation water, the quantity required by plants during periods of insufficient precipitation. It will happen during the dry season. which is during the development of the durian.

$$WF_{blue} = \frac{CWU_{blue}}{Y}$$

When WF_{blue} is the blue water footprint of plants [m^3/ton] (in this study refers to irrigation water from a Pa La-U Reservoir), Y is yield [tons/rai] and CWU_{blue} is the amount of irrigation water required for plants [m^3/rai] which is calculate from compare with ET_c and P_{eff}

If $P_{eff} > ET_c$; $ET_{blue} = 0$
If $P_{eff} < ET_c$; $ET_{blue} = ET_c - P_{eff}$

Then unit convert ET_{blue} [mm.] to CWU_{blue} [m^3/rai].

3. Grey water footprint (WF_{grey}) is an indicator of the degree of freshwater pollution that can be associated with the process step.

$$WF_{grey} = \frac{(\alpha * AR)/(C_{max} - C_{nat})}{Y}$$

When WF_{grey} is the amount of water used to dilute pollutants in water to reach the specified standard value of plants [m^3/ton]. α is a leaching-runoff fraction that is assumed equal to 10% [8]. AR is the quantity of fertilizer usage in a plantation [kg/rai] this study considered only nitrogen fertilizers. C_{max} is the acceptable maximum concentration [kg/m^3] this study will use the surface water quality standard of nitrate-nitrogen (NO_3-N) is equal to 5 mg/l [9]and C_{nat} as a natural concentration in the receiving water [kg/m^3] this study uses an average nitrate-nitrogen (NO_3-N) in 2018-2020 of Pranburi River at the end of the irrigation area which is the convergence point between Pa Lao brook and Pranburi River, the water that flows through it contaminated with agricultural water. Due to the land use along the river before the confluence, there are fruit trees, rubber trees, and field crops, including community waste water. Which may cause of nitrate-nitrogen contamination in water, is equal to 0.00055 kg/m^3 (0.55 mg/l) [6].and Y is yield [tons/rai].

Calculation Water Scarcity Index (WSI)

This study was based on Pfister et al. WSI assessment methodology in analyzing the impact of water use on Pa La-U Durian plantation. The irrigation area of Ban Pa La-U Reservoir was 6,490 rai as shown in Figure 1. Calculated from the proportion of water demand per year compared to the volume of water resources available in the area (Withdrawal-to-Availability: WTA*).

$$WTA^* = \frac{WU}{WA}$$

When WTA* is the proportion of water demand per year compared to the volume of water resources available in the area, WU is the annual water demand in the agricultural, industrial, household, livestock and preserve the ecosystem (m^3/yr), WA is the amount of water resources available in the area (watersheds) (m^3/yr)

$$WSI = \frac{1}{1+e^{-6.4WTA^*(\frac{1}{0.01}-1)}}$$

This study is divided into two cases:

Case 1 Non-irrigation, the volume of water resources available (WA) is only rainfall data in the past 30 years (1991-2020) from the Meteorological department, Hua Hin station.

Case 2 Irrigation (have Ban Pa La-U Reservoir), the amount of water resources available (WA) is rainfall and storage capacity of Ban Pa La-U Reservoir is equal 10,460,000 m^3/yr.

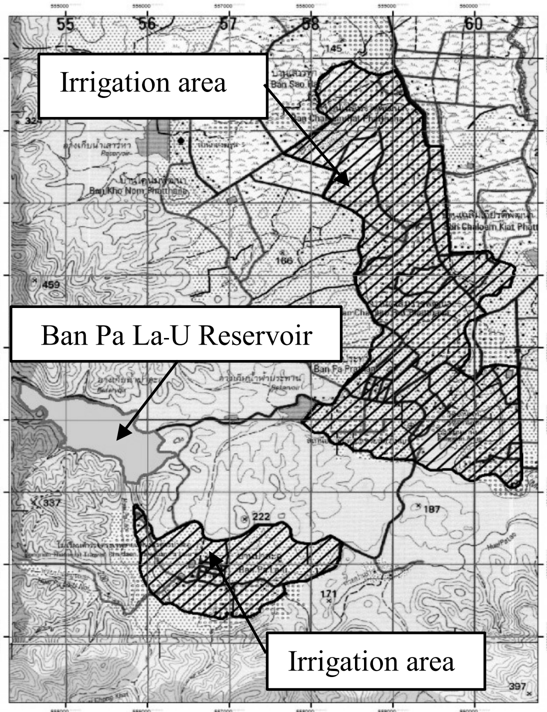

Figure 1 Irrigation area of Ban Pa La-U Reservoir
(Adapted from :Ban Pa La-U Reservoir EIA report [10])

Calculation Water Pollution Level (WPL)

The effect of the grey water footprint depends on the amount of runoff in the waste-receiving area [2], the water pollution level (WPL) has been studied as an indicator of impact. Calculated from the proportion of grey water footprint. (WF_{grey}) with runoff in each area (R_{act}). If the WPL is greater than 1, it means the quality of the water source is contaminated.

$$WPL = \frac{WF_{grey}}{R_{act}}$$

Results and Discussion

Water footprint of Pa la-u-Durian

An in-depth interview questionnaire for water footprint assessment of Pa La-U Durian plantations from farmers in Huai Sat Yai district and gather of the production yield from Agriculture and Cooperatives Office Prachuap Khiri Khan province, Thailand. The results showed that an average Pa La-U Durian plantation area was equal to 1,328.50 rai (2,125,600 m^2). The production yield from Pa La-U Durian was equal to 0.817

tons/rai [5]. The majority of farmers did annual maintenance of leaves, branches, and trunks of durian during September-November and started to reduce the watering of durian in December-January to induce flowering. They returned to watering of durian during February-March which was the flower development stage and in April was a induce young fruit stage then young fruit development stage in May after that they did maximum watering of durian for fruit growth in June and reduce watering in July to August for ripening stage of durian fruit. In terms of the amount of fertilizer used in planting, according to interviews with farmers, the use of formula fertilizer 16-16-16 was equal to 96 kg/rai, 4-24-24 was equal to 64 kg/rai and 12-12-18 was equal to 67.2 kg/rai. After that, taking the amount of fertilizer usage to calculate the nitrate-nitrogen ratio and found that it was equal to 25.98 kg/rai.

From the assessments of water footprint of Pa La-U Durian of 2.79 m^3/kg. This included green water footprint is equal to 1.23 m^3/kg, blue water footprint is equal to 0.85 m^3/kg and grey water footprint is equal to 0.71 m^3/kg, as shown in Table 1.

From Table 2 WF_{grey} was calculated from the use of chemical fertilizers in cultivation. But if the cultivation was organic agriculture the amount of WF_{grey} will be decreased. In this study, in the case of using organic fertilizers to take care of durian trees, 25 kg/tree/yr of manure from dry cow dung mixed with rice straw [11]. And assuming that the yield per plantation area is equal to the case of using chemical fertilizers, 0.817 ton/rai. In the calculation of WF_{grey}, the percentage of nitrogen in organic fertilizer from dry cow manure is 0.46% [12] and the nitrogen leaching ratio of organic fertilizers from the IPCC guidelines [1] was 0.06. The result as shown in Table 2.

Table 1 Water footprint of Pa La-U Durian

yields (ton/rai)	WF_{green}		WF_{blue}		WF_{grey}		WF	
	m^3/rai	m^3/kg	m^3/rai	m^3/kg	m^3/rai	m^3/kg	m^3/rai	m^3/kg
0.817	1,008.46	1.23	692.36	0.85	583.91	0.71	2,284.67	2.79

Table 2 Water footprint of Pa La-U Durian in the case of using organic fertilizers

	Chemical fertilizers	Organic fertilizers
the proportion of nitrogen in fertilizer	3 formulations as follow: 16-16-16 = 0.16 4-24-24 = 0.24 12-12-18 = 0.12	0.0046
chemical application rate per hectare (AR) (kg/rai)	25.98	1.84
leaching fraction (α)	0.1	0.06 [2]
crop yield (ton/rai)	0.817	0.817
WF_{grey} (m^3/rai)	583.91	24.81
WF_{grey} (m^3/kg)	0.71	0.03
WF (m^3/rai)	2,284.67	1,725.59
WF (m^3/kg)	2.79	2.11

And Figure 2 shows the water footprint of Pa La-U Durian at each stage of the plantation, maintenance of leaves, branches, and trunks stage from September to November is the highest water footprint about 35.6% of the total water footprint. Due to this stage of plantation has the greatest demand for water and fertilizer, as dry branches are trimmed after harvest and ready to induce flowering. Because water is an important component of cells by making plant cells to be mature. If the cell is dehydrated or there is not enough water, the shape of the cell will be distorted. In addition, water is a solvent that helps to dissolve plant nutrients in the soil into a solution that plants can absorb. and water as a starting agent for various processes within plants [13].

