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Estimation of Biomass Carbon Storage and Ecological Values of Urban Forest at Chulalongkorn University and its Implications for Carbon Management

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Abstract

Rapid urbanization and increasing greenhouse gas (GHG) emissions over recent decades have intensified climate change and air pollution. However, limited studies have quantified carbon storage and ecosystem services of tropical university campus forests using large-scale inventories and site-specific environmental data, particularly in Southeast Asian megacities such as Bangkok. This study aims to quantify biomass carbon storage and assess key ecosystem services of the urban forest at Chulalongkorn University (CU) and to evaluate their implications for campus-level carbon management. In this assessment, a total of 2,394 trees from a complete tree inventory collected in 2021 and 2022 were analyzed. Biomass carbon storage was estimated using both allometric equations and i-Tree Eco model as complementary approaches under different assumptions and to reflect potential variation between two methods for open-grown urban trees. In addition, the model was employed to evaluate major regulating ecosystem services, including carbon sequestration, air pollution removal, avoided stormwater runoff and oxygen production. To improve local representativeness of model inputs, site-specific hourly meteorological and air pollution data were incorporated. The results revealed that total biomass carbon storage was 1,914.47 tons (7,019.01 tCO₂e) based on manual calculations, whereas the i-Tree Eco model estimated a higher value of 2,796 tons. Furthermore, campus trees were found to sequester 97.81 tons of carbon annually and remove approximately 2.15 tons of air pollutants per year. They also contributed to stormwater management by reducing runoff by 6,460 m³ annually and produced about 260.8 tons of oxygen. Among all species, large and dominant trees in the study area, particularly *Albizia saman*, contributed the most to overall ecosystem services. The findings highlighted the role of urban forest in supporting carbon neutrality goals, tree conservation prioritization, green infrastructure planning and environmental management of the university, while demonstrating their broader value as nature-based solutions for climate mitigation and urban resilience.

Keywords : urban forest; i-Tree Eco; biomass carbon storage; carbon sequestration; ecosystem services

Introduction

Over recent decades, the combined effects of rapid urban expansion and greenhouse gas (GHG) emissions have become key drivers of global climate change. As a consequence, climate-related disasters have led to a fivefold rise in deaths over the past 50 years and displaced approximately 21.5 million people annually. In addition, air pollution has caused more than 7 million deaths each year worldwide [1]. In response to these challenges, forests play a critical role by improving environmental quality. They cover nearly one-third of the Earth's land area [2] and provide four major ecosystem services: provisioning, regulating, supporting, and cultural services [3]. Urban forests, which include all trees within cities and built environments, also offer similar benefits while delivering more immediate and direct impacts due to their proximity to dense populations [4].

However, the extent of urban forests in developing countries has been declining rapidly due to limited support and incentives. In Thailand, urban green spaces have also continued to decrease; however, university campuses still retain substantial tree cover [5]. In addition, universities are important urban carbon management units because they function as “small-scale cities” or “living laboratories,” where sustainability solutions can be tested before being scaled up to the municipal level. Their large physical footprints, high energy consumption, and roles as community hubs enable them to contribute significantly to emission reductions while educating future generations [5-7]. At the city scale, Bangkok has been facing urban heat island effects, air pollution, and flooding due to rapid urbanization, intensive anthropogenic emissions, and limited natural sink capacity. To address these interconnected challenges, standardized and locally grounded carbon assessment programs are needed to support evidence-based planning for urban greening [8, 9].

For effectively addressing climate change, Thailand has enhanced national targets for carbon neutrality and net-zero emissions by 2050 under its Nationally Determined Contributions (NDC 3.0). Within the Land Use, Land-Use Change and Forestry (LULUCF) sector, forests are expected to absorb about 118 million tons of CO₂ equivalent by 2035 [10]. At the institutional level, Chulalongkorn University (CU) has committed to achieving carbon neutrality by

2040 and net-zero emissions by 2050 [11]. For achieving these goals, CU launched the “Chula Race to Zero” initiative, which outlined five strategic approaches: energy transition, improving energy system resilience, creating green growth, lifestyle transition, and the social transition - social support system [5, 11-13]. However, the role of urban forests has not yet been clearly incorporated into the university's carbon neutrality strategies and sustainability reporting framework, despite the extensive tree cover across the campus. In particular, their contributions to carbon storage, a carbon sequestration, and other ecosystem services remain underrecognized. Therefore, localized assessment of the campus forest will provide valuable baseline information for university decision-makers to recognize and prioritize urban forests as an integrated component of future emission reduction policies and sustainability strategies.

At the global scale, carbon accounting and ecosystem service assessments have largely focused on natural forests; thus, benefits provided by urban forests have not been well understood [14]. Regional ecological assessments of urban forests have also been frequently carried out in cities across North America and Europe [15]. Such studies also still remain limited in Thailand, particularly at the university campus forest category. The first study using the i-Tree Eco model in Thailand was conducted by Intasen et al. (2017) to explore its feasibility within Bangkok urban area. Their study found that Bangkok had only 8.6% canopy cover, with trees collectively storing about 3.35 ton ha⁻¹ of carbon and annually sequestering about 0.176 ton ha⁻¹. However, the study could not calculate avoided runoff, PM_{2.5} removal and economic estimates of several ecosystem services [8]. In the second study, conducted at the Chulalongkorn University Centenary Park (CU100 Park) in 2019, park trees were estimated to store 7.84 ton ha⁻¹ of carbon, sequester 1.13 ton ha⁻¹ yr⁻¹, remove 0.14 ton ha⁻¹ of air pollutants annually, and mitigate 18.30 m³ ha⁻¹ of stormwater runoff per year. As the limitation, data from distant air pollution stations and default i-Tree Eco weather stations were used, which might reduce local representation of study site [16]. The third study analyzed regulating ecosystem services across 25 public parks in Bangkok and found that parks totally sequestered 800.7 tons of carbon, avoided 4726.6 m³ of runoff,

and removed 7.27 ton of air pollutants in 2020. However, only four air pollutants (CO , NO_2 , $\text{PM}_{2.5}$, PM_{10}) and limited tree parameters (species and diameter at breast height (DBH)) were used for the model's inputs [9]. In the current study, these limitations were addressed by improving data completeness and incorporating site-specific environmental datasets to enhance the local representativeness of model inputs. However, uncertainties associated with model assumptions, monitoring station distance, inventory quality, and parameter transferability were also acknowledged.

The term “urban forest” includes all trees in cities, towns and suburbs, including both private and public lands, from individual tree and yard trees to parks and wooded fragments [17]. In this study, the term “urban forest” encompasses all trees larger than 3.5 cm DBH within the CU campus, referred to as the “campus forest”. Although the i-Tree Eco model does not specify a mandatory minimum DBH threshold for tree inventories, this DBH range was selected with reference to Thailand's National Forest Inventory practices (2007) and previous urban forest studies that adopted comparable or slightly larger DBH criteria [16, 18]. In addition, while smaller trees currently contribute relatively lower ecosystem services, their inclusion remains important for representing future canopy expansion and long-term forest development. The objectives of this research are: (1) to quantify biomass carbon storage using both manual calculations and i-Tree Eco model; (2) to assess key regulating ecosystem services and their monetary values, including carbon sequestration, air pollution removal, avoided runoff, and oxygen production;

and (3) to evaluate implications of these ecosystem services for campus-level carbon management.

Methodology

Study Area and Period

The study area was the Chulalongkorn University (CU) in the central area of Bangkok, Thailand. For the whole campus, comprehensive complete tree inventory was conducted by the Faculty of Architecture during 2021 and 2022, as illustrated in **Figure 1**. The study area did not include the CU100 Park, Chulalongkorn University Demonstration School, the Faculty of Medicine and King Chulalongkorn Memorial Hospital, due to the data unavailability of the original inventory dataset. However, these exclusions were not expected to largely affect the overall representativeness of the assessment, as the inventory coverage of this study accounted for approximately 89.85 ha, representing 86.75% of the total campus area (103.57 ha).

Tree Inventory Data Description and Data Treatment

The original tree inventory dataset included a total of 2,660 trees with 21 dendrological and environmental parameters. During data collection, all trees with DBH of larger than 3.5 cm were measured; however, not all parameters were available for every tree, resulting in a final dataset of 2,394 trees for analysis after excluding incomplete records. As the inventory was conducted during the summers of 2021 and 2022, (191) trees measured in 2021 were adjusted to represent 2022

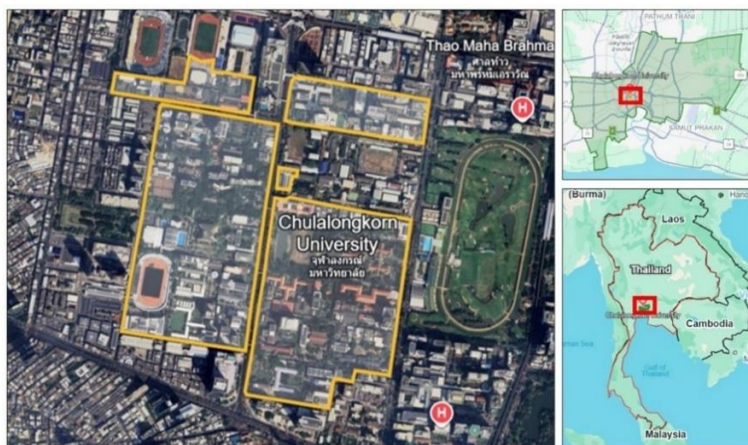


Figure 1 Study area and tree inventory coverage within Chulalongkorn University campus

conditions by adding mean annual growth increments for urban trees in Thailand (0.62 cm for DBH and 0.53 cm for tree height) [19]. These uniform increment values were applied to ensure consistency and because species-specific growth data for urban trees in Thailand are currently limited. Previous studies have also indicated that urban tree species in Bangkok generally exhibit relatively low interspecific variation in growth rates [5, 20, 21]. This adjustment resulted in only a minor change in the overall biomass estimation, with an increase of about 0.13% compared to the unadjusted one.

Manual Calculation of Carbon Storage

Tree biomass was manually estimated in three stages: (1) aboveground biomass (AGB) calculation, (2) belowground biomass (BGB) estimation, and (3) conversion of biomass into carbon storage. Initially, all trees were classified into two groups: evergreen (e.g., *Mimusops elengi*, *Ficus benjamina*, *Alstonia scholaris*) and deciduous species (e.g., *Albizia saman*, *Peltophorum pterocarpum*, *Lagerstroemia speciosa*). Evergreen species represented 47.12%, while deciduous species accounted for 52.88% of the total. This classification was based on published literature and botanical databases, including World Flora Online, e-Flora of Thailand, and Kew Gardens Plants of the World Online, etc. Different allometric equations were applied according to tree category for AGB estimation, and all calculations were performed using Microsoft Excel 2024. For evergreen species, a set of allometric equations developed by Terakunpisut et al. [22] was used to estimate biomass components, including stems, branches, and leaves (Equations 1-4). If the tree is deciduous species, equations of Ogawa et al. [23] were used and those equations were as described below (Equations 5-8):

$$WEs = 0.0509 \times (D^2 H)^{0.91} \quad (1)$$

$$WEb = 0.00893 \times (D^2 H)^{0.977} \quad (2)$$

$$WEl = 0.0140 \times (D^2 H)^{0.669} \quad (3)$$

$$AGBE = WEs + WEb + WEl \quad (4)$$

$$WDs = 0.0396 \times (D^2 H)^{0.9326} \quad (5)$$

$$WDb = 0.003487 \times (D^2 H)^{1.0270} \quad (6)$$

$$WDl = ((28.0 / (Ws + Wb)) + 0.025)^{-1} \quad (7)$$

$$AGBD = WDs + WDb + WDl \quad (8)$$

Where: WEs = mass of the evergreen tree stems (kg), WEb = mass of the evergreen tree branches (kg), WEl = mass of the evergreen tree leaves (kg), D = diameter at breast height of a tree (cm), H = height of a tree (m), AGBE = aboveground biomass of an evergreen tree species (kg), WDs = mass of the deciduous tree stems (kg), WDb = mass of the deciduous tree branches (kg), WDl = mass of the deciduous tree leaves (kg), and AGBD = aboveground biomass of a deciduous tree species (kg).

Total above-ground biomass (AGB) of both evergreen and deciduous tree species was obtained by summation of AGBE and AGBD [5]. Belowground biomass (BGB) was then estimated using the root-to-shoot ratio (R), calculated as a proportion of AGB. IPCC Guidelines for National Greenhouse Gas Inventories (2006) provides default R values for different climate zones and forest types. In this study, R-value of 0.24 was used because Bangkok is located in tropical latitudinal zone [24] and similar studies in Thailand also utilized this value [5]. Total biomass (TB) was calculated as the sum of AGB and BGB. Biomass carbon storage (TC) was then estimated by multiplying TB by a carbon fraction (CF) [25, 26]. A default CF value of 0.47 recommended by the IPCC for tropical and subtropical forests was employed in this study. Finally, carbon storage was converted into carbon dioxide equivalent (CO₂e) using a stoichiometric conversion factor of 3.6663 [5, 27].

Modeling of Ecosystem Services

For the estimation of ecosystem services provided by the CU campus forest, the i-Tree Eco model (version 6.0.39) was utilized. The assessment focused primarily on five regulating ecosystem services: biomass carbon storage, annual carbon sequestration, air pollution removal, avoided stormwater runoff and oxygen production. Air pollution removal was quantified for six pollutants: carbon monoxide (CO), nitrogen dioxide (NO₂), ozone (O₃), particulate matter with diameter ≤ 2.5 μm (PM_{2.5}), particulate matter with diameter between 2.5 and 10 μm (PM_{2.5-10}), and sulfur dioxide (SO₂). To achieve this, a comprehensive set of available tree inventory variables was incorporated in the model, as summarized in **Table 1**.

Table 1 Tree input variables used for ecosystem service estimation in i-Tree Eco

Category	Variable	Unit/Input	Description
Tree Identification	Tree species	-	Common name and scientific name of each tree species
Tree Structure	DBH	cm	Diameter of tree at breast height (1.3 m)
	Total height	m	Total tree height
	Live tree height	m	Height from the ground to live top of the tree
Crown Characteristics	Height to crown base	m	Height from ground to live crown base
	Crown widths	m	Width of the crown in two directions: North-South and East-West
	Crown light exposure (CLE)	0-5	Number of crown sides receiving sunlight (including overhead exposure)
	Crown dieback	%	Percentage of dead crown portion
	Crown missing	%	Missing crown volume compared to full crown
Site Field Information	Land use	Institutional	Land use type in which tree is located
	Strata	Urban	Sub-units by which study area are divided for analysis
	Street tree/ non-street tree	No	Identification if a tree is street tree (Yes) or not (No)
	Public/ private	No	Classification of tree as city managed (public (Yes)) or not (private (No))

Among the tree inputs, live tree height, crown light exposure (CLE), dieback and missing crown percentage, were not directly measured during the field inventory. Therefore, live crown height was assumed to be equal to total tree height because only a small proportion of campus trees exhibited top dieback, while dead branches were routinely pruned for safety management. In addition, CLE, dieback and missing crown percentage were retrospectively estimated through assessing photographs of each inventoried tree. Although this approach did not fully follow the standard field procedures recommended in the i-Tree Eco User Guide, the resulting canopy coverage estimates were generally consistent with values reported in the Campus Tree Plan and Heritage Tree Management of Chulalongkorn University (2024), which applied the i-Tree Canopy model to the same study area and period.

In addition to tree data, hourly precipitation and air pollution data of 2022 for six pollutants were compiled and formatted according to i-Tree submission requirements, and then submitted to the i-Tree database. Rainfall data was obtained from the King Chulalongkorn Memorial Hospital

station (located adjacent to the study site) upon request to the Pollution Control Department (PCD), Thailand. Air pollution data for five pollutants (excluding SO₂) were provided by Bangkok Metropolitan Administration (BMA) from the Ratchathewi District Office station, approximately 1.68 km north of the campus. Due to the unavailability of local SO₂ data, measurements from the Kasetsart University (KU) tower station, located about 12.86 km northeast of the study area, were used. All submitted datasets were validated by the i-Tree team, and subsequently integrated into the model. For meteorological inputs, hourly data for 2022, such as air temperature, solar radiation, wind speed, relative humidity, and atmospheric pressure, were chosen in the model from the nearest National Climatic Data Center station (ID: 484550-99999), located approximately 3.60 km east of the study site.

Air pollution removal in the i-Tree Eco was estimated based on the interaction among forest structure, local weather, and pollutant concentrations. The model calculated pollutant removal through dry deposition processes in which gaseous and particulate pollutants were absorbed or intercepted by tree

surfaces, particularly leaves. Field-measured tree parameters such as species, DBH, crown dimensions, crown condition, and leaf area were integrated with hourly weather and air-quality data to estimate the removal amount of pollutants by vegetation. According to the i-Tree methodology [28], pollutant flux was calculated using Equation 9:

$$F = V_d C \quad (9)$$

Where: F = pollutant flux ($\text{g}/\text{m}^2/\text{s}$), V_d = deposition velocity (m/s), and C = pollutant concentration (g/m^3).