Furthermore, the green water footprint has seasonal fluctuation due to climate change [14] using insufficient rainfall to plant Pa La-U

Durian. Therefore, there must have blue water footprint, which is the irrigation water from the Ban Pa La-U Reservoir to supplement during the dry season and gradually decreases in the rainy season, from February to August and November. So that if there is enough irrigation water to meet the needs of planting Pa La-U Durian at all times. It will more productivity. In addition, it is possible to expand the area for planting. From Table 3 based on the EIA report of Pa La-U Reservoir [10], The data of agricultural irrigation water demand in 2007 and the next 30 years are studied, which are 9.124 million cubic meters and 9.45 million cubic meters per year respectively. This will increase the amount of water for agriculture by 0.326 million cubic meters per year or 326,000 cubic meters per year, if farmers continue to grow crops as before but change from the area of planting fields crops (Nam Wah banana and pineapple) and waste land to Pa La-U Durian that will be able to increase the planting Pa La-U Durian area approximately 455 rais., as shown in Table 3.

Comparison of Water Scarcity Index (WSI) with non-irrigation and have irrigation

It is one of the most commonly used tools to assess the level of water stress in an area. In this study, WSI assessment principles were referenced from [15]. And The levels of water stress are still classified into five categories including extreme condition (WSI >0.9), Severe (0.5 < WSI ≤ 0.9), Stress (WSI = 0.5), Moderate (0.1 ≤ WSI < 0.5) and Low (WSI < 0.1) [16]. In analyzing the effects of water use in Pa La-U Durian cultivation at the level of the irrigation area Ban Pa La-U Reservoir in Huai Sat Yai district, 6,490 rais, was shown in Figure 1. Calculated based on the proportion of annual water demand in the agricultural, industrial, household, livestock and preserve the ecosystem from Ban Pa La-U Reservoir EIA report [10]. It was found that the estimated water demand in irrigation areas in 2037 was 10.942 million cubic meters. compared to the amount of water resources available in the area (watersheds), this will be divided into two cases:

Case 1 Non-irrigation, WSI results is equal 0.93 that is extreme water stress.

Case 2 Irrigation (have Ban Pa La-U Reservoir), WSI results is equal 0.24 that is moderate water stress.

From the results of the study, it was clear that if there is a reservoir in the area, it will result in the level of water stress decreasing from extreme sector to have enough water for the water use of plants. Make the output quality and quantity more in the future.

Water Pollution Level (WPL)

As a relevant local impact indicator, one can calculate the 'water pollution level' (WPL) within a catchment, which measures the degree of pollution. It is defined as the fraction of the waste assimilation capacity consumed and calculated by taking the ratio of the total of grey water footprints in a catchment (ΣWF_{grey}) to the actual run-off from that catchment (R_{act}) and if WPL values exceed 1.0, ambient water quality standards are violated [2].

Assessment of water pollution in this study was caused by the use of nitrogen-containing fertilizers for nourishing the Pa La-U Durian. In the area of Huai Sat Yai district, there are 1,328.5 rais of crop areas. It can be estimated from the water pollution level (WPL) calculation using the equation from [2]. Which used the average monthly runoff the Pranburi River (basin code 1804) from SEA report of Phetchaburi-Prachuap Khiri Khan River Basin Area [17], the catchment area is 1,605.10 km^2 covered in the area Pranburi district Sam Roi Yot district, Hua Hin district, Prachuap Khiri Khan province and Kaeng Krachan district Cha-Am district Tha Yang district, Phetchaburi province that originated from the Tanaosri mountain range in Pranburi.

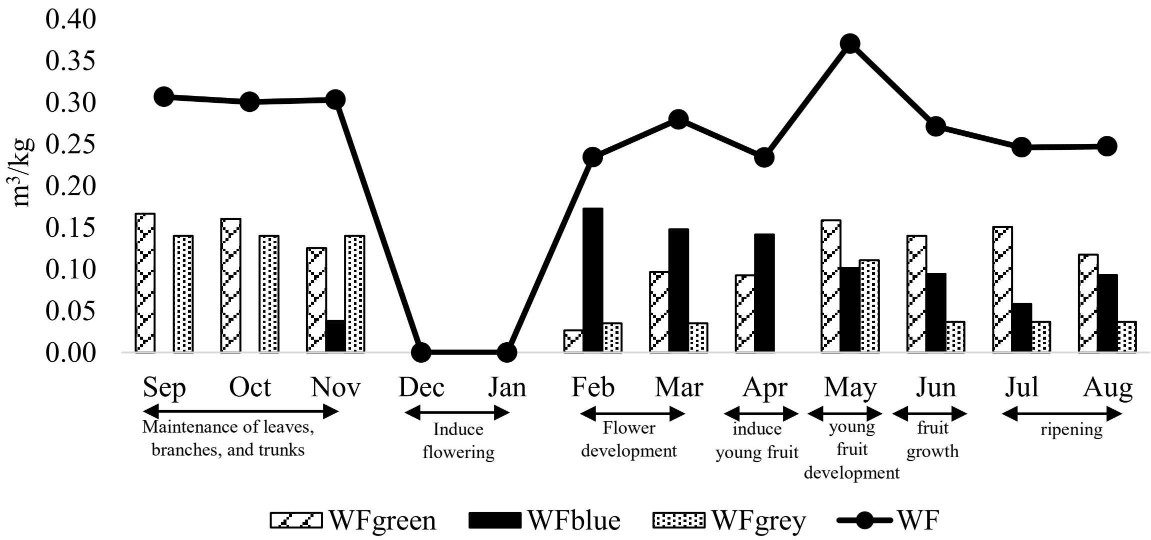

Figure 2 Water footprint of Pa La-U Durian each stage of plantation

Table 3 Past and future crop patterns

Crop	Area (rais)	
	In 2007	In 2027
Rice	35	35
Rubber	85	85
Fruit (lime, jackfruit, mango, coconut and Pa La-U Durian)	4,480	4,480
Soilage (Purple guinea grass, Ruzi Grass)	1,435	1,435
Field plant (Nam Wah banana, pineapple)	405	
Pa La-U Durian		455
Waste land	50	
Total	6,490	6,490
Irrigation water demand (m^3)	9.124×10^6	9.45×10^6

From Table 4, Overall, every month the WPL value is lower than 1 which is low water pollution, so the water pollution level will fluctuate within the year as well. WPL values lower than 1 indicate that there is an average enough river water to dilute the pollutant to below the maximum acceptable level at the basin scale [18].

Water Footprint of Pa La-U Durian and other durians

From Figure 3, When taking the water footprint of Pa La-U Durian comparison with the water footprint of other durians, it was found the water footprint of durian of Mon Thong durian in Rayong province [16] had the highest water footprint value of 3,592 m^3/rai followed by water footprint of Pa La-U Durian, equal to 2,282.06 m^3/rai due to the analysis of the grey water footprint. If analyzing the types of water footprints, it was found that as follows:

Green water footprint found that the Rayong Durian, Chanthaburi Durian, Trat Durian and Pa La-U Durian have a similar green water footprint due to the similar requirement water for durians. But Rayong Durian [19] is most valuable because that area has the amount of rain that is sufficient to requirement water of durian in each growing period, which farmers can rely on rainfalls in the area so there is no need for watering during that time and the amount of effective rainfall depends on the meteorological conditions of each area.