The total mass of removed pollutants was subsequently aggregated across the total leaf area and modeled timeframe to estimate the annual pollution removal of the urban forest.

Results and Discussion

Biomass Carbon Storage and Annual Carbon Sequestration

Based on manual calculations with allometric equations, the total biomass (TB) of trees within the CU campus was estimated at 4,073.33 tons, comprising aboveground biomass (AGB) of 3,284.95 tons (80.65%) and belowground biomass (BGB) of 788.39 tons (19.35%). The total carbon (TC) stored in this biomass was estimated at 1,914.47 tons, equivalent to 7,019.01 tCO_2e . Detailed results are presented in **Figure 2**. This carbon estimate was higher than the 1,237.20 tons reported in a previous assessment of the same study site conducted in 2020 [5], although both studies used similar allometric equations and root-to-shoot ratio. The difference may be attributed to tree growth over time and differences in data acquisition methods, such as geoinformatics technology, Sentinel-2 satellite imagery, and aerial drone photographs in the previous study. In addition, the use of 2016 inventory data for validation may have further contributed to the lower carbon estimate compared with the present field-based inventory study.

For the modeling approach, the i-Tree Eco model generated both carbon storage and annual carbon sequestration, along with their monetary

values. Default economic parameters, including the U.S. EPA social cost of carbon [29] and an exchange rate of 1 USD = 32.68 THB, were applied due to the absence of locally derived ecological valuation data. The model estimated that trees in the CU campus stored a total of 2,796 tons of carbon ($31.12 \text{ ton ha}^{-1}$ based on total campus area), equivalent to approximately 43.6 million THB. In contrast, manually estimated carbon storage was about 31.53% lower than this modeled result. This discrepancy might be due to allometric equations used in manual calculations which are often developed from natural forests or plantations, where lateral crown expansion is typically constrained [30]. Those equations may underestimate biomass components of urban context trees with larger crown area.

In addition, CU campus was dominated by species with naturally broad crown structures (**Table 2**), such as *Albizia saman* (rain tree or Chamchuri), *Pterocarpus indicus* (Burmese rosewood), *Peltophorum pterocarpum* (yellow flame tree), and *Terminalia catappa* (Indian almond). These species were not commonly represented in the forest stands used to develop the applied allometric equations. Consequently, the use of such generalized equations may have contributed to lower carbon estimates compared with the i-Tree Eco model, which applied species- or genus-specific equations and additionally incorporated crown variables into the estimation process. These differences may also be associated with root-to-shoot ratio selection, carbon fraction assumptions, and crown condition variables, which should be further evaluated in future assessments through sensitivity and uncertainty analyses.

Regarding species-level carbon storage patterns, *A. saman*, a widely cultivated non-native species in Thailand because of their high adaptability and favorable growth characteristics [31], contributed the largest share, accounting for 33.7% of the total (**Figure 3a**). This was likely due to its highest abundance across the campus as well as the relatively large size and age of many individuals. Then, *P. pterocarpum* (yellow flame tree) ranked second, followed by *P. indicus*, both of which are native to Thailand [32, 33].

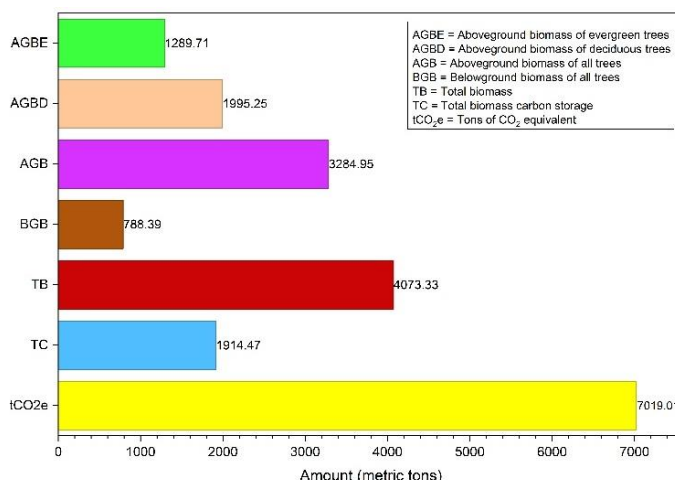


Figure 2 Manually calculated biomass carbon storage in CU urban forest

In terms of carbon sequestration, CU trees were estimated to absorb 97.81 tons of carbon annually, with an associated value of approximately 1.52 million THB per year. Similar to carbon storage, *A. saman* exhibited the highest sequestration capacity, contributing about 14.1% of the total annual carbon sequestration. This suggests that non-native can play a significant role in enhancing both carbon storage and sequestration, although their use should be carefully balanced. Then, *P. indicus* closely ranked second, and *P. pterocarpum* followed as third (**Figure 3b**). The similarity of annual carbon sequestration rates for *A. saman* and *P. indicus* might be due to the fact that many *A. saman* trees were old, affected by varying tree health conditions, and frequently pruned for groundwater conservation

and maintenance purposes, which may have reduced their annual growth and carbon uptake despite their large stored carbon reserves.

The carbon sequestration rate estimated in this study ($1.09 \text{ ton ha}^{-1} \text{ yr}^{-1}$) was very similar to that reported for CU100 Park in 2019 ($1.13 \text{ ton ha}^{-1} \text{ yr}^{-1}$) [16]. The similarity may reflect comparable urban conditions, climate characteristics, and tree growth performance across adjacent areas of the university landscape. In addition, both sites primarily consisted of managed urban green spaces, which likely supported similar levels of tree productivity and carbon uptake. This consistency may further indicate the reliability of carbon sequestration estimates for urban vegetation within the university environment.

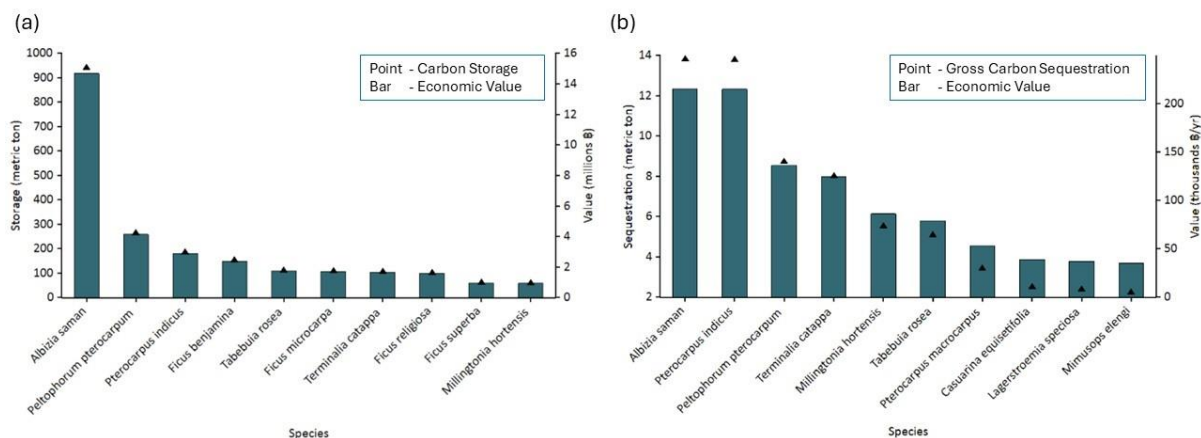


Figure 3 Carbon storage estimations and the associated economic valuation of CU urban forest (a) total carbon storage and (b) annual carbon sequestration

From management perspective, campus carbon-related ecosystem functions were found to depend strongly on a few dominant tree species. However, such excessive reliance could increase vulnerability to pests, diseases, storm damage, and future climate-related stress [28]. Therefore, management strategies should not focus solely on maximizing ecosystem-service outputs, but also on improving long-term

ecological resilience through species diversification. Protecting large mature trees of high-performing species while gradually supplementing future plantings with a broader mixture of native and climate-tolerant species could help maintain ecosystem stability. Suggested management implications of the 10 most common species for future planting strategies are presented in **Table 2**.

Table 2 Carbon contribution and management implications of top 10 dominant campus tree species in CU

Species	Population Percent	Mean DBH (cm)	Carbon Storage (ton)	Carbon Sequestration (ton yr ⁻¹)	Origin Status	Management Implication
<i>Albizia saman</i>	16.8	78.06	941.91	13.81	Exotic	Very high carbon storage and large canopy benefits; maintain mature trees but avoid excessive planting in the future for increasing species diversity
<i>Pterocarpus indicus</i>	12.7	38.72	185.25	13.81	Native	High carbon sequestration and valuable native species; prioritize protection and future planting
<i>Peltophorum pterocarpum</i>	6.9	65.45	265.34	8.73	Native	Good ecosystem-service contribution and shade provision [34]; suitable for continued but balanced planting
<i>Tabebuia rosea</i>	6.8	47.53	111.23	5.08	Exotic	Moderate carbon contribution with ornamental and drought tolerant values [35]; suitable as a supplementary species rather than dominant planting
<i>Pterocarpus macrocarpus</i>	4.0	37.67	59.69	3.41	Native	Native species with good long-term carbon storage potential; suitable for expanded planting
<i>Terminalia catappa</i>	4.0	51.82	106.30	8.01	Native	High canopy [36] and carbon benefits with strong climate resilience; recommended for continued planting in suitable areas
<i>Terminalia ivorensis</i>	3.1	34.23	24.17	1.75	Exotic	Lower carbon contribution despite moderate abundance; future planting should be limited to maintain species balance
<i>Millingtonia hortensis</i>	3.0	33.64	59.81	5.52	Native	Moderate ecosystem-service contribution; useful for increasing species diversity in urban landscapes
<i>Mimusops elengi</i>	2.7	34.62	28.94	2.25	Native	Native evergreen species with moderate ecosystem benefits; suitable for diversified and resilient planting
<i>Lagerstroemia speciosa</i>	2.1	35.22	25.11	2.39	Native	Native ornamental species with moderate carbon benefits; suitable for enhancing species diversity and landscape value

Regarding institutional carbon goals, the estimated carbon storage and sequestration demonstrated that the campus urban forest contributed directly to GHGs mitigation to some extents. CU reported total GHGs emissions of 49,755 tCO₂eq during the 2022 - 2023 academic year [12]. Based on the results of this study, campus trees annually sequestered 97.81 tons of carbon (358.64 tCO₂eq) representing about 0.72% of the total emissions. Although this contribution was relatively small, the potential role of campus forests in providing additional nature-based ecosystem services beyond carbon benefits should not be overlooked. These findings also suggested the need to establish suitable forest-based emission reduction targets and to consider campus forest as a component alongside the current five key strategies under the “Chula Race to Zero” initiative. Such efforts could prioritize the conservation and expansion of campus tree cover to enhance carbon stocks and ecosystem benefits.

Air Pollution Removal and Stormwater Runoff Reduction

The results indicated that CU trees removed approximately 2.15 metric tons of air pollutants (here: 1000 kg = 1 metric ton), with an associated economic value of about 728,000 THB (**Figure 4a**). Among the pollutants, O₃ removal was highest, amounting to 0.712 tons per year (292,167.8 THB), followed by PM_{2.5-10} at 0.619 tons per year (169,611 THB). NO₂ ranked third, with 0.574 tons removed annually, corresponding to an economic value of 235,634 THB. Then, CO, PM_{2.5}, and SO₂ followed, with removal amounts of 0.135, 0.066, and 0.057 tons per year, respectively. In this study, SO₂ data may not have fully represented conditions within the study area because they were obtained from a far station. However, since pollutant removal was calculated separately for SO₂ in the model [28], this limitation likely affected only the accuracy of the SO₂ estimates rather than the overall calculation of other pollutants.

The findings of pollution removal can be explained by the pollutant removal mechanisms of trees. Trees remove gaseous pollutants such as CO, NO₂, O₃, and SO₂ primarily through

stomatal uptake and absorption by leaf surfaces [37], whereas particulate matter (PM_{2.5} and PM_{2.5-10}) is captured through deposition onto leaf surfaces [38]. Among these pollutants, ozone and nitrogen dioxide are generally removed more efficiently due to their higher reactivity and stronger interaction with leaf physiological processes, while particulate matter removal is influenced by leaf surface characteristics and environmental factors [39]. In contrast, carbon monoxide exhibits relatively low removal efficiency due to its weak interaction with plant surfaces [38]. This pattern is consistent with the results presented in **Figure 4a**.

According to the study by Intasen et al., the annual air pollution removal in Bangkok in 2013 was estimated at 0.008 ton ha⁻¹ [8], which was substantially lower than the value obtained in the present study (0.024 ton ha⁻¹). This difference was likely associated with lower tree canopy cover and smaller tree diameter sizes within the broader urban area of Bangkok compared with the well-managed and mature urban forest of the university campus. However, the estimated value in this study was more comparable to the average pollution removal reported for 25 parks in Bangkok (0.031 ton ha⁻¹) [9], possibly due to the greater canopy cover and larger DBH of urban park vegetation relative to the earlier citywide assessment.

For the avoided runoff estimation, i-Tree Eco estimated based on rainfall interception by tree canopies [28]. Although various tree components (leaves, branches, and bark) can intercept rainfall, the model considers only interception by leaves. The economic value of avoided runoff was estimated using values from the U.S. Forest Service's Community Tree Guide Series, with a unit value of 77.16 THB/m³ applied in this study due to the lack of local data [40]. The results showed that CU campus trees reduced surface runoff by approximately 6,460 m³ per year, corresponding to an indicative economic value of about 500,000 THB. The same pattern to carbon sequestration was observed for the top three contributing tree species to avoided runoff (**Figure 4b**) because of the most dominant species across the campus.

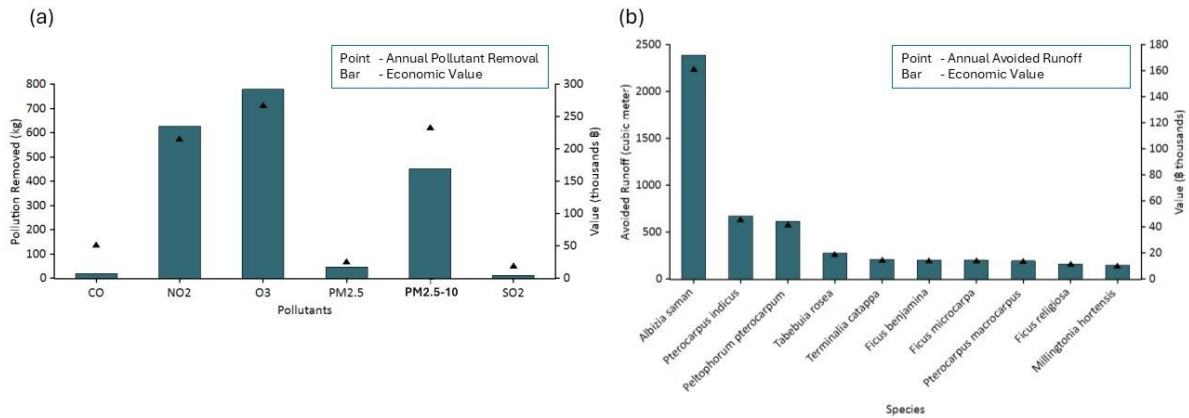


Figure 4 Key ecosystem services of CU urban forest
(a) annual pollution removal and (b) avoided runoff and their associated economic values

The study area covered approximately 103.57 ha, of which nearly 60% consisted of impervious surfaces such as roads, buildings, and pavements. During the 2022 study period, annual rainfall reached approximately 2,378 mm, representing substantial rainfall input to the campus hydrological system. Under these conditions, the presence of urban trees contributed to stormwater regulation by reducing runoff volume by up to 71.89 m³ ha⁻¹, thereby helping to reduce pressure on drainage infrastructure. However, the actual runoff reduction could vary depending on annual rainfall patterns and climatic conditions. In comparison, the avoided runoff provided by trees in 25 parks in Bangkok showed lower average value (22.94 m³ ha⁻¹) [9], possibly due to differences in leaf area and lower annual rainfall during the study period. An earlier study of Bangkok urban area reported an even lower runoff interception value (~ 0.75 m³ ha⁻¹) [8], likely due to substantially lower tree cover and smaller tree sizes.

Oxygen Production by Urban Trees

In the i-Tree Eco model, oxygen production by urban trees is estimated based on carbon sequestration using a stoichiometric conversion factor (32/12). For complete inventory datasets such as this study, oxygen production is calculated from gross carbon sequestration without accounting for decomposition, resulting in slightly higher estimates. As the result, CU campus trees were estimated to produce approximately 260.8 metric tons of oxygen per

year, with the same top ten contributing tree species presented in **Figure 3b**. Among these, *A. saman* (36.82 ton yr⁻¹), *P. indicus* (36.81 ton yr⁻¹), and *P. pterocarpum* (23.29 ton yr⁻¹) were the highest contributors, largely due to their dominance across the campus and their relatively large sizes, which enhance carbon uptake and oxygen release.

However, the economic valuation of oxygen production was excluded in the model because atmospheric oxygen is abundant and its monetary significance is considered limited [28]. In addition, the economic values of ecosystem services in this study should be interpreted as indicative estimates rather than precise locally validated ones because local economic data were largely unavailable; therefore, the model primarily applied U.S.-based valuation coefficients. Consequently, the direct transferability of these economic parameters to the Thai socio-economic context may be limited. Nevertheless, the valuation results remained useful for illustrating the relative magnitude and planning relevance of ecosystem services. For example, the estimated carbon-related benefits were generally comparable with emerging carbon pricing mechanisms and voluntary carbon markets in Thailand.

Conclusions

This study quantified the biomass carbon storage and ecosystem services provided by the CU urban forest using manual method and

i-Tree Eco. The results consistently demonstrated that a few dominant species, particularly *A. saman*, *P. indicus*, and *P. pterocarpum*, contributed substantially to ecosystem services provision across the campus. However, long-term urban forest management should balance between ecosystem-service performance and ecological resilience, by conserving large mature trees while gradually increasing species diversity through future plantings of native and climate-tolerant species. In addition, maintaining healthy crown condition and adequate growing space are essential for sustaining ecosystem functions.

In addition, the existing carbon storage represented the total amount of carbon currently stored within campus forest, whereas annual carbon sequestration reflected the yearly uptake of atmospheric carbon. Although these ecosystem services contributed to the university's carbon neutrality goals, campus forests should be considered as complementary nature-based solutions that support, but do not replace, direct GHGs emission reductions in the energy, transportation, and waste sectors. Moreover, the reported estimates should be interpreted as inventory-based and model-based assessments subject to uncertainty associated with common equations, fixed root-to-shoot ratios, default carbon fractions, monetary valuation coefficients, excluded campus areas, and spatial variability in weather and air pollution data. Consequently, the precision of the estimated values may be influenced by assumptions embedded within the applied equations, parameters, monitoring stations and valuation approaches.

To enhance robustness and practical applicability, further research should incorporate local monetary data, uncertainty and sensitivity analyses, DBH-class assessment, spatial distribution analysis of ecosystem services, long-term canopy monitoring, improved manual calculations based on species-specific equations, and expanded spatial coverage. Integrating ecosystem-service assessment with CU's annual greenhouse gas inventory could further strengthen campus sustainability planning and green infrastructure investment. Overall, the study underscored the role of urban forests as effective nature-based solutions (NBS) for

climate change mitigation, air quality improvement, and urban resilience. At a broader scale, the outcomes of this research may support urban environmental policy development and green infrastructure planning in cities seeking sustainable and climate-resilient solutions.

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Assessment of Pollutant Dispersion in Emergency Scenarios at an Oil Terminal: A Case Study Using the ALOHA Model

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Abstract

This study assesses pollutant dispersion and associated safety impacts resulting from kerosene leakage at oil terminal facilities located in Bangkok and Samut Prakan, Thailand, using the ALOHA (Areal Locations of Hazardous Atmospheres) software to simulate vapor dispersion and fire scenarios. The assessment focused on evaluating the hazard distances of the Flammable Area of Vapor Cloud, Toxic Threat Zone, and Thermal Radiation from Pool Fire under different meteorological conditions. A total of ten simulation scenarios were simulated, consisting of seven scenarios in Bangkok (Scenario 1.1–1.7) and three scenarios in Samut Prakan (Scenario 2.1–2.3).

The results suggest that the flammable vapor cloud area remained relatively constant across all scenarios, hazard distances of approximately 22 m in Bangkok and 23 m in Samut Prakan. This finding suggests that kerosene has a low evaporation rate, causing the flammable vapor cloud to remain confined near the leakage source within the bund wall area and to be minimally influenced by meteorological conditions.

For the Toxic Threat Zone, Samut Prakan exhibited significantly greater impact distances than Bangkok. The AEGL-1 distances ranged from 55–60 m and AEGL-2 distances ranged from 24–26 m in Samut Prakan, whereas Bangkok showed AEGL-1 distances of 33–37 m and AEGL-2 distances of 22–23 m. These differences may be explained by the larger fuel storage capacity, larger tank dimensions, and greater containment areas in Samut Prakan, which may have promoted higher evaporation and vapor accumulation in the atmosphere.

The assessment of Thermal Radiation from Pool Fire revealed substantially larger impact distances in Samut Prakan compared with Bangkok. Thermal radiation distances at 10 kW/m² were approximately 95–96 m in Samut Prakan and 63–64 m in Bangkok. At 5 kW/m², the distances were approximately 134–135 m in Samut Prakan and 90–91 m in Bangkok, while at 2 kW/m², the distances were approximately 208–210 m in Samut Prakan and 140–142 m in Bangkok. These results suggest that Thermal Radiation from Pool Fire may represent the most extensive hazard compared with the Flammable Area of Vapor Cloud and Toxic Threat Zone.

Overall, Samut Prakan exhibited greater hazard distances for all parameters than Bangkok, which may be associated with its larger storage tanks, greater fuel inventory, and larger containment areas, potentially resulting in larger fuel puddles and higher vapor generation. The findings also suggest that the dispersion behavior of kerosene in this study may resemble quasi-heavy gas behavior which may cause vapor clouds to accumulate near ground level and generate hazards primarily within the near-field region close to the leakage source. In contrast, the dominant hazard associated with the incident was Thermal Radiation from Pool Fire, which produced the widest impact area.

The results of this study can support safety and environmental management planning in industrial areas involving fuel storage and handling operations, contributing to improved emergency preparedness and more effective mitigation of risks associated with flammable liquid leakage incidents. However, this study did not include sensitivity analysis; therefore, the observed relationships between hazard distances and site characteristics should be interpreted with caution.

Keywords : Kerosene; ALOHA Model; Consequence Analysis; Toxic Threat Zone; Thermal Radiation; Oil Terminal

Introduction

Industrial accidents involving oil storage facilities have demonstrated that fuel leakage and fire incidents can generate hazardous vapor clouds, toxic gases, thermal radiation, and explosion hazards, potentially affecting workers and nearby communities, particularly in densely populated urban areas. Therefore, The assessment of hazard distances is therefore an important element of emergency response planning, including evacuation planning, area control, and operational decision-making. Consequence assessment is a fundamental component of quantitative risk analysis for hazardous material releases and is widely applied to support risk-informed decision making in industrial facilities [1].

Several studies investigated toxic gas dispersion and emergency response planning using ALOHA. Yoksahachat (2016) [2] reported that chlorine leakage could affect nearby communities within several kilometers under downwind conditions and emphasized the importance of preventive maintenance and shelter-in-place strategies. Tseng et al. (2012) [3] further demonstrated that wind speed and atmospheric stability significantly influenced toxic dispersion distances. In addition, studies involving flammable liquid leakage and pool fire scenarios suggested that leak size and fuel quantity strongly affect hazard distances and emergency response requirements (Permnam, 2021) [4].

Thermal radiation behavior associated with kerosene pool fires has also been extensively studied. Patel and Sohani (2015) [5] reported that kerosene pool fires could produce thermal radiation hazard distances exceeding 100 m under certain conditions. Parent et al. (2019) [6] demonstrated that soot radiation and pool diameter were dominant factors controlling thermal radiation intensity, while Mišić et al. (2018) [7] suggested that thermal radiation may represent one of the dominant hazards associated with kerosene leakage incidents, particularly in

densely populated urban areas. Furthermore, aviation fuel vapor clouds may exhibit near-field hazard characteristics and quasi-heavy gas behavior under low wind speed and stable atmospheric conditions, although ALOHA may have limitations in predicting near-field dispersion due to “near-field patchiness.”

However, most previous studies focused primarily on toxic industrial chemicals, liquefied gases, refinery products, or isolated fire scenarios [8, 9]. Limited studies have investigated aviation kerosene leakage in urban oil terminal facilities, particularly in Thailand, using a unified modeling approach that comparatively evaluates Toxic Threat Zone, Flammable Area of Vapor Cloud, and Thermal Radiation from Pool Fire under different meteorological conditions.

Therefore, this study applies the ALOHA model to assess hazard distances associated with aviation kerosene leakage scenarios in oil terminal facilities located in Bangkok and Samut Prakan, Thailand, in order to support emergency preparedness and industrial risk management.

Materials and Methods

Atmospheric dispersion models are used to estimate how pollutant concentrations vary over time and space after being released into the air. In this study, the ALOHA model was employed to simulate vapor dispersion and estimate the concentration levels and exposure durations under defined emergency scenarios. The model provides quantitative information regarding airborne concentration levels and potential exposure time; however, it does not calculate the probability of injury or health outcomes for exposed individuals.

Based on a review of relevant literature and technical guidelines, the assessment of pollutant dispersion under emergency conditions at oil terminal facilities was conducted through a structured modeling approach, as described in the following sections.

Goal and Scope of the Study

The case study oil terminals are located in Bangkok and Samut Prakan, Thailand, where kerosene is only stored in large aboveground storage tanks. and therefore multi-fuel interaction scenarios were not considered. The facilities are located in urbanized areas surrounded by residential and commercial land uses, indicating the potential for significant off-site consequences in the event of a major accident.

The goal of this study is defined as follows:

- 1) To assess hazard distances associated with toxic vapor dispersion resulting from aviation fuel leakage (Toxic Threat Zone).
- 2) To evaluate the flammable vapor cloud hazard distances associated with aviation fuel leakage (Flammable Area of Vapor Cloud).
- 3) To assess the thermal radiation hazard distances resulting from pool fire scenarios caused by aviation fuel leakage (Thermal Radiation from Pool Fire).

Research Instruments

The tools used in this study are as follows:

- 1) ALOHA (Areal Locations of Hazardous Atmospheres) software was employed to perform atmospheric dispersion modeling of hazardous chemical releases.
- 2) Google Earth software was used to visualize and overlay the dispersion

modeling results onto geographic maps in order to illustrate the spatial extent of affected areas.

Data Used in the Study

1. Meteorological Data

Meteorological data used in this study were based on five-year average observations (2020–2024) obtained from the Don Mueang Meteorological Station (Bangkok) and the Suvarnabhumi Airport Meteorological Station (Samut Prakan) [10], representing local atmospheric conditions at the respective oil terminal facilities. Key parameters considered in the simulations included wind speed, wind direction, measurement height, atmospheric stability, surface roughness, cloud cover, and relative humidity. These parameters were incorporated into the ALOHA model to characterize atmospheric dispersion conditions and evaluate their influence on the transport and hazard distances of released kerosene vapor under different seasonal meteorological conditions.

2. Chemical Data

The chemical substance analyzed in this study is kerosene, which represents the primary component of Kerosene fuel stored at the study sites. The physicochemical and hazard parameters used as input for the ALOHA model are summarized in **Table 1**.

Table 1 Physicochemical and Hazard Parameters of Kerosene Used in the Simulation

Parameter	Value
Chemical Name	Kerosene
Flashpoint	(Tagliabue Closed Cup ASTM D56) 38 °C (100 °F) (Min) [11, 12]
Autoignition	210 °C (410 °F) [11]
Combustion Products	Highly dependent on combustion conditions. A complex mixture of airborne solids, liquids, and gases including CO, CO ₂ , and unidentified organic compounds will evolve during combustion [11]
Molecular Weight	140.00 g/mol [13]
Acute Exposure Level Guidelines 1 (AELG-1) (60 min)	290 mg/m ³ [14, 15]
Acute Exposure Level Guidelines 2 (AELG-2) (60 min)	1100 mg/m ³ [14, 15]
Acute Exposure Level Guidelines 3 (AELG-3) (60 min)	N/A [14, 15]
Protective Action Criteria (PAC-1)	290 mg/(cu m) [16]
Protective Action Criteria (PAC-2)	1100 mg/(cu m) [16]
Protective Action Criteria (PAC-3)	4100 mg/(cu m) [16]
Lower Explosive Limit (LEL)	7000 ppm [11]
Upper Explosive Limit (UEL)	50000 ppm [11]
Ambient Boiling Point	160.0 °C [11]

Parameter	Value
Vapor Pressure at Ambient Temperature	8.09×10^{-5} atm [11]
Ambient Saturation Concentration	80.9 ppm (0.0081%) [17]
Heat Capacity (gas,const.press)	3400 J/(Kg@800°K, 101325 Pa) [17]
Heat Capacity (liq,const.press)	2100 J/(Kg@288.15°K, 101325 Pa) [17]
Heat of Combustion	42800000 J/kg [12]
IDLH	No data available

Note: AEGL-3 was unavailable (N/A) for kerosene in the ALOHA database. Therefore, Toxic Threat Zone assessments in this study were based only on AEGL-1 and AEGL-2 criteria. Although PAC-3 values were available from the Protective Action Criteria database, they were not used in the present analysis.

3. Scenario Definition for Dispersion Modeling

The leakage scenarios were defined for two oil terminal locations: Bangkok and Samut Prakan. The selected storage tank in Bangkok has a height of 15 m, a diameter of 24 m, and a fuel inventory of 5.85 million liters, corresponding to 90% of its maximum capacity. The selected storage tank in Samut Prakan has a height of 19.5 m, a diameter of 33 m, and a fuel inventory of 13.5 million liters, also corresponding to 90% of its maximum capacity. In both locations, the largest storage tank was selected to represent a conservative scenario. This selection was adapted from the principle used in the Thai Ministerial Regulation on Oil Depots B.E. 2556, Clause 48(5) [18] and National Fire Protection Association. 2024. NFPA 11 [19], which requires the quantity of foam concentrate to be calculated based on the tank requiring the maximum amount of foam solution.

For both study areas, the leakage scenario was assumed to occur from a 12-inch diameter opening, corresponding to the actual 12-inch fuel pipeline connected to the storage tank. Therefore, the 12-inch leak diameter represents a full-bore rupture scenario of the pipeline. The release height was defined at approximately 5% of the total tank height above the tank bottom because the pipeline in

both locations is installed at the lower section of the tank (5% above the tank bottom). This assumption reflects the actual engineering configuration of the storage tank pipeline system.

The assumed failure mechanism was severe structural damage to the pipeline caused by an earthquake or significant ground subsidence. Under such conditions, the flexible pipe section connected to the metallic piping may experience excessive tensile stress and tearing, resulting in fuel leakage from a vertical fixed-roof storage tank. Accordingly, the selected 12-inch leak diameter and 5% release height were intended to represent a realistic but conservative leakage scenario for emergency planning and hazard assessment.

To account for seasonal meteorological variability, five-year average meteorological data from 2020 to 2024 that was summarized in **Table 2** atmospheric data. Simulation scenarios for the Bangkok study site and Samut Prakan study site were used for all twelve months of the year that was summarized in **Table 3** and the condition in **Table 4**. The simulation scenarios were then categorized according to prevailing wind directions to evaluate hazard distances and potential risk areas under seasonal wind conditions.