Table 4 Water Pollution Level (WPL) of Pa La-U Durian

Month	Quantity of nitrogen fertilizers (kg/rai)	WF_{grey} (m^3/rai)	WF_{grey} (MCM)	R_{act} (MCM)	WPL
Sep	5.12	114.54	0.15	95.06	0.002
Oct	5.12	114.54	0.15	179.27	0.001
Nov	5.12	114.54	0.15	90.2	0.002
Dec	0	0	0.00	20.23	0.000
Jan	0	0	0.00	9.28	0.000
Feb	1.28	28.64	0.04	6.02	0.006
Mar	1.28	28.64	0.04	10.25	0.004
Apr	0	0.00	0.00	12.56	0.000
May	4.03	90.20	0.12	20.16	0.006
Jun	1.34	30.07	0.04	42.65	0.001
Jul	1.34	30.07	0.04	57.26	0.001
Aug	1.34	30.07	0.04	124.4	0.000

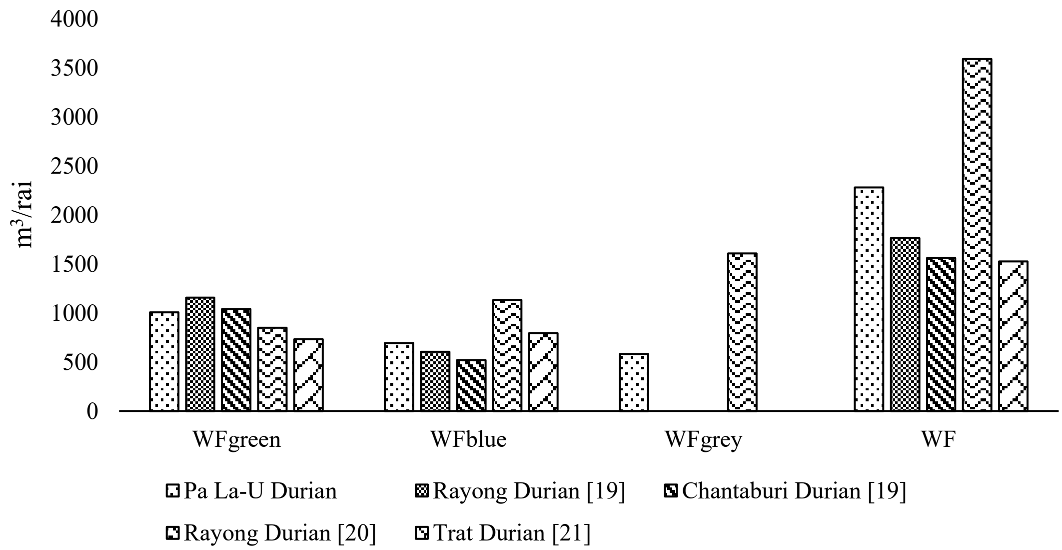

Figure 3 Water Footprint of Pa La-U Durian and other durians

Blue water footprint foot print found that the Rayong Durian, Chanthaburi Durian, Trat Durian and Pa La-U Durian have a similar blue water footprint. But the Rayong Durian [20] is the most valuable because the result of the study has the highest requirement water of durian compared to other research. And the amount of effective rainfall is insufficient to requirement water of durian in each period of growth the most. Therefore, water from irrigation or other water sources must be supported during times of water shortage.

Grey water footprint it was studied that in Pa La-U Durian and Rayong Durian [20]. The grey water footprint of Rayong Durian is 2.76 times more than Pa La-U Durian because the amount of fertilizer used per planting areas will have the greatest impact on the grey water footprint. Obviously, Rayong Durian uses more fertilizer than Pa La-U Durian, may be based on soil data from Land Development Department [22], found that the soil in Huai Sat Yai district was more fertile. The soil series found in Klaeng district, Rayong province, which is the district that grows the most durians in Rayong province, most of the areas are soil group 45 and soil group 34. Which is a soil with low to medium fertility, the soil is brown, yellow or red. While in Huai Sat Yai district most of the area is soil group 36, which is moderately fertile soil, brown soil color. So, the color of the soil indicates the amount of organic matter, the soil is dark brown to black, it means that the soil is very fertile. And also the terrain, Klaeng district is plain while Huai Sat Yai district is mountains interspersed with plain and Pranburi River is the main river flowing through, the climate is characterized by high relative humidity and the temperature is low at night. In the rainy season, there will be water flowing down from the mountain top bringing nutrients to replenish the agricultural areas every year. As mentioned above, it may be the reason why Pa La-U Durian uses less quantities of chemical fertilizers.

Water Footprint of Pa La-U Durian and other economic crops

Economic crops refer to plants that are important to life not just used as a food source to generate energy for humans and animals or used as a material for building housing only. But it includes consumption in all forms, it also has outstanding commercial characteristics both within the country and abroad, can be cultivated as a career generate income for farmers and the country. Currently, an important economic crop of Thailand and make money for farmers and the country continually including rice, rubber, sugar cane, cassava and oil palm, can be seen that all 5 plants are classified in the field crops group. But durian is classified as garden plant and also a fruit that creates value in exports to China as number 1.

From Figure 4, When taking the water footprint of Pa La-U Durian comparison with the water footprint of other economic crops, it was found that the highest water footprint is rubber and then Pa La-U Durian, rice, Rayong durian, oil palm, cassava and sugarcane, respectively. Because when considering the yield product in 2020, rubber has a yield equal 224 kg/rai, while sugarcane has a yield equal 7.90 ton/rai [23]. Obviously increasing productivity will result in a reduction in the water footprint. So effective water resources management and enough for crops that will make crops more productive.

And comparison with the water footprint of Rayong durian, that is lower than water footprint of Pa La-U Durian. Because The yield of Rayong durian is more than twice, that of the main durian grown in Thailand, located in the eastern part of Chanthaburi and Rayong, in the southern is Chumphon Province. And about 60-70% of total domestic production will be exported. Eastern durians are grown for both domestic and international trade, while Pa La-U Durian are only sold for domestic consumption. Due to the limitation of the planting area only in Huai Sat Yai district and water shortages in the area.

Conclusion

According to the water footprint assessment of Pa La-U Durian when compared with the total water requirement, green water footprint is 44.2%, blue water footprint is 30.3%, and grey water footprint is 25.5%. It can be seen that the rainfall is not enough to plant Pa La-U Durian. So, irrigation water is needed to support the requirement. Which the Ban Pa La-U Reservoir it will make the Huai Sat Yai district have more water resources for agriculture. Along with efficient irrigation water allocation planning according with the monthly requirement of Pa La-U Durian by using the water footprint. And it can expand the planting area of Pa La-U Durian, thereby increasing farmers' income because the sales value of this product is as high as 250-400 baht per kilogram.

Guidelines for reducing the water footprint by reducing the grey water footprint farmers should be encouraged to using organic fertilizers, biological fertilizers or microorganisms. The amount of grey water footprint was reduced by 559.1 m^3/rai (0.68 m^3/kg), using chemical fertilizers equal to 583.91 m^3/rai (0.71 m^3/kg), but using organic fertilizers 24.81 m^3/rai (0.03 m^3/kg). This will result in a decrease in the water footprint of 1,725.59 m^3/rai (2.11 m^3/kg). Besides that, to reducing the impact on the environment it will contribute to the development of sustainable agriculture.