Table 2 Atmospheric Data

Scenario	Parameter and Value						
	Wind Speed and Direction (average at 10 m height)	Ground Roughness	Cloud Cover	Air Temperature (average)	Stability Class	Inversion Height	Relative Humidity (average)
1.1	2.48 m/s from East	Urban or Forest	6 tenths	27 °C	C	No Inversion	62 %
1.2	2.8 m/s from South	Urban or Forest	6 tenths	29 °C	C	No Inversion	68 %
1.3	3.17 m/s from SSW	Urban or Forest	6 tenths	30 °C	C	No Inversion	72 %
1.4	3 m/s from West	Urban or Forest	6 tenths	29.5 °C	C	No Inversion	77 %
1.5	3.42 m/s from SW	Urban or Forest	6 tenths	29 °C	C	No Inversion	75 %

Scenario	Parameter and Value						
	Wind Speed and Direction (average at 10 m height)	Ground Roughness	Cloud Cover	Air Temperature (average)	Stability Class	Inversion Height	Relative Humidity (average)
1.6	2.47 m/s from North	Urban or Forest	6 tenths	26 °C	C	No Inversion	78 %
1.7	2.46 m/s from NE	Urban or Forest	6 tenths	27 °C	C	No Inversion	66 %
2.1	2.13 m/s from East	Open country	6 tenths	28 °C	C	No Inversion	72 %
2.2	2.9 m/s from South	Open country	7 tenths	29 °C	C	No Inversion	75 %
2.3	2.14 m/s from ENE	Open country	6 tenths	27 °C	C	No Inversion	66 %

Table 3 Simulation Scenarios for the Bangkok and Samut Prakan Study Site

Scenario No.	Release Condition	Wind Direction	Month(s)	Model Applied
1.1	Flammable fuel leakage without ignition	East	January	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.2	Flammable fuel leakage without ignition	South	February, March, April, May	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.3	Flammable fuel leakage without ignition	South–Southwest (SSW)	June	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.4	Flammable fuel leakage without ignition	West	July, September	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.5	Flammable fuel leakage without ignition	Southwest	August	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.6	Flammable fuel leakage without ignition	North	October	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
1.7	Flammable fuel leakage without ignition	Northeast	November, December	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
2.1	Flammable fuel leakage without ignition	East	October, November, January	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
2.2	Flammable fuel leakage without ignition	South	February, March, April, May, June, July, August, September	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire
2.3	Flammable fuel leakage without ignition	Northeast	December	Toxic Vapor Cloud; Flammable Threat Zones
	Flammable fuel leakage with ignition			Thermal Radiation from Pool Fire

Table 4 The Release Rate for the Bangkok and Samut Prakan Study Site

Scenario	Parameter and Value			
	Max Average Sustained Release Rate (vapor release rate to atmosphere)	Total Amount Released (vapor)	Maximum Puddle Area	Note
1.1	11.8 Kg/min (averaged over ≥ 1 min)	708 kg	1,455.6 m ²	Chemical escaped as liquid and formed an evaporating puddle; puddle spread to 43 m diameter
1.2	12.6 kg/min (averaged over ≥ 1 min)	746 kg		
1.3	14.9 kg/min (averaged over ≥ 1 min)	878 kg		
1.4	13.8 kg/min (averaged over ≥ 1 min)	815 kg		
1.5	14.9 kg/min (averaged over ≥ 1 min)	880 kg		
1.6	9.36 kg/min (averaged over ≥ 1 min)	552 kg		
1.7	9.92 kg/min (averaged over ≥ 1 min)	585 kg		
2.1	10.1 kg/min (averaged over ≥ 1 min)	600 kg	1,645 m ²	Chemical escaped as liquid and formed an evaporating puddle; puddle spread to 46 m diameter
2.2	14.4 kg/min (averaged over ≥ 1 min)	851 kg		
2.3	9.6 kg/min (averaged over ≥ 1 min)	568 kg		

The effect of secondary containment was incorporated into the ALOHA simulations through the Maximum Puddle Area parameter. For each study site, the maximum puddle area was calculated based on the effective containment area enclosed by the surrounding bund wall. It was assumed that the released fuel remained within the secondary containment system and did not overflow beyond the bund boundary.

The calculated maximum puddle areas were 1,455.6 m² for the Bangkok site and 1,645 m² for the Samut Prakan site. These values were entered into ALOHA as user-defined Maximum Puddle Area inputs to constrain liquid pool expansion and to estimate subsequent evaporation rates, vapor dispersion, and thermal radiation impacts.

Results and Discussion

The Assessment Results

ALOHA simulation results for kerosene leakage scenarios at the Bangkok and Samut Prakan study sites are presented in **Tables 5 and 6**. Hazard distances estimates for the Flammable Area of Vapor Cloud, Toxic Threat Zone, and Thermal Radiation from Pool Fire were evaluated and compared under representative meteorological conditions.

The results showed that the flammable vapor cloud hazard distance was limited to approximately 22 m from the release point, indicating that the flammable threat zone remained largely confined within the containment dike surrounding the storage tank. The ALOHA model did not generate graphical

threat contours in the immediate vicinity of the release source, which may be associated with near-field dispersion limitations.

The maximum Toxic Threat Zone extended to approximately 34 m from the release point based on the Acute Exposure Guideline Levels (AEGs), indicating a relatively localized health impact area. In contrast, the Thermal Radiation from Pool Fire scenario produced the largest hazard distance, reaching approximately 142 m at a thermal radiation level of 2 kW/m². These results suggest that thermal radiation represents the most extensive hazard associated with the simulated kerosene leakage scenario.

The results showed that the maximum flammable vapor cloud hazard distance was approximately 23 m from the release point, indicating that the flammable threat zone remained largely confined within the containment dike surrounding the storage tank. The ALOHA model did not generate graphical threat contours in the immediate vicinity of the release source, which may be associated with near-field dispersion limitations.

The maximum Toxic Threat Zone extended up to 60 m from the release point based on the Acute Exposure Guideline Levels (AEGs), indicating a relatively localized health impact area. In contrast, the Thermal Radiation from Pool Fire scenario produced the largest hazard distance, reaching approximately 210 m from the source. These findings suggest that thermal radiation represents the most extensive hazard associated with the simulated kerosene leakage scenario.

Table 5 The assessment results at the Bangkok study site

Model Applied	Result						
	1.1 East Wind	1.2 South Wind	1.3 South South-west Wind	1.4 West Wind	1.5 South-west Wind	1.6 North Wind	1.7 North North-east Wind
Flammable Threat Zones (Estimates)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)	Red: 22 m (4200 ppm)
	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)	Yellow: 22 m (700 ppm)
Toxic Vapor Cloud (Estimates)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)	AEGL-2: 22 m (1100 mg/m ³)
	AEGL-1: 34 m (290 mg/m ³)	AEGL-1: 36 m (290 mg/m ³)	AEGL-1: 37 m (290 mg/m ³)	AEGL-1: 36 m (290 mg/m ³)	AEGL-1: 36 m (290 mg/m ³)	AEGL-1: 33 m (290 mg/m ³)	AEGL-1: 34 m (290 mg/m ³)
Thermal Radiation from Pool Fire (Estimates)	Red: 64 m (10.0 kW/m ²)	Red: 63 m (10.0 kW/m ²)	Red: 63 m (10.0 kW/m ²)	Red: 63 m (10.0 kW/m ²)	Red: 63 m (10.0 kW/m ²)	Red: 64 m (10.0 kW/m ²)	Red: 64 m (10.0 kW/m ²)
	Orange: 91 m (5.0 kW/m ²)	Orange: 90 m (5.0 kW/m ²)	Orange: 90 m (5.0 kW/m ²)	Orange: 90 m (5.0 kW/m ²)	Orange: 90 m (5.0 kW/m ²)	Orange: 91 m (5.0 kW/m ²)	Orange: 91 m (5.0 kW/m ²)
	Yellow: 142 m (2.0 kW/m ²)	Yellow: 141 m (2.0 kW/m ²)	Yellow: 140 m (2.0 kW/m ²)	Yellow: 140 m (2.0 kW/m ²)	Yellow: 140 m (2.0 kW/m ²)	Yellow: 141 m (2.0 kW/m ²)	Yellow: 142 m (2.0 kW/m ²)

Table 6 The assessment results at the Samut Prakan study site

Model Applied	Result		
	2.1 East Wind	2.2 South Wind	2.3 East North-east Wind
Flammable Threat Zones (Estimates)	Red: 23 m (4200 ppm)	Red: 23 m (4200 ppm)	Red: 23 m (4200 ppm)
	Yellow: 23 m (700 ppm)	Yellow: 23 m (700 ppm)	Yellow: 23 m (700 ppm)
Toxic Vapor Cloud (Estimates)	AEGL-2: 25 m (1100 mg/m ³)	AEGL-2: 26 m (1100 mg/m ³)	AEGL-2: 24 m (1100 mg/m ³)
	AEGL-1: 58 m (290 mg/m ³)	AEGL-1: 60 m (290 mg/m ³)	AEGL-1: 55 m (290 mg/m ³)
Thermal Radiation from Pool Fire (Estimates)	Red: 96 m (10.0 kW/m ²)	Red: 95 m (10.0 kW/m ²)	Red: 96 m (10.0 kW/m ²)
	Orange: 135 m (5.0 kW/m ²)	Orange: 134 m (5.0 kW/m ²)	Orange: 135 m (5.0 kW/m ²)
	Yellow: 209 m (2.0 kW/m ²)	Yellow: 208 m (2.0 kW/m ²)	Yellow: 210 m (2.0 kW/m ²)

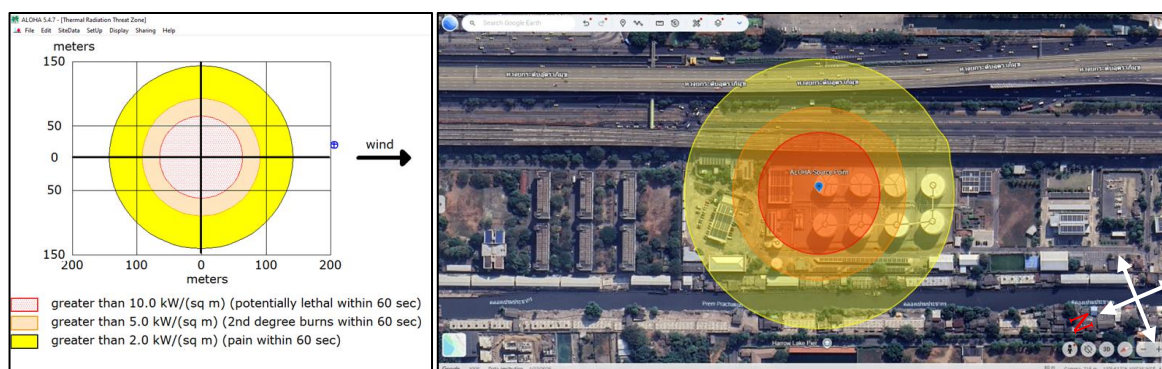


Figure 1 The maximum predicted thermal radiation impact distance in Bangkok study site.

The hazard zone (Threat Zone) assessment results for the kerosene leakage scenario generated using the ALOHA model and overlaid on Google Earth satellite imagery. The figure identifies the release source location (ALOHA Source Point) and the corresponding impact areas predicted by the model. The revised figure has been enhanced with higher resolution and includes a linear scale bar (80 m) and a north arrow referenced to True North to improve spatial interpretation and map readability.

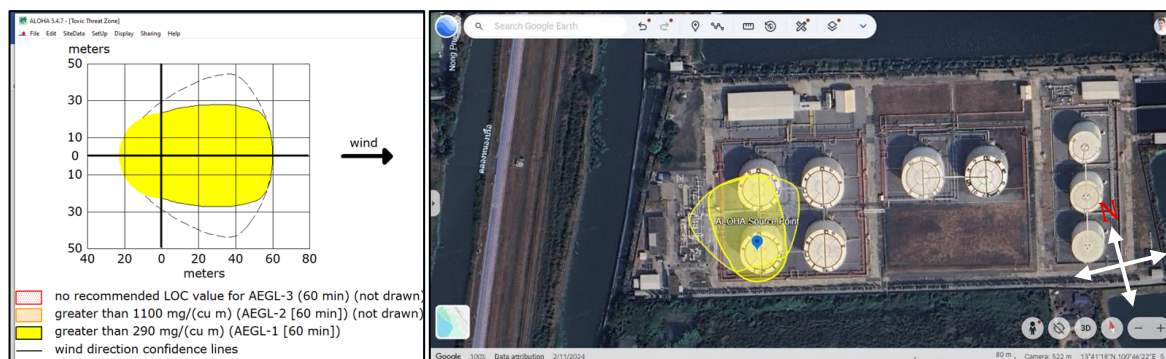


Figure 2 The maximum predicted Toxic Threat distance in Samut Prakan study site.

The hazard zone (Threat Zone) assessment results for the kerosene leakage scenario generated using the ALOHA model and overlaid on Google Earth satellite imagery. The figure identifies the release source location (ALOHA Source Point) and the corresponding impact areas predicted by the model. The revised figure has been enhanced with higher resolution and includes a linear scale bar (80 m) and a north arrow referenced to True North to improve spatial interpretation and map readability.

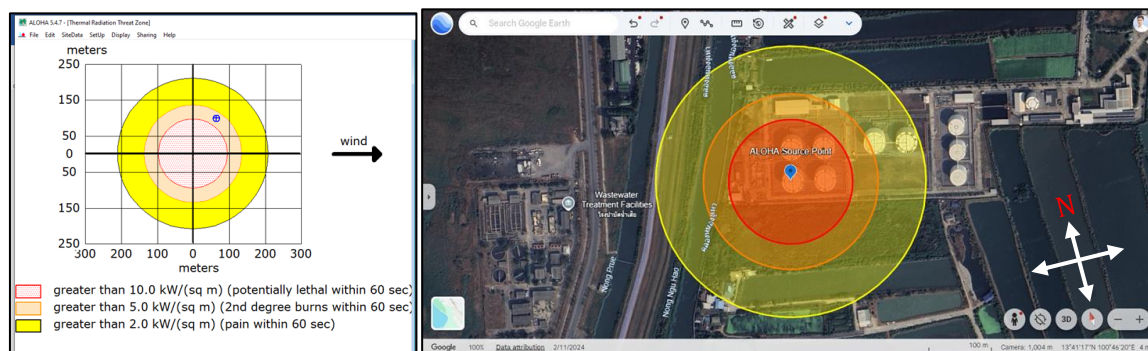


Figure 3 The maximum predicted thermal radiation impact distance in Samut Prakan study site.

The hazard zone (Threat Zone) assessment results for the kerosene leakage scenario generated using the ALOHA model and overlaid on Google Earth satellite imagery. The figure identifies the release source location (ALOHA Source Point) and the corresponding impact areas predicted by the model. The revised figure has been enhanced with higher resolution and includes a linear scale bar (100 m) and a north arrow referenced to True North to improve spatial interpretation and map readability.

Overall Assessment of the Flammable Area of Vapor Cloud for Scenarios 1.1–1.7

The results indicated that the Flammable Area of Vapor Cloud remained relatively constant across Scenarios 1.1–1.7, with a maximum hazard distance of approximately 22 m from the release point.

The relatively short flammable hazard distance may be attributed to the low vapor pressure and slow evaporation rate of kerosene. As a result, the quantity of vapor available to form a flammable mixture with air may have remained limited, which could have contributed to combustible vapor accumulation near the liquid surface and release location rather than dispersion over longer distances.

The results suggest that meteorological variations had limited influence on the flammable hazard distance within the investigated range of conditions. Although wind speed varied between 2.46 and 3.42 m/s, the Red Zone (60% LEL) and Yellow Zone (10% LEL) remained unchanged at approximately 22 m. This observation suggests that, within the investigated wind speed range, atmospheric transport was insufficient to significantly extend the flammable vapor cloud. Similarly, air temperature varied from 26 to 30°C without producing noticeable changes in hazard distance. Relative humidity also varied between 62% and 78% but showed no apparent influence on the flammable threat zone. This finding is consistent with the expectation that flammable vapor generation is governed primarily by fuel properties, such as vapor pressure, flash point, and evaporation rate, rather than by atmospheric humidity.

The overall distribution of flammable hazard distances for scenarios 1.1–1.7 is illustrated in the **Figure 4**.

Overall Assessment of the Toxic Threat Zone for Scenarios 1.1–1.7

The Toxic Threat Zone associated with kerosene leakage remained relatively limited across Scenarios 1.1–1.7. The maximum AEGL-1 hazard distance reached 37 m in Scenario 1.3 under south-southwesterly (SSW) wind conditions, whereas AEGL-2 remained approximately 22 m in all scenarios. Similar to the flammable vapor cloud results, ALOHA did not generate graphical threat contours near the release source because of limitations associated with near-field dispersion behavior.

Although meteorological conditions varied among the scenarios, AEGL hazard distances remained within a relatively narrow range. These findings suggest that atmospheric conditions may have influenced vapor dispersion to some extent; however, the relatively low evaporation rate and quasi-heavy gas characteristics of kerosene may have played a more important role in controlling toxic hazard distances. Slightly greater AEGL-1 distances were observed at higher temperatures, whereas no clear relationship was identified between relative humidity and hazard distance. It should also be recognized that atmospheric dispersion predictions are subject to uncertainties associated with source characterization, meteorological inputs, and inherent model assumptions, which may influence the accuracy of predicted hazard distances [20].

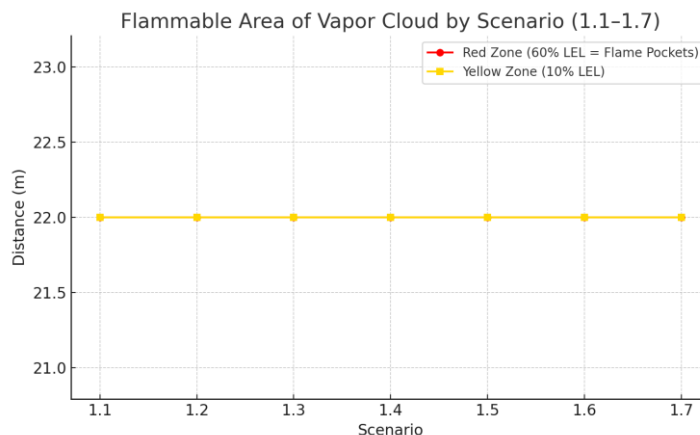


Figure 4 Comparison of Flammable Threat Zone Distances for Scenarios 1.1–1.7 at the Bangkok Study Site

The overall distribution of toxic hazard distances for scenarios 1.1–1.7 is illustrated in the **Figure 5**.

Overall Assessment of Thermal Radiation from Pool Fire for Scenarios 1.1–1.7

Thermal Radiation from Pool Fire produced the largest hazard distances among all evaluated scenarios. The maximum predicted hazard distances were approximately 64 m, 91 m, and 142 m for thermal radiation levels of 10, 5, and 2 kW/m², respectively. According to ALOHA hazard criteria, these radiation levels may result in severe injury, second-degree burns, or minor burn injuries following prolonged exposure.

The thermal radiation hazard distances remained relatively consistent across all scenarios, with Red Zone (10 kW/m²), Orange Zone (5 kW/m²), and Yellow Zone (2 kW/m²) distances ranging from 63–64 m, 90–91 m, and 140–142 m, respectively. This limited variation suggests that meteorological conditions had only a minor influence on thermal radiation hazard distances within the investigated range. Instead, thermal radiation hazards appeared to be governed primarily by pool fire characteristics, particularly pool diameter and heat release rate.

The overall distribution of thermal radiation distances for Scenarios 1.1–1.7 is illustrated in the **Figure 6**.

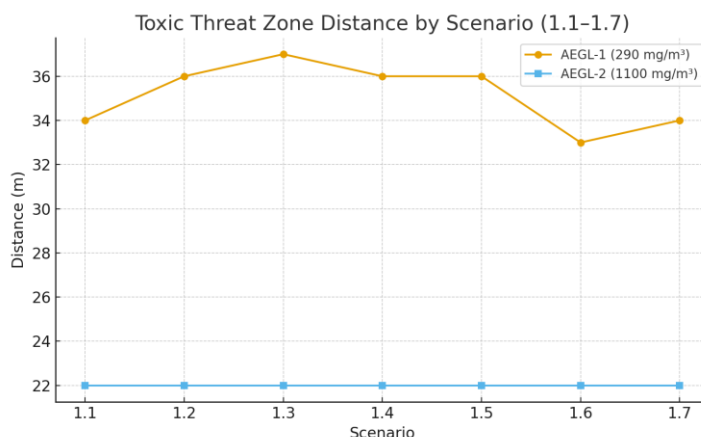


Figure 5 Comparison of Toxic Threat Zone Distances for Scenarios 1.1–1.7 at the Bangkok Study Site

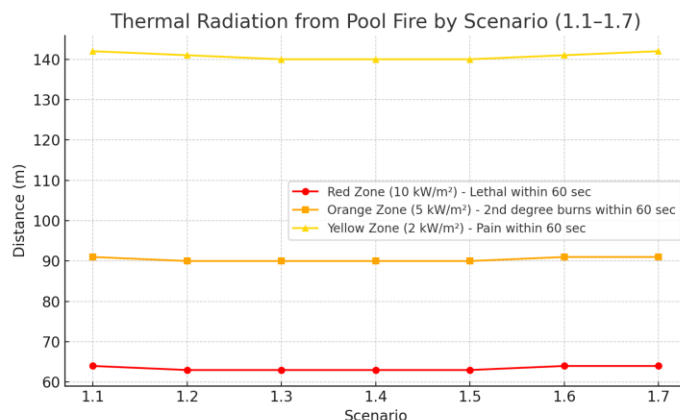


Figure 6 Comparison of Thermal Radiation Distances for Scenarios 1.1–1.7 at the Bangkok Study Site

Overall Assessment of the Flammable Area of Vapor Cloud for Scenarios 2.1–2.3

The simulation results showed that the Flammable Area of Vapor Cloud remained consistent across Scenarios 2.1–2.3, with a maximum hazard distance of approximately 23 m from the release source. The predicted flammable threat zone was confined within the containment dike surrounding the storage tank, indicating that combustible vapor accumulation remained localized near the release area.

Similar to the Bangkok scenarios, ALOHA did not generate graphical threat contours in the immediate vicinity of the release source because of limitations associated with near-field dispersion behavior. Therefore, the extent of the Flammable Area of Vapor Cloud was illustrated separately, as shown in **Figure 10**.

Despite variations in meteorological conditions, including wind speed (2.13–2.90 m/s), air temperature (27–29°C), and relative humidity (66–75%), no significant variation in flammable hazard distance was observed. Both the Red Zone (60% LEL) and Yellow Zone (10% LEL) remained at approximately 23 m across all scenarios. These findings suggest that, within the investigated range of meteorological conditions, flammable hazard distances were influenced more strongly by the physical properties of kerosene than by atmospheric variability. Consequently, the flammable vapor cloud remained restricted to the near-field region surrounding the storage tank.

The overall distribution of flammable hazard distances for Scenarios 2.1–2.3 is illustrated in the **Figure 7**.

Overall Assessment of the Toxic Threat Zone for Scenarios 2.1–2.3

The Toxic Threat Zone predicted for the Samut Prakan oil terminal extended farther than that observed in the Bangkok scenarios. The maximum AEGL-1 and AEGL-2 hazard distances were predicted in Scenario 2.2, reaching approximately 60 m and 26 m from the release source, respectively. Compared with the Flammable Area of Vapor Cloud, the Toxic Threat Zone exhibited greater sensitivity to meteorological variability, particularly for AEGL-1, which consistently extended farther than AEGL-2 due to its lower concentration threshold.

Although Scenario 2.2 was characterized by the highest wind speed, air temperature, and

relative humidity, the increase in hazard distance remained relatively small. These findings suggest that meteorological conditions may have influenced vapor transport and near-ground dispersion to some extent; however, the overall variation among scenarios was limited. Consequently, toxic hazard distances appear to be influenced not only by atmospheric conditions but also by kerosene evaporation behavior and vapor generation characteristics.

Acute inhalation toxicity and long-term environmental air quality impacts represent different assessment endpoints. Although kerosene is not considered highly toxic in terms of short-term inhalation exposure, it may still contribute to VOC emissions and photochemical ozone formation under atmospheric conditions.

The overall distribution of toxic hazard distances for Scenarios 2.1–2.3 is illustrated in the **Figure 8**.

Overall Assessment of Thermal Radiation from Pool Fire for Scenarios 2.1–2.3

Thermal Radiation from Pool Fire produced the largest impact distances among all evaluated hazards in the Samut Prakan scenarios. The maximum predicted hazard distances were approximately 96 m, 135 m, and 210 m for thermal radiation levels of 10, 5, and 2 kW/m², respectively. According to the ALOHA hazard criteria, these radiation levels may result in severe injury, second-degree burns, or minor burn injuries following short-term exposure.

Only minor differences were observed among Scenarios 2.1–2.3, with variations of approximately 1–2 m across all thermal radiation threat zones. Despite differences in meteorological conditions and release characteristics, the predicted thermal radiation distances remained highly consistent. This observation suggests that thermal radiation hazards were influenced more strongly by pool fire characteristics, such as burning area and fuel combustion properties, than by atmospheric variability. Compared with the Flammable Area of Vapor Cloud and Toxic Threat Zone, Thermal Radiation from Pool Fire generated the widest impact area, highlighting its significance as the dominant hazard associated with the simulated kerosene leakage scenarios.

The overall distribution of thermal radiation distances for Scenarios 2.1–2.3 is illustrated in the **Figure 9**.

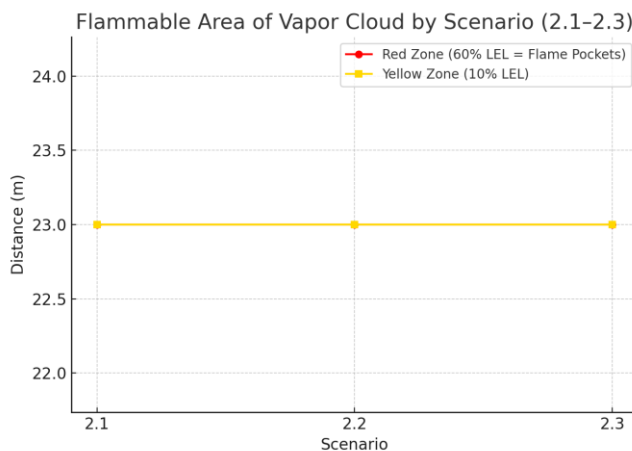


Figure 7 Comparison of Flammable Threat Zone Distances for Scenarios 2.1–2.3 at the Samut Prakan Study Site

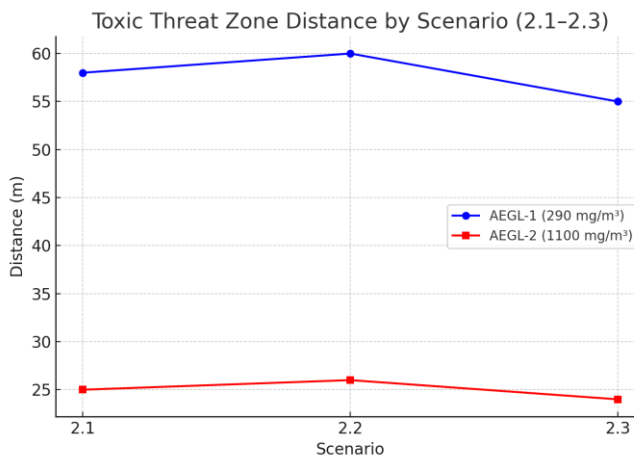


Figure 8 Comparison of Toxic Threat Zone Distances for Scenarios 2.1–2.3 at the Samut Prakan Study Site

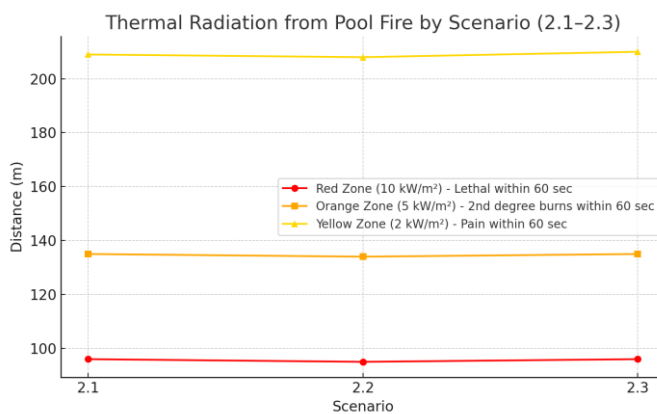


Figure 9 Comparison of Thermal Radiation Distances for Scenarios 2.1–2.3 at the Samut Prakan Study Site

Comparison of Hazard Impact Distances between Bangkok and Samut Prakan

A comparative analysis of kerosene leakage consequences was conducted between the Bangkok and Samut Prakan study sites. Hazard distances associated with the Flammable Area of Vapor Cloud, Toxic Threat Zone, and Thermal Radiation from Pool Fire were evaluated and compared. The results are summarized in **Table 7** and presented graphically in the figures below.

Comparison with Previous Studies

Although direct validation using field measurements was beyond the scope of this study, the simulation results were compared with findings reported in previous ALOHA-based assessments of aviation fuel releases [21]. The Risk Assessment and Hazard Analysis study conducted for Aviation Turbine Fuel

(ATF) storage facilities reported that aviation fuel vapor clouds generally exhibited near-field hazard characteristics and quasi-heavy gas behavior, with vapor accumulation occurring close to the release source, particularly under low wind speed conditions. Similar behavior was observed in the present study, where the Flammable Area of Vapor Cloud remained confined within the bunded area and exhibited limited hazard distances despite variations in meteorological conditions.

The ATF study also identified thermal radiation from pool fire scenarios as one of the most significant consequences associated with aviation fuel releases. This observation is consistent with the present findings, in which Thermal Radiation from Pool Fire produced substantially greater impact distances than both the Flammable Area of Vapor Cloud and the Toxic Threat Zone.

Table 7 Comparison of Hazard Impact Distances between Bangkok and Samut Prakan study sites

Parameter	Bangkok (m)	Samut Prakan (m)
Flammable Area of Vapor Cloud (Red Zone)	22.0	23.0
Toxic AEGL-1	35.0	58.0
Toxic AEGL-2	22.0	25.0
Thermal 10 kW/m ²	63.5	95.5
Thermal 5 kW/m ²	90.5	134.5
Thermal 2 kW/m ²	141.0	209.0

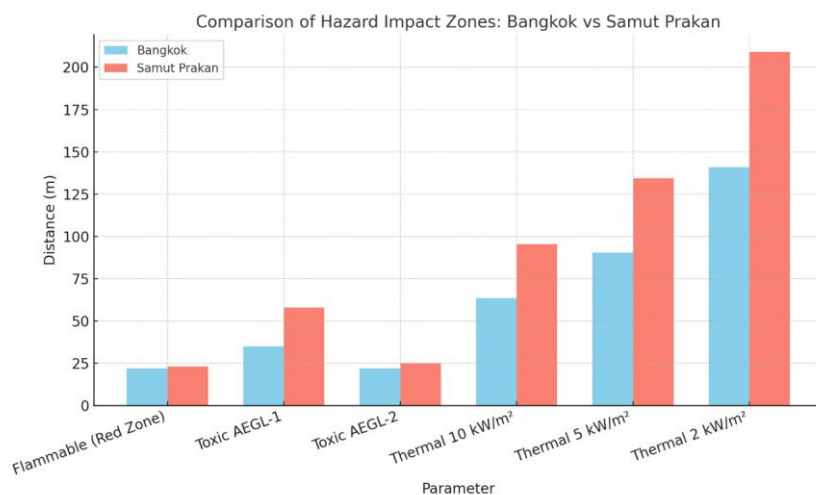


Figure 10 Comparison of Hazard Impact Distances between Bangkok and Samut Prakan Study Site

Similarly, Mišić et al. (2018) [7] evaluated thermal radiation hazards resulting from kerosene pool fires using both ALOHA and PHAST consequence modeling software. Their study demonstrated that thermal radiation distances increased with release rate, fuel quantity, and pool diameter, and identified Thermal Radiation from Pool Fire as the dominant hazard associated with kerosene release incidents. Comparable results were obtained in the present study, where thermal radiation represented the largest hazard zone among all evaluated consequences. While Mišić et al. focused on kerosene releases from railway tanker accidents, the present study examined leakage scenarios from fixed-roof storage tanks in oil terminal facilities. Nevertheless, both studies highlighted the importance of pool fire consequences in emergency planning for kerosene storage and handling operations.

Mišić et al. (2018) [7] further reported that ALOHA and PHAST produced comparable hazard distances despite differences in predicted

release rates, suggesting that ALOHA can provide reasonable preliminary estimates for consequence assessment and emergency response planning. Overall, the consistency between the present findings and previously published studies supports the applicability of ALOHA for preliminary hazard assessment of kerosene release scenarios and provides additional confidence in the observed hazard patterns.

Sensitivity Analysis of Meteorological Parameters

A sensitivity analysis was conducted to evaluate the influence of wind speed and atmospheric stability on the predicted hazard distances. Scenario 2.2 was selected as the base case because it produced the maximum Toxic Threat Zone among the original simulations. Wind speed and atmospheric stability class were varied independently while all other source, chemical, and site-specific parameters were kept constant. The results are summarized in **Table 8**.

Table 8 Sensitivity analysis of wind speed and atmospheric stability class on predicted hazard distances

Sensitivity Case	Variable Tested	Wind Speed (m/s)	Stability Class	Other Input Parameters	Flammable Area of Vapor Cloud (m)	AEGL-1 (m)	AEGL-2 (m)	Thermal Radiation 2 kW/m ² (m)
Base Case	Reference condition	2.90	C Slightly Unstable	Constant	23	60	26	208
W1	Wind speed sensitivity	1.50	C Slightly Unstable	Constant	18	161	62	208
W2	Wind speed sensitivity	4.00	C Slightly Unstable	Constant	23	58	25	208
S1	Stability sensitivity	2.90	A Very Unstable	Constant	23	24	23	208
S2	Stability sensitivity	2.90	D Neutral	Constant	27	88	36	208
S3	Stability sensitivity	2.90	F Stable	Constant	34	264	98	208

The results indicate that atmospheric stability had a substantially greater influence on hazard distances than wind speed. When wind speed was varied from 1.5 m/s (W1) to 4.0 m/s (W2), the Flammable Area of Vapor Cloud changed only slightly, ranging from 18–23 m. Similarly, Thermal Radiation from Pool Fire remained unchanged at approximately 208 m. Toxic hazard distances exhibited moderate sensitivity to wind speed, with AEGL-1 varying from 58 m to 161 m and AEGL-2 varying from 25 m to 62 m. The largest toxic hazard distances occurred under the lowest wind speed condition (1.5 m/s), indicating that reduced atmospheric dilution allowed vapor concentrations to remain above AEGL thresholds over longer distances.