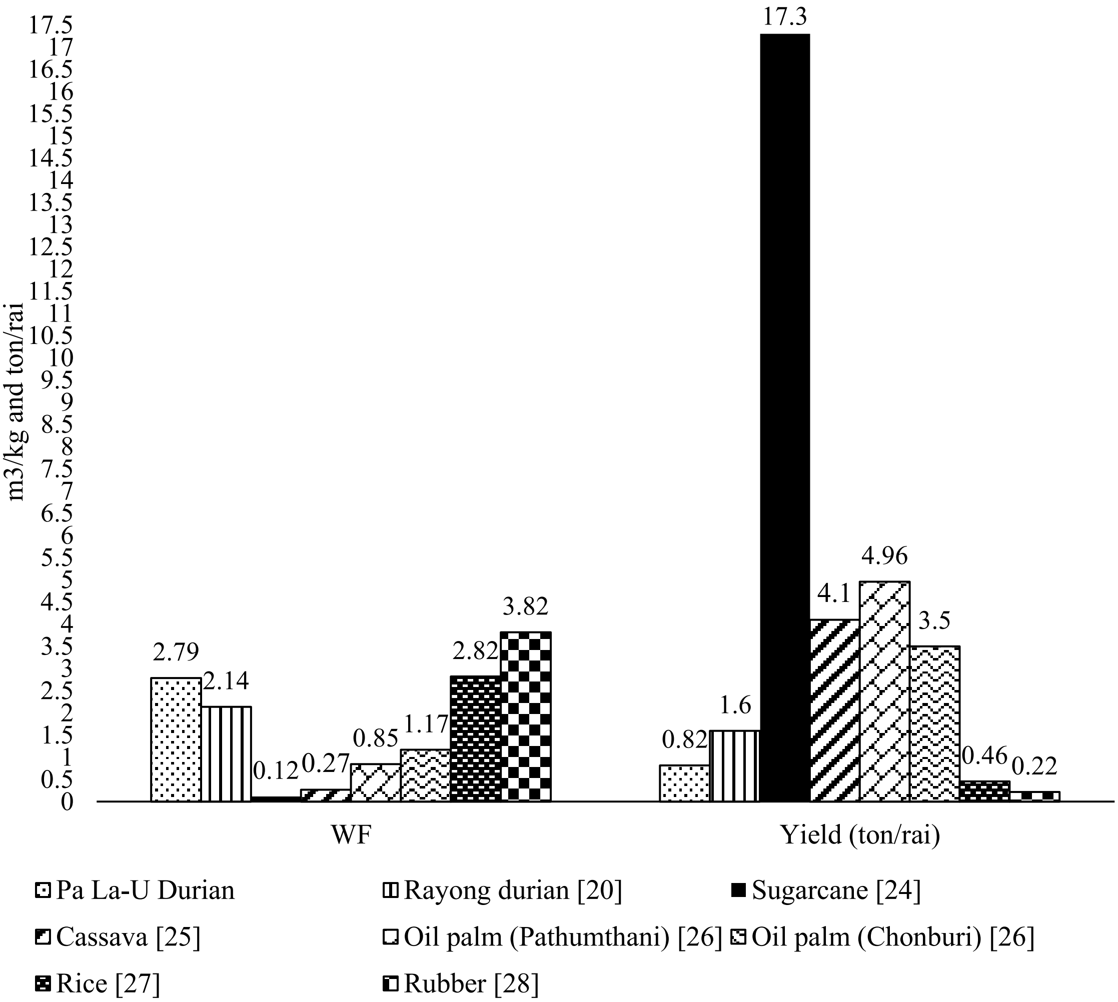

Figure 4 Water Footprint of Pa La-U Durian and other economic crops

For taking the crop coefficient (K_c) in each cultivation period from this research to be used to evaluate the amount of water consumption in CWR-RID and ROS program of the Royal Irrigation Department. It shows the demand for irrigation water that needs to be increased of Pa La-U Durian. in Huai Sut Yai Subdistrict, Ban Pa La-U Reservoir irrigation area. Approximately 692.36 m^3/rai which that needs irrigation water in November and February to August. And also used in gathering data to analyze water demand and plan appropriate water allocation in accordance with the needs of plants grown in irrigated areas and cover all aspects. Among them, the sufficiency of water is the main factor that makes decisions for farmers to change their crops from upland crops, such as pineapple and banana, to more easily durians in Pa La-U Durian. Because it gives a high return value, an average of 300 baht per kilogram.

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Thai Environmental Engineering Journal Vol. 37 No. 2 (2023) : 77-88
www.eeat.or.th

Air Quality Analysis in the Selected Urban and Suburban Areas in Central Thailand by Compact and Useful $PM_{2.5}$ Instrument with Gas Sensors (CUPI-G)

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Abstract

Air pollution is a major environmental issue in Asian developing nations because of its negative consequences. In Thailand, it is a serious problem, not only in metropolitan areas, but also throughout large areas of the country. Ratchathewi district was selected as an urban observation site due to its location, and Mueang Samut Sakhon district was chosen as a suitable suburban observation site with many small industries. The main objective of the study is to investigate the temporal variations and correlations in $PM_{2.5}$ and trace pollutant gases in relation to the meteorological conditions at the urban and suburban sites during the observation period using the Compact and Useful $PM_{2.5}$ Instrument with Gas Sensors (CUPI-G). The air quality observations were conducted for two weeks respectively from 11th to 25th February 2023 at the Ratchathewi site and from 14th to 28th November 2022 at the Mueang Samut Sakhon site using the CUPI-G. During the observations, air pollutant concentrations detected at the Ratchathewi site were in the range of 9.8-248.9 $\mu g/m^3$ for $PM_{2.5}$, 526.2-2221.2 ppb for CO, 20.9-1888.4 ppb for NO, 18.1-155.5 ppb for NO_2, 27.4-213.5 ppb for O_x and 1.1-88.9 ppb for O_3. At the Mueang Samut Sakhon site, they ranged from 3.4-172.5 $\mu g/m^3$ for $PM_{2.5}$, 426.5-989.9 ppb for CO, 10.4-321.5 ppb for NO, 6.8-95.3 ppb for NO_2, 1.5-143.3 ppb for O_x and 5.3-57.7 ppb for O_3. Compared with the ambient air quality standards for Thailand, the results showed that both sites experienced pollution from photochemical oxidants in addition to particulate matter. The CUPI-G showed that it was an applicable instrument for air quality observations in both urban suburban areas. Due to the different correlations between air pollutants in each area, additional research is necessary to address specific atmospheric patterns in order to tackle the air pollution issues in Thailand.

Keywords : CUPI-G; air pollution; urban area; suburban area; Thailand

Introduction

Air pollution in metropolitan centers of Asian developing nations is a major environmental problem due to its high levels and the related negative consequences on human health, ecosystems and climate [1]. In 2019, air pollution ranked among the top 10 risk factors for death, accounting for about 8% of all fatalities (more than 41 thousand) in Thailand. Thailand's life expectancy was lowered by 1 year due to air pollution [2]. Thailand's poor air quality is a serious issue, not just in metropolitan areas but throughout large areas of the nation [3]. Pollutant concentrations are greatly influenced by topography, land use and meteorological factors such as rain intensity, temperature, and wind speed. Thailand has a tropical climate with an average temperature of about 30°C, with temperature changes throughout the seasons because it is located 15° above the equator [4].

The conventional method for managing air quality, assessing trends and estimating exposure for epidemiological analysis has been to measure air pollutant concentrations at fixed-location monitoring sites. Despite an increase in the number of monitoring sites around the world, coverage is insufficient. It is frequently limited to major cities to reliably assess exposure in the many and varied regions where people reside [5]. Miniaturization has increased the prominence of a generation of devices that are sometimes referred to as "low-cost sensors," even though the great majority of these observations still use established analytical reference procedures [6]. In fact, they may differ from earlier technologies not just in price but also in weight, size, and power consumption. They are a sort of device that spans a wide range of technologies, and as a result, they generate measurements with a wide range of accuracy [6]. Together with the conventional instruments used in atmospheric studies, they can contribute to providing some further information.

The compact and useful $PM_{2.5}$ instrument with gas sensors (CUPI-G) is made up of a palm-sized optical $PM_{2.5}$ sensor created by Nagoya University and Panasonic Corporation, a temperature and humidity sensor, and four electrochemical sensors for gaseous pollutants (CO, NO, NO_2, and O_x) from Alphasense Company, UK. The CUPI-G was started to be used in the Aakash Project, which deals with air pollution brought on by massive post-harvest burning of rice straw in the states of Punjab and Haryana in northwest India, in October and November in 2019 [7]. In account of its suitability for multipoint observations, it can be beneficial to obtain useful results, especially in developing nations where the large and expensive standard instruments can be installed so infrequently to find the reliable data on air quality.

As of 2017, the population density in Mueang Samut Sakhon district was 596.94/km^2 while it was 10,146.50/km^2 in Ratchathewi district [8]. In central Thailand, Ratchathewi district in the heart of Bangkok is surrounded by neighborhoods of urban areas. Due to its central location in the city, the area is home to many well-known landmarks, educational institutions and medical facilities. Therefore, it can well represent the urban area in the central part of Thailand. On the other hand, Mueang Samut Sakhon is the capital district of central Thailand's Samut Sakhon province: formerly an agricultural and fisheries-based province which currently has many small factories. Small businesses lack the funds to install environmental equipment that would aid in environmental protection. As a result, Samut Sakhon is one of the country's most polluted provinces [9]. Samut Sakhon province had the worst polluted air in Thailand in 2018 [10]. It was therefore selected as a suitable suburban site for the air quality study.