In contrast, atmospheric stability produced much larger variations in the predicted hazard zones. Under highly unstable conditions (Class A), AEGL-1 and AEGL-2 distances decreased to 24 m and 23 m, respectively, whereas under stable conditions (Class F), they increased substantially to 264 m and 98 m. Flammable hazard distances also increased from 23 m under Class A conditions to 34 m under Class F conditions. These results indicate that atmospheric stability strongly influences vapor cloud dilution and dispersion behavior. Stable atmospheric conditions suppress vertical mixing and promote the accumulation of vapors

near ground level, resulting in significantly larger Toxic Threat Zones.

Thermal Radiation distances remained constant across all sensitivity cases, confirming that thermal radiation hazards are controlled primarily by pool fire characteristics, such as burning area and heat release rate, rather than by meteorological variability. Overall, the sensitivity analysis demonstrates that atmospheric stability is the dominant meteorological parameter affecting toxic vapor dispersion, while wind speed has a secondary influence and thermal radiation hazards remain largely insensitive to the meteorological conditions evaluated in this study [22].

Conclusions

This study evaluated the potential consequences of aviation fuel (kerosene) leakage at oil terminal facilities in Bangkok and Samut Prakan, Thailand, using the ALOHA dispersion model. Flammable vapor cloud, toxic exposure, and thermal radiation hazard zones were assessed to support emergency response planning and risk management. The main findings are summarized as follows:

Overall comparison of kerosene leakage simulation scenarios

Table 9 Summary Comparison of Kerosene Leakage Simulation Results

Comparison Category	Bangkok (Scenario 1.1–1.7)	Samut Prakan (Scenario 2.1–2.3)
Scenario	7 scenarios (multiple wind directions)	3 scenarios (dominant east–south wind patterns)
Flammable Area (Red/Yellow Zone)	22 m (constant across all scenarios)	23 m (constant across all scenarios)
Toxic Threat Zone (AEGL-1/AEGL-2)	AEGL-1: 33–37 m AEGL-2: 22 m	AEGL-1: 55–60 m AEGL-2: 24–26 m
Thermal Radiation (Pool Fire)	10 kW/m²: 63–64 m 5 kW/m²: 90–91 m 2 kW/m²: 140–142 m	10 kW/m²: 95–96 m 5 kW/m²: 134–135 m 2 kW/m²: 208–210 m
Overall Impact Severity	Shorter hazard distances	Longer hazard distances

A comparison of kerosene leakage consequences between the Bangkok and Samut Prakan oil terminals showed that the Samut Prakan site consistently produced greater hazard distances across all evaluated parameters, particularly for the Toxic Threat Zone and Thermal Radiation from Pool Fire.

The Flammable Area of Vapor Cloud remained limited and relatively similar at both

locations, with hazard distances of approximately 22 m in Bangkok and 23 m in Samut Prakan. The flammable threat zone was confined within the containment dike surrounding the storage tanks, indicating that flammable hazards were largely restricted to the near-field region.

For the Toxic Threat Zone, Samut Prakan exhibited greater AEGL-1 and AEGL-2 distances (58 m and 25 m, respectively) than Bangkok

(35 m and 22 m, respectively), indicating a larger potential impact area.

Thermal Radiation from Pool Fire produced the largest impact distances among all evaluated hazards. In Samut Prakan, hazard distances reached approximately 95.5 m, 134.5 m, and 209 m at thermal radiation levels of 10, 5, and 2 kW/m², respectively, compared with 63.5 m, 90.5 m, and 141 m in Bangkok. These findings suggest that thermal radiation hazards were influenced more strongly by physical fire characteristics, such as pool size and fuel quantity, than by meteorological variability. Thermal radiation intensity is primarily governed by pool diameter and heat release rate [23], which may explain the substantially larger hazard distances observed in the pool fire scenarios. The results are consistent with previous studies reporting that pool diameter and heat release rate are primary factors governing thermal radiation intensity and hazard distance.

Overall, the findings indicate that the principal hazard associated with kerosene leakage is not long-range flammable vapor cloud dispersion but rather thermal radiation from pool fire and the accumulation of vapors in the near-field region surrounding the release source. The observed dispersion characteristics also suggest quasi-heavy gas behavior, with vapor accumulation occurring predominantly near ground level rather than following conventional Gaussian-type dispersion patterns.

Influence of Kerosene Properties on Hazard Distance Assessment

The results suggest that the dispersion behavior of kerosene differs from that of both typical light gases and conventional dense gases due to its relatively low vapor pressure, low evaporation rate, and high boiling point. Consequently, kerosene vapor clouds remained largely confined to the vicinity of the release source, producing limited flammable hazard distances and localized vapor accumulation.

The observed dispersion characteristics may be described as a transitional dispersion regime exhibiting quasi-heavy gas behavior. In the near-field region, vapor accumulation appeared to be influenced primarily by fuel properties and limited evaporation, resulting in ground-level accumulation within the bunded area. These dispersion characteristics may resemble certain aspects of dense-gas dispersion, including restricted vertical mixing and localized vapor concentrations.

At greater distances from the release source, atmospheric transport processes became increasingly important, and dispersion patterns appeared to be influenced by meteorological factors such as wind speed, turbulence, temperature, and atmospheric stability. Under far-field conditions, the observed dispersion behavior showed characteristics consistent with Gaussian atmospheric diffusion processes [24]. Under these conditions, the dispersion behavior showed characteristics more consistent with Gaussian-type dispersion.

Overall, the findings suggest that kerosene vapor dispersion cannot be adequately described by a single dispersion mechanism. Instead, the observed behavior appears to represent a transitional dispersion regime in which near-field transport exhibits quasi-heavy gas characteristics, while far-field dispersion becomes increasingly influenced by atmospheric mixing processes.

Influence of Meteorological Conditions on Hazard Distances

Meteorological conditions influenced the predicted hazard distances to varying degrees depending on the hazard type. Among the parameters considered, wind speed and air temperature appeared to have a greater influence on the Toxic Threat Zone than on the Flammable Area of Vapor Cloud and Thermal Radiation from Pool Fire. In contrast, relative humidity showed only a limited effect on the predicted hazard distances.

The results suggest that toxic vapor dispersion was moderately sensitive to meteorological variability. Slight increases in Toxic Threat Zone distances were observed under conditions of higher wind speed and temperature, which may have enhanced vapor transport and evaporation. However, the magnitude of these changes remained relatively small, indicating that atmospheric conditions were not the sole factors controlling toxic hazard distances.

The Flammable Area of Vapor Cloud showed minimal variation across all scenarios despite changes in meteorological conditions. This behavior may be associated with the relatively low vapor pressure and slow evaporation rate of kerosene, which limited the formation of flammable vapor concentrations beyond the immediate vicinity of the release source. Consequently, the flammable hazard zone remained largely confined to the near-field region surrounding the storage tank.

Thermal Radiation from Pool Fire exhibited the least sensitivity to meteorological conditions. Hazard distances remained relatively consistent across all scenarios, suggesting that thermal radiation was influenced more strongly by pool fire characteristics, such as burning area, fuel quantity, and heat release rate, than by atmospheric variability. This observation is consistent with consequence analysis theory, which indicates that pool fire consequences are generally controlled by fuel inventory and burning area rather than meteorological variability [25].

Meteorological conditions influenced the Toxic Threat Zone more than the Flammable Area of Vapor Cloud and Thermal Radiation from Pool Fire. However, the overall effect remained limited compared with fuel properties and release characteristics. The sensitivity analysis demonstrated that atmospheric stability exerted a greater influence on toxic hazard distances than wind speed, while thermal radiation hazards remained largely unaffected by the meteorological conditions considered in this study.

Influence of Physical Site Characteristics

Physical site characteristics appeared to play an important role in determining the predicted hazard distances. The Samut Prakan facility contained larger storage tanks with greater fuel inventories than those at the Bangkok site, which may have contributed to larger release quantities and more extensive hazard zones. In addition, release size remained an important factor, as larger leak openings generally resulted in greater fuel discharge and increased potential for vapor generation.

The presence of containment structures, such as bund walls surrounding the storage tanks, also influenced the predicted consequences. These structures restricted the spread of leaked fuel and confined liquid accumulation within a defined area, thereby limiting the extent of vapor generation and dispersion. As a result, the Flammable Area of Vapor Cloud remained relatively consistent across all scenarios despite variations in meteorological conditions and release quantities.

The low evaporation rate of kerosene resulted in relatively limited vapor generation, causing flammable hazard distances to remain relatively short and, in some cases, graphical threat contours could not be displayed because

the hazard zone was confined to the immediate vicinity of the release source. These findings highlight the importance of both fuel properties and site-specific physical characteristics in determining the extent of hazard zones associated with kerosene leakage incidents.

In contrast, the Samut Prakan study site is located in a more open environment characterized by agricultural land and fewer surrounding structures. As a result, in the event of a fuel leakage incident, vapor dispersion may extend over a wider area compared with the Bangkok site.

These differences in surrounding terrain and land use conditions contribute to variations in dispersion behavior between the two study areas and should therefore be considered when evaluating hazard zones and emergency response planning.

Limitations and Recommendations

This study has several limitations that should be considered when interpreting the results. First, ALOHA is primarily intended for emergency response planning and short-term release scenarios. The model is less suitable for evaluating long-duration releases exceeding one hour and does not simulate the dispersion of combustion products such as smoke generated during fire incidents. In addition, ALOHA may not generate graphical threat contours for low-volatility substances with limited dispersion distances, as observed in some kerosene release scenarios.

Second, the simulations were based on long-term average meteorological data (2020–2024), which may not fully represent extreme weather conditions. Consequently, the predicted hazard distances should be interpreted as representative estimates rather than worst-case scenarios. Furthermore, ALOHA does not explicitly account for complex terrain, buildings, or other obstacles that may influence local airflow patterns and vapor dispersion. A sensitivity analysis was performed to evaluate the influence of wind speed and atmospheric stability on the predicted hazard distances. The results indicated that atmospheric stability exerted a greater influence on toxic hazard distances than wind speed; however, a formal uncertainty analysis was not performed.

Third, the present study focused on leakage scenarios involving fixed-roof storage tanks and did not consider other potential release

sources, such as pipelines, valves, pumps, or fuel transportation vehicles. In addition, escalation scenarios, including domino effects, BLEVE events, secondary fires, and simultaneous failures of storage tanks and secondary containment systems, were beyond the scope of this study. Such events could increase fuel spread area, pool fire dimensions, vapor generation, and associated hazard distances.

Another limitation is that direct model validation was not performed using field measurements, accident investigation records, or alternative consequence modeling software. Although the simulation results were qualitatively compared with findings reported in previous aviation fuel consequence assessment studies and showed similar hazard patterns, the predicted hazard distances remain dependent on the assumptions, input parameters, and algorithms incorporated within the ALOHA model.

Therefore, the predicted Threat Zones should be interpreted as model-based consequence estimates intended to support emergency preparedness and risk assessment rather than regulatory safety distances or legally enforceable exclusion zones. Actual hazard extents may vary depending on site-specific conditions, meteorological variability, release characteristics, and model assumptions. Although ALOHA is suitable for rapid screening-level consequence assessment and emergency planning, advanced models such as PHAST, FLACS, and CFD may provide more detailed predictions in complex industrial or urban environments. Future studies should incorporate model validation using accident records or field measurements, evaluate extreme meteorological conditions and multiple release scenarios, and apply advanced consequence modeling techniques to improve the robustness and accuracy of hazard assessments. For practical emergency planning, the results should be integrated with GIS-based spatial information, evacuation planning, emergency response procedures, and applicable regulatory requirements.

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Anthropogenic CO and NO_x Emission Inventory in Thailand

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Abstract

Air pollution remains a critical environmental issue in Thailand, particularly in relation to Carbon Monoxide (CO) and Nitrogen Oxides (NO_x), which are closely linked to transportation, industrial activities, biomass burning, and energy consumption. Although CO and NO_x concentrations in Thailand may not always exceed national air quality standards, they are critical primary precursors for secondary pollutants, particularly tropospheric ozone [5], making the monitoring of their emission inventories essential for effective air quality management. This study aimed to investigate the spatial distribution, emission sources, and seasonal variability of anthropogenic CO and NO_x emissions in Thailand during 2014–2024 using the CAMS-GLOB-ANT v6.2 emission inventory obtained from the ECCAD database. It should be noted that this dataset covers strictly anthropogenic sources and agricultural open burning, and does not include natural forest fire emissions. The results indicate that CO and NO_x exhibit similar spatial distributions, with relatively high emissions concentrated in the Central and Eastern regions, particularly in major urban, industrial, and transportation corridors. In contrast, emissions in the Northeastern region are more spatially dispersed, whereas the Northern and Southern regions display localized or corridor-like patterns influenced by topography and settlement structure. Road transportation was identified as the dominant source of emissions in most regions, while agricultural waste burning, industrial processes, refineries, and power generation contributed differently depending on regional economic characteristics. Monthly analysis showed that both CO and NO_x emissions increased from March to May, with peak levels in May, reflecting the combined effects of late dry-season biomass burning and meteorological conditions favorable to pollutant accumulation. Overall, the findings demonstrate that anthropogenic CO and NO_x emissions in Thailand are strongly shaped by regional economic activities, land-use characteristics, and seasonal factors, underscoring the need for region-specific air pollution management strategies.

Keywords : anthropogenic; carbon monoxide; nitrogen oxides; Thailand; emission inventory

Introduction

Air pollution is a major global environmental problem [1]. The impacts are not limited to local emission sources; rather, pollutants can be transported across borders and react in atmosphere, thereby affecting air quality at regional and global levels. In addition, primary pollutants can interact in chemical reactions to form secondary pollutants, such as ground-level ozone and secondary particulate matter [2]. These pollutants pose risks to public health and can accumulate and be transported over long distances in the atmosphere.

Thailand's economic development across the agricultural, industrial, transportation, and tourism sectors, in conjunction with technological advancement and population growth, has resulted in a sustained increase in the demand for natural resources and energy [3]. Energy consumption particularly the use of fossil fuels in industrial production processes, transportation, and other anthropogenic activities has led to the emission of air pollutants from point sources, area sources, and mobile sources. These emissions exert significant impacts on environmental quality and public health and constitute a critical challenge for long-term sustainable development. Major air pollutants include Particulate Matter (PM₁₀ and PM_{2.5}), Sulfur Dioxide (SO₂), Nitrogen Oxides (NO_x), Carbon Monoxide (CO), Ozone (O₃), and Volatile Organic Compounds (VOCs) [4].

Carbon Monoxide (CO) is one of the air pollutants that can influence to greenhouse gas emission such as Carbon Dioxide (CO₂) and Methane (CH₄). CO emissions are predominantly generated by anthropogenic activities, including biomass burning, fossil fuel combustion, industrial processes, and transportation. The accumulation of CO in the atmosphere therefore not only deteriorates air quality and adversely affects human health but also alters atmospheric chemical composition. In particular, CO plays a significant role in tropospheric ozone formation through its involvement in photochemical reactions [5]. Consequently, elevated atmospheric CO concentrations have implications for both the climate and the environment at regional and global levels [4].

Nitrogen Oxides (NO_x), comprising nitric oxide (NO) and nitrogen dioxide (NO₂), which have negative impacts on the environment and human health [6]. The primary sources of NO_x are high-temperature combustion processes, particularly from the transportation sector, electricity generation from fossil fuels, industrial processes, and open burning, such as agricultural residue burning and forest fires [7, 8]. In urban areas characterized by high vehicle density, NO_x emissions from road transportation are recognized as the most significant source and are closely associated with urban air quality problems. In the atmosphere, NO_x undergoes chemical reactions that lead to the formation of secondary pollutants, including ozone and acid rain [5, 9]. These processes contribute to the degradation of ecosystems, water resources, soils, and infrastructure.

Emission Inventory is a comprehensive database that quantifies the amounts of air pollutants released into the atmosphere over a specific year or other defined time period [7]. Emissions are categorized by source type in order to identify major contributors to air pollution and to support the development of targeted control strategies. Emission inventories have a wide range of applications, including their use as input data for atmospheric and geographic modeling, forecasting future pollution scenarios, and informing the design of air quality management policies and mitigation measures [8].

Previous studies on air pollutant emission inventories in Thailand have employed both bottom-up and top-down approaches. Vongmahadlek et al. (2009) developed a national emission inventory for Thailand using activity-based bottom-up methods, providing valuable sectoral and regional estimates [10]. Pham et al. (2007) estimated ozone precursor emissions from power plants and industrial facilities in the Central and Eastern regions, highlighting the significant contributions of energy and industrial sectors to NO_x emissions [11]. Despite these efforts, there remains a need for long-term, nationally consistent analyses that cover all regions and emission sectors over a recent multi-year period. This study addresses that gap by utilizing the CAMS-GLOB-ANT v6.2 global anthropogenic emission inventory, which

provides spatially and temporally consistent data from 2014 to 2024.

This study aims to examine the emissions of Carbon Monoxide (CO) and Nitrogen Oxides (NO_x) in Thailand using data derived from an emission inventory. It also seeks to identify and analyze the various emission sources contributing to these air pollutants. The findings are intended to provide supporting information for sustainable environmental management and public health protection.

It is also important to note that while ambient concentrations of CO and NO_x in Thailand may not always be extremely high compared to national air quality standards, their critical importance lies in their role as primary precursors for secondary pollutants, particularly tropospheric ozone [5], which remains a persistent air quality challenge in the country. Therefore, a comprehensive understanding of their emission inventories is essential for effective secondary pollutant management.

Materials and Methods

Study Area

This study investigates air pollutant emissions across Thailand, which is located in Southeast Asia between latitudes 5°37'–20°27'N and longitudes 97°22'–105°37'E. The analysis covers the entire territory of the country and is divided into six regions: Northern, Northeastern, Central, Eastern, Western, and Southern Thailand. This regional classification allows for the

examination of spatial emission patterns and the identification of differences in emission sources associated with regional economic activities and geographical characteristics.

Data Sources

This study utilizes secondary data obtained from the Emissions of Atmospheric Compounds and Compilation of Ancillary Data (ECCAD) database, which compiles emission inventory data from multiple global datasets. Specifically, the study employs data from the Copernicus Atmosphere Monitoring Service (CAMS-GLOB-ANT) version 6.2.

The CAMS-GLOB-ANT v6.2 dataset provides global anthropogenic air pollutant emission data with a spatial resolution of 0.1° × 0.1°. The dataset includes both monthly and yearly emission data and is categorized by pollutant type and emission sector. The CAMS-GLOB-ANT dataset is developed by integrating multiple existing global and regional expert emission inventories, utilizing a combination of atmospheric modeling, meteorological data, and satellite observations. It scales historical baseline emissions to the current year using projected activity data and trend analyses. This methodology ensures a consistent global representation of anthropogenic emissions, although it relies on broader assumptions compared to localized bottom-up inventories [12]. In this study, emission data for the period 2014–2024 were selected. The detailed dataset description is presented in **Table 1**.

Table 1 Detail of information

Parameter	Unit	Introduction	Sector	Data sources
CO	Tg	CAMS Global anthropogenic emissions	Road transportation (TRO)	CAMS-GLOB-ANT-v6.2
NO _x			Agriculture waste burning (AWB)	
			Refineries (REF)	
			Industrial process (IND)	
			Residential (RES)	
			Commercial (COM)	
			Solids waste and wastewater (SWD)	
			Fugitives (FEF)	
			Off Road Transportation (TNR)	
			Power generation (ENE)	
			Ships (SHP)	
			Agriculture livestock (AGL)	
			Agriculture soils (AGS)	

The selection of CAMS-GLOB-ANT v6.2 as the primary dataset provides a consistent and comprehensive top-down anthropogenic emission inventory, which is crucial for long-term national-scale monitoring. While Thailand has several bottom-up emission inventories that offer localized details [10], bottom-up approaches in developing countries often face limitations regarding data availability, frequent updates, and spatial consistency across all sectors. Compared to other well-known global and regional emission inventories such as EDGAR (Emission Database for Global Atmospheric Research) and REAS (Regional Emission inventory in Asia), the CAMS-GLOB-ANT v6.2 offers a distinct advantage in terms of temporal recency. While REAS version 3 provides detailed Asian emissions but extends only up to the year 2015, and EDGAR updates may exhibit temporal lags, CAMS-GLOB-ANT integrates historical baselines with projected activity data to provide highly consistent, updated monthly emissions up to the year 2024. This continuous temporal coverage makes it particularly suitable for analyzing recent long-term trends, including capturing the emission anomalies during the COVID-19 pandemic. It must be explicitly clarified that this dataset focuses strictly on anthropogenic sources and agricultural open burning, and does not capture natural forest fire emissions. In Thailand, forest fires are a dominant source of CO and a significant contributor to NO_x; therefore, fire-specific datasets such as FINN (Fire Inventory from NCAR), GFED (Global Fire Emissions Database), or GFAS (Global Fire Assimilation System) would be more appropriate for fire-inclusive studies. By excluding forest fires, the present study avoids the extreme seasonal anomalies introduced by natural fire events, thereby allowing for a focused evaluation of human-induced emission trends [13-15].

Data Processing and Analysis

The emission data from the CAMS-GLOB-ANT v6.2 database are provided in NetCDF (Network Common Data Form) format. In this study, data processing and analysis were conducted using the Python programming language, following a systematic three-step workflow: (1) Data extraction: NetCDF files were downloaded from the ECCAD database and read using the netCDF4 and xarray libraries

in Python, extracting CO and NO_x emission variables for each sector and year from 2014 to 2024. (2) Spatial processing: A shapefile boundary of Thailand and its six administrative regions was used to spatially clip the global dataset, and gridded emission values were aggregated by region using GeoPandas and regionmask libraries. (3) Data analysis and visualization: Aggregated emission data were analyzed to examine spatial distribution patterns, inter-annual emission trends by sector, and monthly seasonal variability. Results were visualized using Matplotlib and Cartopy libraries to produce spatial maps, time-series plots, and stacked bar charts.

Results and Discussion

CO and NO_x Emissions in Thailand

The spatial distribution maps of the average emissions of Carbon Monoxide (CO) (**Figure 1a**) and Nitrogen Oxides (NO_x) (**Figure 1b**) In Thailand, during the period 2014–2024 indicate that both pollutants exhibit similar spatial patterns. Areas with relatively high emission levels are mainly concentrated in the Central region, particularly the Bangkok Metropolitan Region and its surrounding areas, as well as along major urban corridors and key economic zones of the country. This pattern may be explained by the geographical characteristics of the Central region, which consists largely of river plains with several major rivers flowing through the area [16]. Consequently, riverbank areas have historically developed as important economic centers, supporting various activities that act as major sources of NO_x and CO emissions [17].

In the Northeastern region, the spatial distribution of CO and NO_x emissions covers a broader area compared with other regions and is not limited to major urban centers but extends across communities in several provinces. This pattern corresponds with the region's topography, which is predominantly characterized by plateau landscapes [16], together with an extensive transportation network connecting different provinces. In addition, the Northeastern region contains the largest agricultural areas in Thailand [18], where fuel combustion activities, including agricultural practices and transportation, may contribute to CO and NO_x emissions.

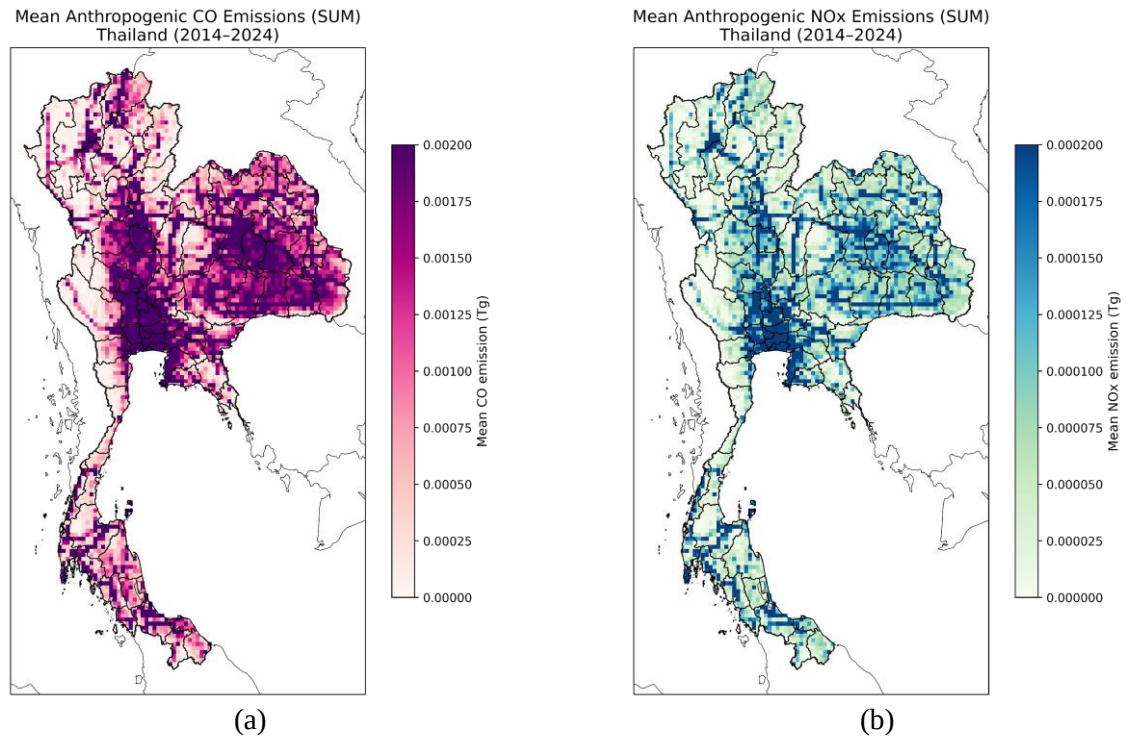


Figure 1 Spatial distribution of the average anthropogenic Carbon Monoxide (a) and Nitrogen Oxides (b) emissions during the period 2014–2024

In the Northern region, emissions of CO and NO_x appear as scattered clusters within urban basins and valley areas rather than forming a continuous distribution, as observed in the Central region. This spatial pattern is consistent with the region's mountainous terrain, which consists of high mountain ranges and intermontane valleys or river plains [16]. As a result, emission hotspots tend to occur along transportation corridors that pass-through valleys, where economic activities and population are more concentrated, leading to higher energy consumption and combustion-related emissions of both CO and NO_x.

In the Eastern region, relatively high emissions of CO and NO_x are observed in several areas. This pattern is consistent with the location of the Eastern Economic Corridor (EEC), which covers three provinces Chachoengsao, Chonburi, and Rayong [19]. These areas host numerous industrial estates, refineries, power plants, and transportation infrastructure, all of which contribute to elevated emissions of NO_x and CO.

In the Southern region, the distribution of CO and NO_x emissions generally follows a linear pattern along the peninsula and coastal

urban centers rather than being uniformly distributed across the entire region. This pattern corresponds with the geographical characteristics of southern Thailand, which consists of a narrow peninsula extending along the coastline [16]. Economic activities and settlements are concentrated along major transportation routes, port cities, tourism centers, and coastal areas [19]. Consequently, pollutant emissions tend to cluster along key infrastructure corridors rather than being widely dispersed. Moreover, compared with the Central and Eastern regions, the Southern region has a relatively smaller heavy industrial base and lower urban density, resulting in lower overall average emissions of both pollutants.

Overall, the spatial analysis indicates that the distribution of CO and NO_x emissions in Thailand during 2014–2024 is closely associated with both geographical characteristics and regional economic structures. Major economic regions, such as the Central and Eastern regions, exhibit higher emission levels due to the concentration of urban areas, industrial activities, and transportation networks. In contrast, emissions in the Northeastern region are more widely dispersed due to extensive transportation

networks and agricultural land use, while emissions in the Northern and Southern regions tend to appear as localized clusters or linear patterns along transportation corridors. These findings suggest that the spatial distribution of air pollutants not only reflects the locations of emission sources but also mirrors the broader spatial development patterns of Thailand, highlighting the importance of region-specific air pollution control strategies rather than a uniform national approach. However, it should be emphasized that the relationships between emission distributions and socio-economic factors such as population density, regional GDP, and land use are presented here as hypotheses based on descriptive spatial patterns. Further quantitative analyses incorporating statistical correlation with population density, regional GDP, and land-use data are required to scientifically confirm these underlying drivers.

CO and NO_x emissions in each region of Thailand

The total anthropogenic CO and NO_x emissions, along with their top sectoral contribution percentages across all six regions, are quantitatively summarized in **Table 4**. This sectoral breakdown highlights the significant variations in emission sources driven by specific regional economic activities.

CO emission

(**Figure 3**) The trends in annual average Carbon Monoxide (CO) emissions in Thailand during the period 2014–2024, classified by region and emission source. The results indicate that road transportation is the dominant source of CO emissions in several regions of the country, including the Central, Eastern, Northern, and Western regions. This is followed by agricultural waste burning and refinery activities, respectively. This trend highlights the important role of the transportation sector as a major source of Carbon Monoxide emissions, which mainly result from fuel combustion in internal combustion engines, particularly in densely populated urban areas and major economic centers where vehicle use is intensive [20].

In the Northeastern region, the pattern of CO emissions varies over time. During 2014–2019, road transportation remained the primary emission source, followed by agricultural waste burning. However, during 2020–2024, emissions from agricultural waste burning exceeded those

from transportation. This pattern corresponds with the economic structure of the region, which is characterized by extensive agricultural areas and the cultivation of major crops such as rice, sugarcane, and cassava. Post-harvest burning of agricultural residues therefore contributes significantly to CO emissions [21].

In the Southern region, although transportation remains the primary source of CO emissions, refinery activities represent the second-largest source, exceeding emissions from agricultural waste burning. This reflects the role of energy-related activities and petroleum industries in certain parts of the region, as well as transportation associated with trade and tourism, which are important components of the regional economy.

Another important finding is the noticeable reduction in CO emissions from the transportation sector in 2020 across all regions of Thailand, with a decrease of approximately 27.47% compared with 2019. This reduction is consistent with the global situation during the COVID-19 pandemic, when many countries implemented restrictions on travel and economic activities, resulting in significant decreases in vehicle usage and fuel combustion. This observation is also consistent with the Thailand Pollution Situation Report 2020 by the Pollution Control Department, which reported that the COVID-19 outbreak led to reduced travel and transportation activities in the country [22]. Several studies have similarly reported significant reductions in emissions from transportation and industrial activities during this period [23, 24].

To quantitatively validate the visual similarity in spatial patterns, a spatial correlation analysis was conducted between the mean anthropogenic CO and NO_x emissions across all grid cells. The results demonstrated a statistically significant positive correlation between the spatial distributions of CO and NO_x (Pearson $r = 0.695$, $R^2 = 0.482$, $p < 0.001$), as illustrated in **Figure 2**. This significant correlation confirms that the primary anthropogenic sources of both pollutants are highly co-located, predominantly driven by the same combustion activities in urban, industrial, and transportation hubs.

As shown in **Table 2**, AWB exhibited a significant increasing trend in CO emissions during 2014–2024 ($p < 0.01$), whereas RES, COM, REF, and SWD showed significant decreasing trends ($p < 0.05$). The remaining

sectors did not exhibit statistically significant temporal trends.

Overall, the analysis of CO emission trends by region and emission source indicates that emission patterns are closely related to the dominant economic activities of each region. Regions with highly developed urban areas and transportation infrastructure tend to have transportation as the main emission source, whereas regions with extensive agricultural land are more influenced by emissions from biomass or agricultural residue burning. Therefore, examining emissions by both region and source sector is essential for developing air pollution control measures that are appropriate to regional contexts.

NO_x emission

(**Figure 4**) The trends in annual average Nitrogen Oxides (NO_x) emissions in Thailand during the period 2014–2024, classified by region and emission source, indicate that NO_x emissions are strongly associated with regional economic structures, energy consumption patterns, and human activities. Road transportation represents the primary emission source in several regions, including the Central, Northern, Northeastern, Western, and Southern regions. This is mainly due to high-

temperature combustion processes in internal combustion engines, which promote reactions between nitrogen and oxygen in the air, leading to the formation of NO_x. Diesel engines, widely used in the transportation sector, are particularly significant contributors because of their higher combustion temperatures [25].

The Central region, which serves as the country's main economic hub and has a high population density, shows that NO_x emissions are predominantly generated from the transportation sector, followed by industrial processes and energy production. This pattern reflects the concentration of urban activities, transportation networks, and industrial estates in the Bangkok Metropolitan Region and its surrounding areas, where energy and fuel consumption are substantial. Previous research has also indicated that power plants and industrial facilities in the Central and Eastern regions play an important role in generating air pollutants such as NO_x [11]. Furthermore, a detailed statistical trend analysis of NO_x emissions by key sectors in the Central region is summarized in **Table 3**. The results highlight the significant trends and statistical reliability ($p\text{-value} < 0.05$) of major emission sources over the study period.