Although previous studies were conducted in India [7] and in Japan [11] by using the CUPI-G, there is a gap in the understanding of its applicability in the atmospherically relevant conditions in Thailand. Furthermore, different conclusions have been reached under the influence of complex topography, meteorological conditions, and pollutant emissions because the relationship between photochemical smog and particulate pollutants is difficult to quantify and has shown great differences in research areas, time scales, and research methodologies [12]. Therefore, the main objectives of the study are to apply the CUPI-G in the urban area, Ratchathewi district and the suburban area of Mueang Samut Sakhon district and to investigate the temporal variations and correlations in $PM_{2.5}$ and trace pollutant gases in relation to the meteorological conditions during the observation period.

Methodology

Monitoring Instrument

The compact and useful $PM_{2.5}$ instrument with gas sensors (CUPI-G) was mainly used in this study. The CUPI-G has dimensions of 18 cm x 21cm x 30 cm and weighs only 5 kg. It is simple to operate, low-cost, easy to handle, and low power consumption. The price of the small sensors is 1/100 of large standard instruments. Moreover, the data can be stored inside for more than one year and can be transmitted to internet cloud server via mobile phone network. It can be operated by using solar panels all day long without any power supply for more than one year [13]. It is controlled with a CPU Raspberry pi A^+. It consists of a SHT3x-ARP sensor from the Sensirion Sensor Company for temperature and relative humidity, a palm-sized optical $PM_{2.5}$ sensor developed by Nagoya University and Panasonic Corporation for $PM_{2.5}$, and four electrochemical sensors from the Alphasense Company, UK: a CO-B4 sensor for carbon monoxide (CO), a NO-B4 sensor for nitric oxide (NO), a NO2-B43F sensor for nitrogen dioxide (NO_2), and an Ox-B431 sensor for oxidizing gas O_x (O_3+NO_2) as shown in Figure 1. When primary pollutants, primarily nitrogen oxides (NO_x) and hydrocarbons (HCs) emitted from factories and automobiles, are exposed to sunlight, photochemical reactions take place and produce secondary pollutants with strong oxidizing power called photochemical oxidants (O_x) [14]. O_3 and NO_2 are measured together using the Ox-B431 sensor. Therefore, in order to calculate the O_3 concentration, the NO_2 concentration must be subtracted from the O_x concentration.

The limits of the performance warranties for different electrochemical sensors are as follows: 1000 ppm for the CO-B4 sensor, 20 ppm for the NO-B4 sensor, 20 ppm for the NO2-B43F sensor, 20 ppm for O_3 and 20 ppm for NO_2 for the Ox-B431 sensor [15-18]. The palm-sized $PM_{2.5}$ sensor can detect particles with a diameter as small as 0.3 µm by estimating particle size from the distribution of light scattering intensities from single particles. Based on previous laboratory and field studies, it could measure $PM_{2.5}$ concentrations as high as 600 $\mu g/m^3$ with constant sensitivity [19]. Field observations revealed that it provided accurate data in both urban and suburban locations and was in strong agreement with the closest reference instruments [19, 20]. To connect with the raspberry pi for the data editing and data transfer from CUPI-G, the SCP software was downloaded and installed on the PC. A small LED display within the CUPI-G displays the data (date and time, $PM_{2.5}$ value, software version, and temperature) a few minutes after the instrument is turned on. Once the LAN adaptor and PC are connected, the observation data can be downloaded using the SCP software and CUPI-G's data response time is 31 seconds per one time.

The relationships identified in the field are only valid for a certain location, chemical climatology, and brief period, according to the studies, which show that the validation responses of gas sensors evaluated in the laboratory and the field observations commonly diverge [21]. The CUPI-G was validated with the collocated standard instruments by the mathematical correction method that considered the effects of temperature and relative humidity before the air quality observations [23-26].

Air Quality Observations

By the time the main source of air pollution in Bangkok and its vicinity was from road transport [27], the observations were conducted for 14 days respectively using the CUPI-G near the roadside (approximately 100 meters) in an urban area and a suburban area in central Thailand to analyze the variations and correlations of air pollutants during the study period. The air quality observation sites with CUPI-G instrument are described in Figure 2. The topographic map was created using ArcGIS software with permission from Esri, Maxar, Earthstar Geographics, and the GIS User Community (base map from Esri, HERE, Garmin, OpenStreetMap Contributors, and the GIS User Community).

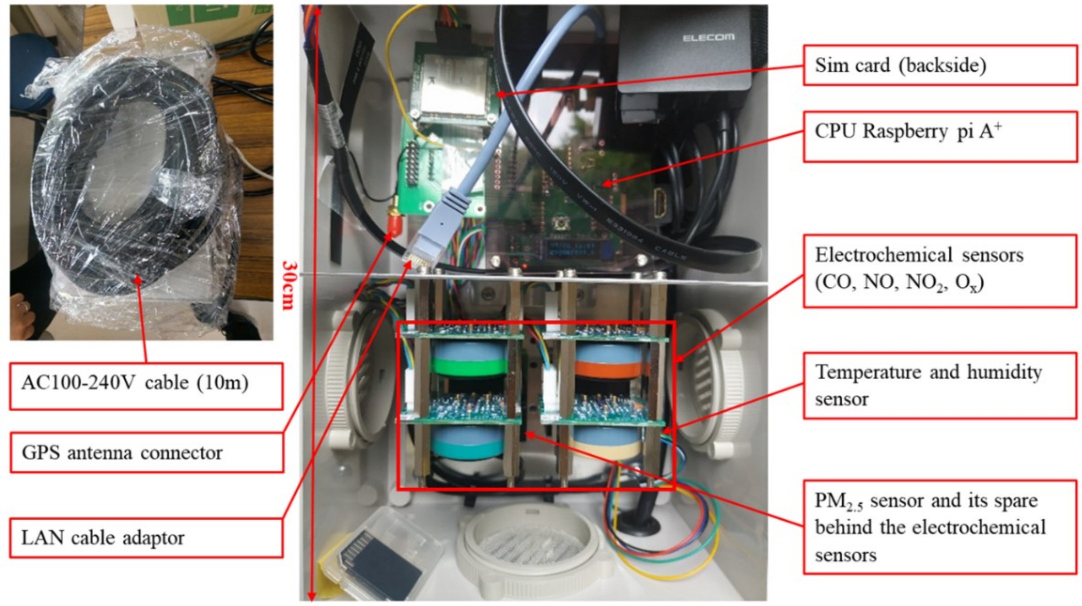

Figure 1 Composition of the CUPI-G instrument

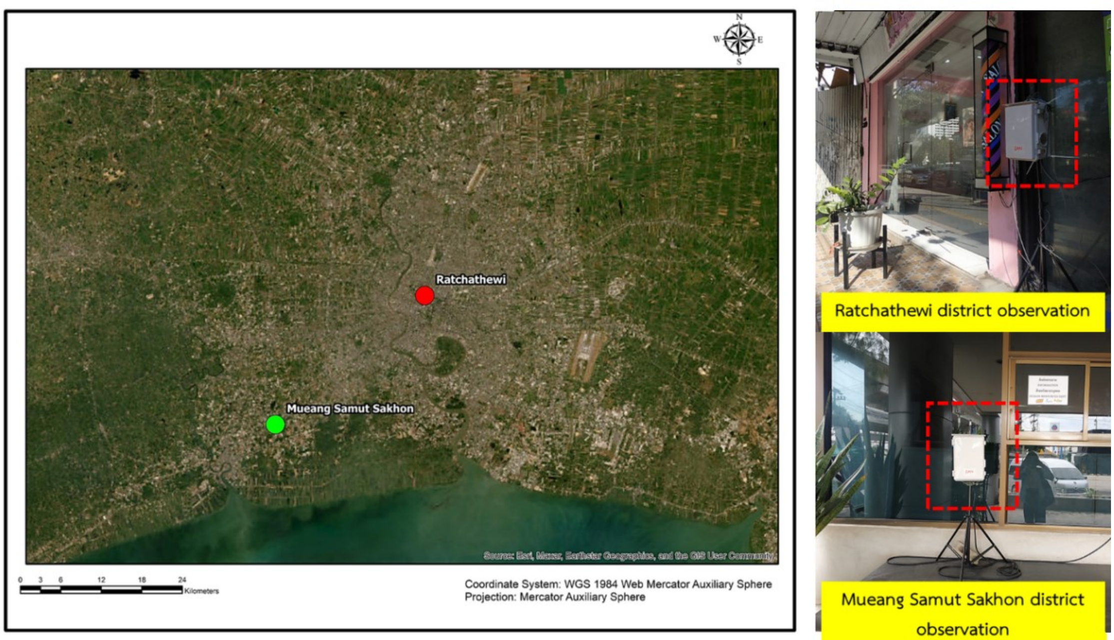

Figure 2 Air quality observation locations observed by the CUPI-G in central Thailand

In the urban area of Ratchathewi district, we observed the air quality using the CUPI-G from 11th to 25th February 2023. According to [28], the observation period was considered to be the end of the cool season in Thailand. At the Mueang Samut Sakhon district suburban site, the air quality was observed using the CUPI-G from 14th to 28th November 2022. Although [28] claimed the study period as the start of the cool season, the rainy season was not yet over at that time. At both sites, the CUPI-G was installed under the roof because it needs to be in a location that can block off direct sunlight for the best results. Detailed information about the observation sites is described in Table 1.

Table 1 Detailed information of air quality observation locations

Observation site	Area	Location	Study Period
Ratchathewi (13°45'34.90"N, 100°32'8.00"E)	Urban	Ground floor in front of a residential building, Ratchathewi district, Bangkok province	February 11-25, 2023
Mueang Samut Sakhon (13°35'34.90"N, 100°20'12.30"E)	Suburban	Ground floor of Sathaporn Co., Ltd., Mueang Samut Sakhon district, Samut Sakhon province	November 14-28, 2022

Data Analysis

The output data from CUPI-G instrument at the observation sites were calculated with the validated equations to provide reliable data for these locations. Due to the high time resolution of CUPI-G (31 seconds), the sample size (n) of Ratchathewi site was 37883 and (n) of Mueang Samut Sakhon site was 37782 during the observation period. A Pearson correlation analysis was conducted to analyze the correlation between each air pollutant and meteorological data to achieve better understanding of air pollution patterns in each area. In this study, the R Openair Package was mainly used for time series analysis to recognize the temporal variations of the air pollutants in each area which are important to reveal the regular air pollution patterns on a daily and weekly basis. The temporal variation plots used bootstrap resampling to calculate the 95% confidence interval in the mean, which can produce more accurate estimates than applying assumptions based on normality, especially when there are few data available [29].

Results and Discussions

Correlation between the Air Pollutants and Meteorological Factors

According to the Pearson correlation analysis, all the findings were significant with $p < 0.01$. As shown in Figure 3, at the Ratchathewi site, temperature had strong positive correlations with NO_2 (r=0.62), O_x (r=0.69) and O_3 concentrations (r=0.64), whereas it had a moderate positive correlation with CO concentrations (r=0.34). Moreover, there was a small negative correlation between temperature and $PM_{2.5}$, (r=0.22) while a small positive correlation was between temperature and NO (r=0.27). Humidity had strong negative correlations with NO_2 (r=0.80), O_x (r=0.81) and O_3 concentrations (r=0.65) while it possessed a weak negative correlation with CO concentrations (r=0.26) and NO concentration (r=0.24). $PM_{2.5}$ had weak positive correlations with NO_2 (r=0.29) and O_x concentrations (r=0.25). CO had a strong positive correlation with NO concentration (r=0.66) while it had moderate positive correlations with NO_2 (r=0.46), O_x (r=0.46) and O_3 concentrations (r=0.35). NO had moderate positive correlations with NO_2 (r=0.46) and O_x concentrations, (r=0.41) although it possessed a small positive correlation with O_3 concentrations (r=0.26). NO_2 had strong positive correlations with O_x (r=0.94) and O_3 concentrations (r=0.66). O_x had a high positive correlation with O_3 concentrations (r=0.88).

At the Mueang Samut Sakhon site, temperature had strong positive correlations with CO (r=0.64), NO_2 (r=0.62), O_x (r=0.78) and O_3 concentrations (r=0.79) while humidity had strong negative correlations with them to be 0.59, 0.58, 0.76, and 0.79 respectively and a moderate positive correlation with $PM_{2.5}$ (r=0.31) In contrast to the Ratchathewi site, $PM_{2.5}$ had weak negative correlations with O_x (r=0.23) and O_3 concentrations (r=0.23). CO had strong positive correlations with O_x (r=0.54) and O_3 concentrations (r=0.53) while it had a moderate positive correlation with NO_2 concentrations (r=0.45). NO had a moderate positive correlation with NO_2 concentrations (r=0.41) although it possessed a small positive correlation with O_x concentrations (r=0.25). NO_2 had strong positive correlations with O_x (r=0.90) and O_3 concentrations (r=0.62). O_x had a high positive correlation with O_3 concentrations (r=0.90).

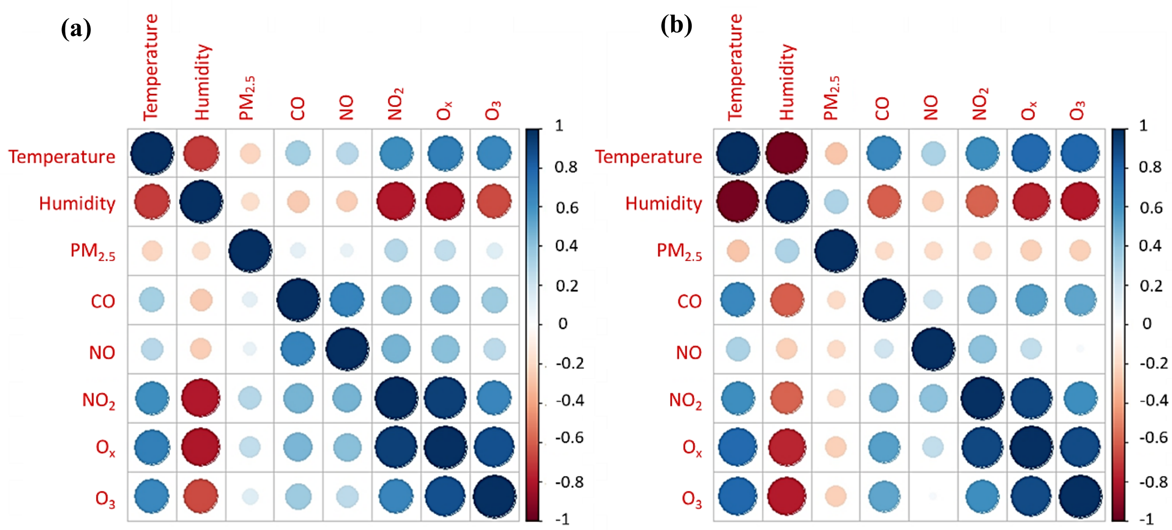

Figure 3 Correlation between the air pollutants and meteorological factors at **(a)** the Ratchathewi and **(b)** Mueang Samut Sakhon observation sites

It was discovered that the relationship between temperature and photochemical oxidant concentration was linear [30, 31] and the simulations predicted that O_3 increased with temperature in both urban and polluted rural settings [32]. In this study, the positive correlation between temperature and photochemical oxidants was significantly discovered at both urban and suburban sites. Furthermore, in different areas and at different times, $PM_{2.5}$ and O_3 have displayed varying relationships. The correlation between $PM_{2.5}$ and O_3 in the Changsha-Zhuzhou-Xiangtan district (Hunan province, in Central China) is positive in the summer, negative in the winter, and primarily negative during the rest of the year [33, 34]. In this study, it was found that there were different small correlations between $PM_{2.5}$ and the photochemical aerosols at both sites.

At Ratchathewi site, the positive correlation possibly occurred because the secondary particles were formed by photochemical reactions under the strong solar radiation at the end of the cool season [19, 33]. However, in Mueang Samut Sakhon site, a negative correlation was possibly found because high $PM_{2.5}$ concentrations might reduce the visibility and sunlight intensity which determined the formation of surface ozone [35, 12]. The other possibility might be that the rain can wash out the particulate matter during the observation period [34]. CO had positive correlations with tropospheric ozone and its precursors at both observation sites. According to [36, 37], the sequence of reactions, equation (1), equation (2), and equation (3) reveals the chain mechanism for ozone production in which the CO oxidation by O_2 is catalyzed by the HO_x chemical family ($HO_x = H + OH + HO_2$) and by NO_x as shown below.

$$CO + OH \overset{O_2}{\rightarrow} CO_2 + HO_2 \quad (1)$$

$$HO_2 + NO \rightarrow OH + NO_2 \quad (2)$$

$$NO_2 + hv \overset{O_2}{\rightarrow} NO + O_3 \quad (3)$$

Temporal Variations of Air Pollutants at Ratchathewi Site

At the Ratchathewi site, it was raining on February 15, 2023, during the sampling period according to [38], $PM_{2.5}$ concentration was slightly decreased with NO_2 and O_x concentrations. Although repetitively comparable patterns occurred for all air pollutants, they reached their peaks in the afternoon of February 17 as shown in Figure 4. During this observation period, air pollutant concentrations per 31 seconds detected at the Ratchathewi site were in the range of 9.8-248.9 μg/m^3 for $PM_{2.5}$, 526.2-2221.2 ppb for CO, 20.9-1888.4 ppb for NO, 18.1-155.5 ppb for NO_2, 27.4-213.5 ppb for O_x and 1.1-88.9 ppb for O_3.

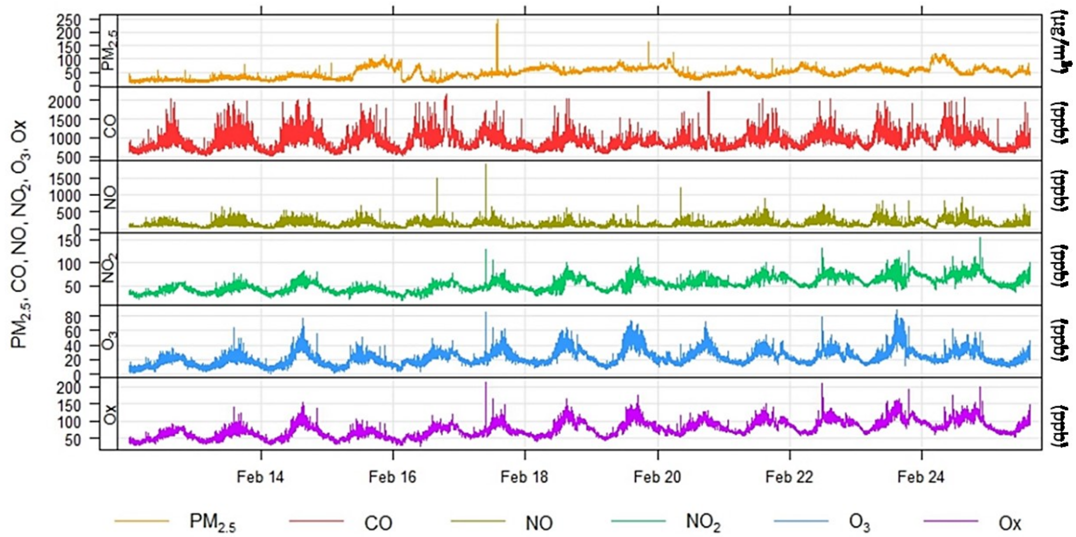

Figure 4 Time Series of air pollutants at Ratchathewi site on 31 seconds resolution in February 2023

According to [39], at the Bangkok city center, the morning rush hour starts from 6:00 AM with the average speed of 32 km/h, and the most congested time in the morning is from 7:00 AM to 8:00 AM with the average travel speed of 26 km/h. The evening rush hour starts from 3:00 PM with the average speed of 28 km/h, and the most congested time in the evening is from 5:00 PM to 6:00 PM with the average speed of 22 km/h. Figure 5 illustrates the hourly variations of $PM_{2.5}$ concentration, which peaked during morning rush hour, gradually decreased, and then surged again from evening rush hour. As the wind speed was not strong enough to disperse, the $PM_{2.5}$ was still suspended in the nighttime. The trace gases started to rise slightly during morning rush hour, peaked at midday, and then started to decline gradually. Traffic-related pollutants photochemically interacted with sunlight to form tropospheric ozone, as described in the preceding section.

Temporal Variations of Air Pollutants at Mueang Samut Sakhon Site

At the Mueang Samut Sakhon site, it was raining for seven days on 15th, 16th, 17th, 23rd, 24th, 25th, and 26th November 2022 according to [38]. $PM_{2.5}$ concentration was found in a fluctuating pattern opposite to photochemical oxidizing gases as shown in Figure 6. CO concentration was found to be high on November 16, 2022, but was not too high on other days with the reason that might be the unusual traveling in Samut Sakhon Province. For the hosting of APEC Economic Leaders' Week in 2022, the Thailand government established three special public holidays on November 16-18 in Bangkok, Nonthaburi, and Samut Prakan Provinces [40]. At the Mueang Samut Sakhon site, the measured pollutant concentrations per 31 seconds ranged from 3.4-172.5 µg/m^3 for $PM_{2.5}$, 426.5-989.9 ppb for CO, 10.4-321.5 ppb for NO, 6.8-95.3 ppb for NO_2, 1.5-143.3 ppb for O_x and 5.3-57.7 ppb for O_3.

As it was raining on most of the days, the temporal variations might not be considered to be representative as those of the Ratchathewi site. For the hourly variations, $PM_{2.5}$ concentration was highest during the morning rush hour, decreased sharply, and then slightly rose from the evening rush hour as shown in Figure 7. Ozone concentration gradually increased starting from 6:00 AM, reached its highest around 2:00 PM, and decreased gradually although the other pollutants did not change much. Both rainfall intensity and its land use might have been important factors affecting the air quality besides the traffic volume during the observation period. However, the air pollution patterns were not clearly identified because of rain during the observation period.

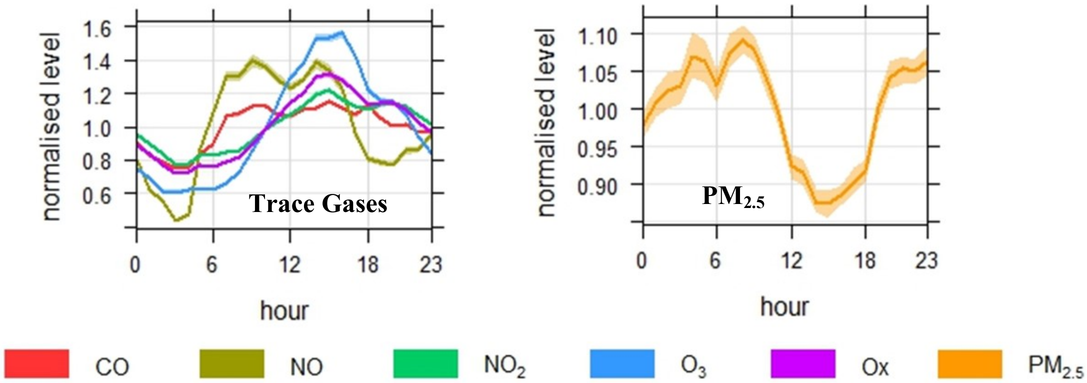

Figure 5 Diurnal variations of air pollutants on 31 seconds resolution at Ratchathewi site

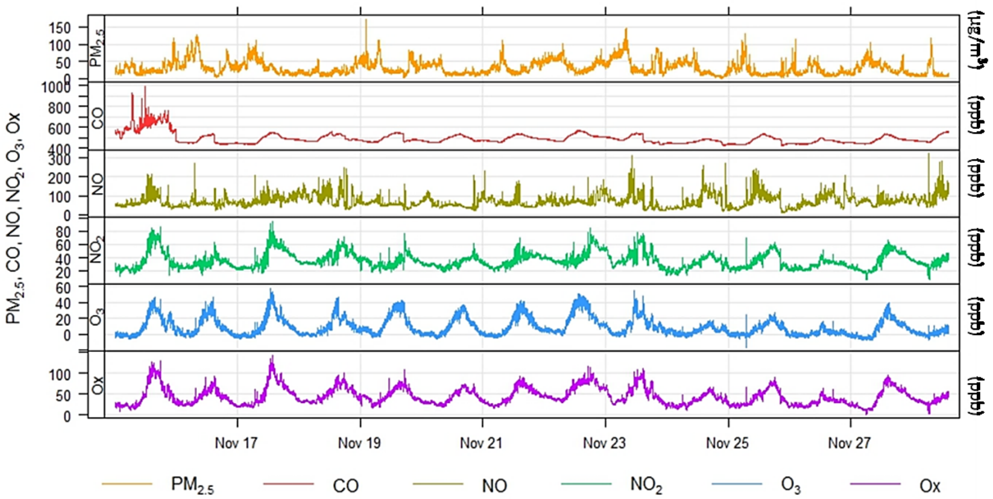

Figure 6 Time series of air pollutants at Mueang Samut Sakhon site on 31 seconds resolution in November 2022

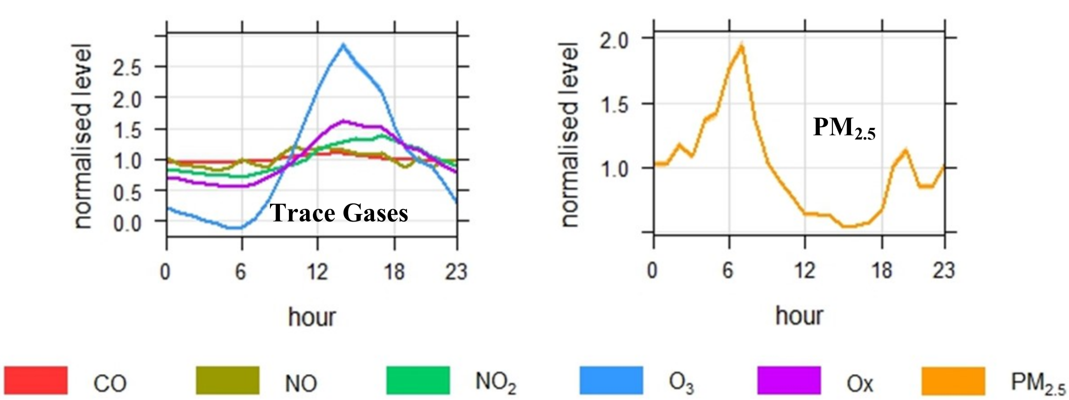

Figure 7 Diurnal variations of air pollutants on 31 seconds resolution at Mueang Samut Sakhon site

Comparison of Averaged Air Quality Results

In Ratchathewi observation, the 1h average results showed that the concentrations of air pollutants (CO, NO_2, and O_3) were observed under the national ambient air quality standards in Thailand [41]. The 1h average data from the Mueang Samut Sakhon observation revealed that the levels of air pollutants (CO, NO_2, and O_3) were below permissible limits for the national ambient air quality standards. According to the Thailand State of Pollution Report, CO levels in Thailand have been below the acceptable range [42]. Although there is no information about the O_x concentration in Thailand's air quality standard, if we compare it to Japan's air quality standard of 60 ppb, it might be said that both observation sites experience pollution from photochemical oxidants in addition to particle matter [43]. Over the past ten years, ozone levels in Thailand have exceeded the national guideline of 100 ppb. The maximum 1h average value of ozone has been recorded at 123 ppb, reaching the Thailand threshold by 193 ppb, according to monitoring stations across the nation [3].

When $PM_{2.5}$ standard is based on 24h, it is necessary to compare with the 24h average CUPI-G results. Therefore, as shown in Figure 8, at the Ratchathewi study site, the 24h average $PM_{2.5}$ concentrations were detected higher than the old standard on 15th, 18th, 19th, 22nd, 23rd, 24th, and 25th February 2023. The maximum detected value was 70.5 µg/m^3 on 24th February 2023 during the observation period. In the Mueang Samut Sakhon observation, the 24h average $PM_{2.5}$ concentrations were below the old national standard during the study period. The Ratchathewi urban site had significantly higher air pollutant concentrations than the Mueang Samut Sakhon suburban area.

Table 2 Comparison of 1h average air quality results at the observation sites

Parameter	Mean ± Standard Deviation		National Ambient Air Quality Standards [41]
	CUPI-G (Ratchathewi District)	CUPI-G (Mueang Samut Sakhon District)	
Temperature (°C)	30.1 ± 2.7	29.5 ± 2.3	-
Humidity (%)	57.3 ± 13.8	74.7 ± 10.1	-
$PM_{2.5}$ Concentration (µg/m^3)	47.7 ± 20.4	30.6 ± 20.5	< 50 (old) < 37.5 (from 1st June 2023) (24 hours)
CO Concentration (ppb)	903.2 ± 214.0	493.2 ± 50.5	< 30 x 10^3
NO Concentration (ppb)	143.9 ± 86.2	70.5 ± 32.0	-
NO_2 Concentration (ppb)	53.5 ± 14.7	35.7 ± 11.9	< 170
O_3 (O_x-NO_2) Concentration (ppb)	22.8 ± 10.4	9.2 ± 11.4	< 100
O_x Concentration (ppb)	76.4 ± 22.9	44.9 ± 20.9	-

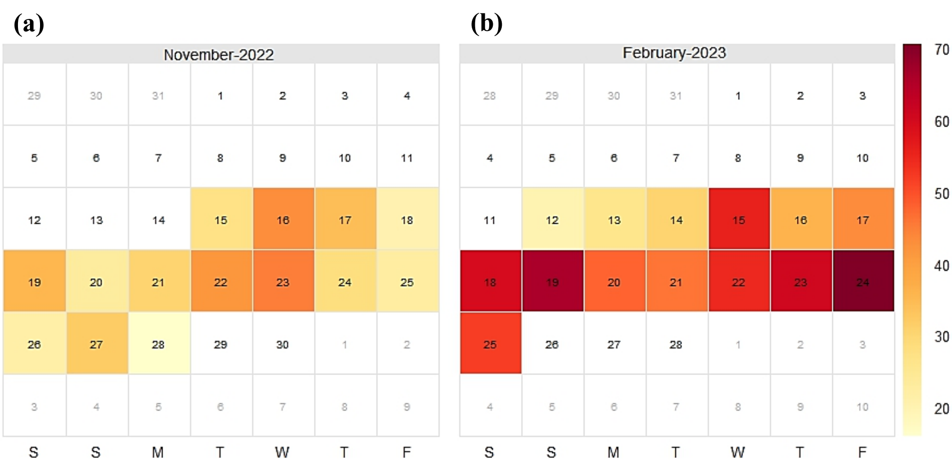

Figure 8 Calendar plots of 24h average $PM_{2.5}$ concentrations at **(a)** Mueang Samut Sakhon site, and **(b)** Ratchathewi site

Conclusion

The air quality observations were conducted for 14days using CUPI-G in the Ratchathewi district urban area, and the Mueang Samut Sakhon district suburban area to investigate the specific temporal variations and air pollution patterns. During the observation period, air pollutant concentrations detected at the Ratchathewi site were 47.7±20.4 μg/m^3 for $PM_{2.5}$, 903.2±214.0 ppb for CO, 143.9±86.2 ppb for NO, 53.5±14.7 ppb for NO_2, 22.8±10.4 ppb for O_3, and 76.4±22.9 ppb for O_x. Conversely, at the Mueang Samut Sakhon site, the measured pollutant concentrations were 30.6±20.5 μg/m^3 for $PM_{2.5}$, 493.2±50.5 ppb for CO, 70.5±32.0 ppb for NO, 35.7±11.9 ppb for NO_2, 9.2±11.4 ppb for O_3, and 44.9±20.9 ppb for O_x. In this study, the CUPI-G showed that it was an applicable compact instrument for atmospheric studies in both urban and suburban areas in Thailand although the observation span was limited. In both observations, it proved as an auxiliary instrument to check the technical problems or the necessity of periodical calibrations and maintenance of standard instruments in the governmental monitoring stations.

We discovered that the air pollution patterns in particular locations were substantially influenced by meteorological conditions. They were possibly impacted by the land use patterns in different urban and suburban observation sites and unfortunately, land use analysis was not discovered in this study. The results showed that both particulate matter and photochemical oxidant pollution occurred in the urban and suburban observation sites. According to the different correlations of $PM_{2.5}$ and concentrations of oxidizing gases, photochemical formation of small secondary particles might happen in the urban site, while high $PM_{2.5}$ might reduce the formation of surface ozone in the suburban site. We found that the correlations of particulate matter and photochemical oxidants showed obvious spatial and temporal differences in this study. Due to the complex atmospheric chemistry in each specific area, additional research is needed to address air pollution issues and understand the air pollution pattern particularly in order to tackle the air pollution problems in Thailand.

Acknowledgement

This work has been partially supported by the 2020 Postgraduate Scholarship, the Faculty of Graduate Studies, Mahidol University, and the Graduate School of Global Environmental Studies, Kyoto University. We would like to thank Ms. Pitchaya Piyaviriyakul for her assistance during the observations.

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ISSN (PRINT) : 1686 - 2961
ISSN (ONLINE) : 2673 - 0359

Vol. 37 No. 2 May – August 2023