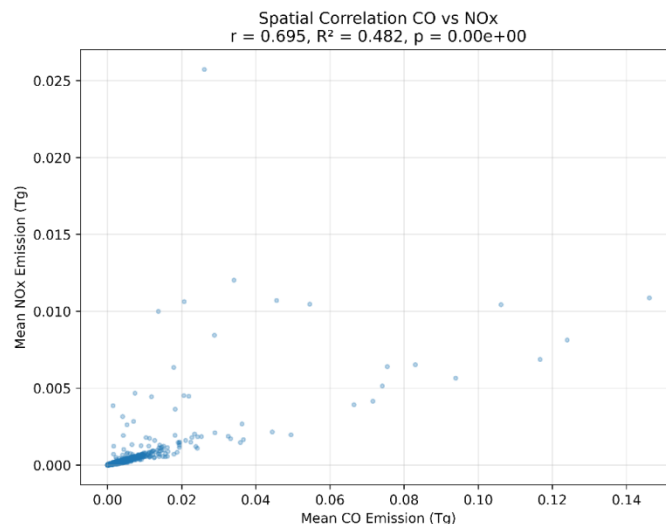


Figure 2 Spatial correlation between the mean anthropogenic Carbon Monoxide (CO) and Nitrogen Oxides (NO_x) emissions in Thailand during the period 2014–2024

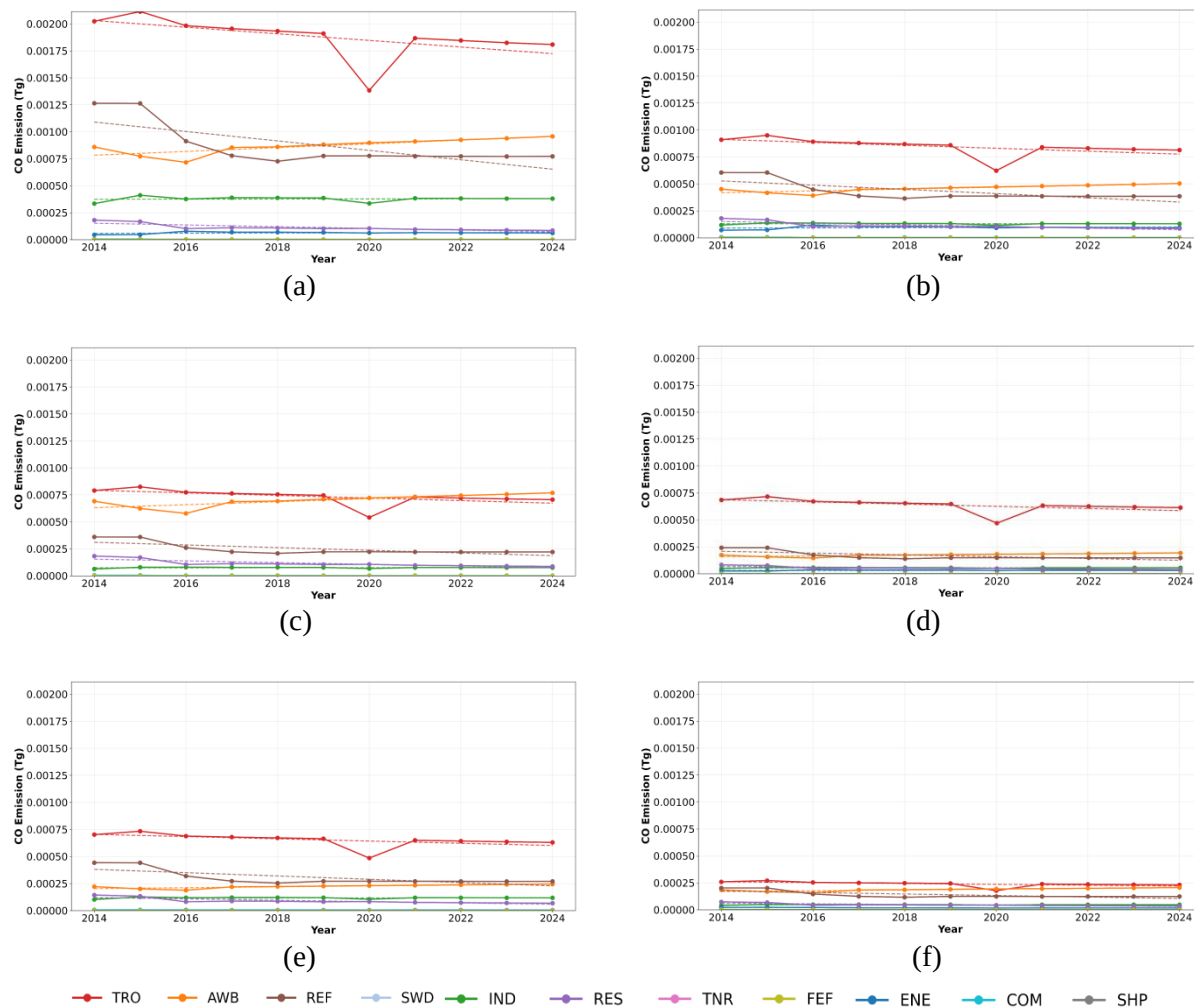


Figure 3 Trends of Carbon Monoxide (CO) emission by sector across the (a) Central, (b) Eastern, (c) Northeastern, (d) Northern, (e) Southern, and (f) Western regions of Thailand during the period 2014–2024. Abbreviations: TRO (Road transportation), AWB (Agriculture waste burning), REF (Refineries), IND (Industrial process), RES (Residential), COM (Commercial), SWD (Solids waste and wastewater), FEF (Fugitives), TNR (Off-Road Transportation), ENE (Power generation), SHP (Ships), AGL (Agriculture livestock), AGS (Agriculture soils)

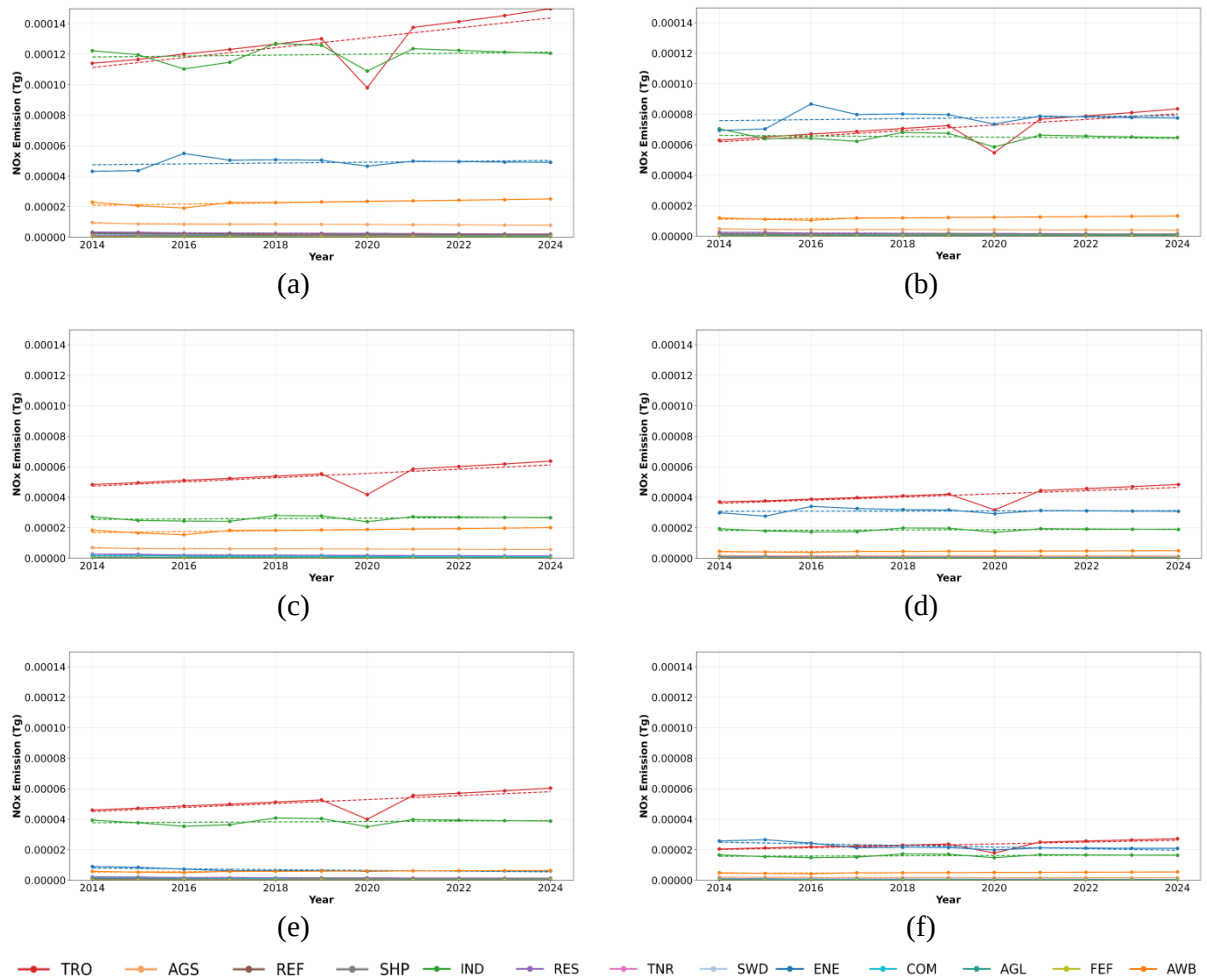


Figure 4 Trends of Nitrogen Oxide (NO_x) emission by sector across the (a) Central, (b) Eastern, (c) Northeastern, (d) Northern, (e) Southern, and (f) Western regions of Thailand during the period 2014–2024. Abbreviations: TRO (Road transportation), AWB (Agriculture waste burning), REF (Refineries), IND (Industrial process), RES (Residential), COM (Commercial), SWD (Solids waste and wastewater), FEF (Fugitives), TNR (Off-Road Transportation), ENE (Power generation), SHP (Ships), AGL (Agriculture livestock), AGS (Agriculture soils)

In the Eastern region, emissions from the energy production sector constitute the largest share of NO_x emissions, followed by transportation and industrial processes. This finding corresponds with the role of the region as a major industrial and energy base of Thailand, particularly within the Eastern Economic Corridor (EEC), where numerous power plants, oil refineries, and large industrial facilities are located [19]. Combustion processes associated with electricity generation and energy production therefore, represent significant sources of NO_x emissions.

For the Northern and Western regions, the results indicate that transportation remains the dominant emission source, followed by energy production and industrial activities. This pattern reflects the importance of transportation networks that connect medium-sized cities and facilitate regional goods movement.

In the Northeastern region, although transportation is the primary emission source, industrial processes and agricultural waste burning represent secondary sources of NO_x emissions. This pattern corresponds with the economic structure of the region, which is

characterized by extensive agricultural areas. Biomass burning can also generate NO_x emissions, although the emission intensity per activity is generally lower than that associated with fossil fuel combustion [26].

In the Southern region, NO_x emissions are primarily generated from road transportation, followed by industrial processes. This pattern is consistent with the regional economic structure, which relies heavily on goods transportation, tourism, and urban development along coastal areas.

Another notable observation is the reduction in NO_x emissions from road transportation, industrial processes, and energy production in 2020 across all regions. Compared with 2019, emissions decreased by 15.26%, 24.53%, and 13.22%, respectively. This decline is likely associated with travel restrictions and the slowdown of economic activities during the COVID-19 pandemic, consistent with the CO emission reduction discussed above. Satellite-based studies have reported significant decreases in NO_2 , a key component of NO_x , in many countries during lockdown periods [24]. Le Quéré et al. reported that global carbon emissions declined substantially in early 2020, with nearly half of the reduction attributed to changes in ground transportation activity, highlighting the transportation sector as one of the most responsive sources to disruptions in social and economic activities [23]. Therefore, the decline in NO_x emissions observed across all regions in 2020 is likely linked to the simultaneous reductions in mobility, industrial production, and energy demand.

Overall, the results indicate that NO_x emissions in Thailand are closely related to the dominant economic activities of each region. Areas with highly developed urban systems and dense transportation networks tend to be dominated by emissions from the transportation sector, whereas regions with large industrial and energy bases, such as the Eastern region, show a greater contribution from energy production and industrial activities.

Average monthly CO and NO_x emissions

(Figure 5) The monthly average emissions of Carbon Monoxide (CO) and Nitrogen Oxides (NO_x) in Thailand during the period 2014–2024 indicate that emissions of both pollutants tend to

increase from March to May, corresponding to the summer season, with the highest values observed in May. Emissions then gradually decline from the middle to the end of the year. This pattern reflects the seasonal variation of emission activities, which is influenced by both anthropogenic activities and meteorological conditions. To better understand the underlying activities driving these monthly patterns, emissions were further disaggregated by sector (Figure 5). The sectoral monthly variations reveal that while baseline emissions from road transportation (TRO) and industrial processes (IND) remain relatively constant throughout the year, the sharp peak observed between March and May is predominantly driven by a surge in Agricultural Waste Burning (AWB). This quantitative sectoral breakdown confirms that the late dry-season emission peak is strongly tied to specific agricultural calendar events rather than uniform increases across all anthropogenic sectors.

The elevated emissions of CO and NO_x in May can be explained by the seasonal characteristics of Thailand. This period corresponds to the late dry season and the transition period before the onset of the monsoon. In many parts of the country, particularly in the Northern and Northeastern regions, agricultural residue burning, stubble burning commonly occur as farmers prepare land for the next cultivation cycle. These biomass burning activities are important sources of CO and NO_x emissions [27].

From a meteorological perspective, weather conditions and ventilation capacities vary significantly across Thailand's regions and cannot be generalized. During the hot season, when emissions peak, the atmosphere is not necessarily stable; in fact, the boundary layer height is often higher due to strong solar radiation. However, pollutant accumulation during this period is largely driven by specific meteorological events, such as temperature inversions or periods of cooler and more stable atmospheric conditions that occasionally trap emissions near the surface. Coupled with the absence of wet scavenging from rainfall during the late dry season, these localized conditions exacerbate the build-up of biomass burning emissions near ground level.

From a meteorological perspective, the period before the monsoon season is often characterized by relatively stable atmospheric conditions, low wind speeds, and limited air circulation. These conditions reduce the dispersion of pollutants and promote the accumulation of pollutants near the surface. In addition, the absence of rainfall during the late dry season limits the wet removal of pollutants from the atmosphere, resulting in higher pollutant accumulation compared with the rainy season [28].

As the rainy season begins, typically from June onwards, emissions or the atmospheric accumulation of CO and NO_x tend to decrease. Increased rainfall enhances the removal of pollutants from the atmosphere and reduces their

accumulation. Damsri, S. and Promkaew, A. reported that concentrations of Carbon Monoxide and Nitrogen Oxides are generally higher during the summer season than during the winter season [29].

Overall, emissions of CO and NO_x are influenced by multiple factors, including biomass burning during the late dry season, energy consumption, and transportation activities in urban areas, as well as meteorological conditions before the monsoon that favor the accumulation of pollutants in the atmosphere. These findings highlight the combined influence of anthropogenic activities and natural factors in shaping the seasonal variability of air pollutant emissions in Thailand.

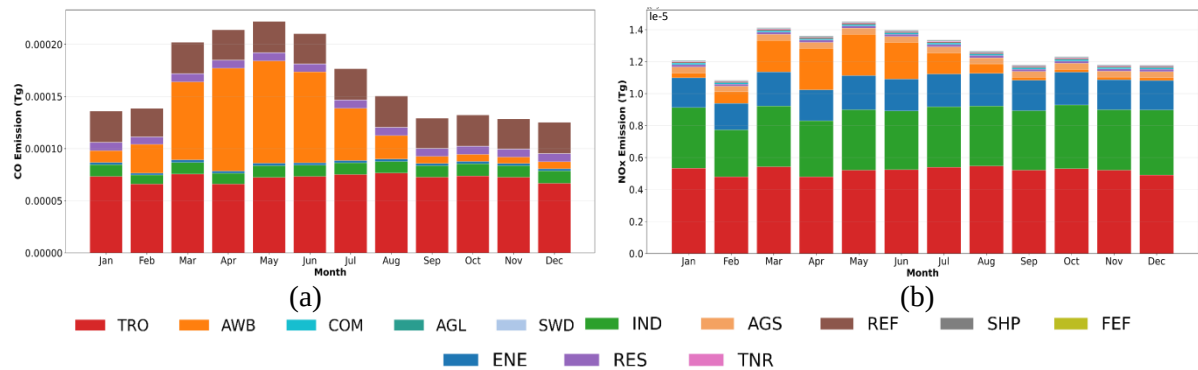


Figure 5 Monthly average emissions of (a) Carbon Monoxide (CO) and (b) Nitrogen Oxides (NO_x) classified by emission sectors in Thailand during the period 2014–2024.

Table 2 Annual trend analysis of CO emissions by key sectors in the Central region (2014–2024).

Sector	Slope (Tg/year)	Correlation (R)	R-squared (R ²)	P-value	Significance
Road transportation (TRO)	-3.06E-05	-0.542	0.294	0.085	Not Sig.
Industrial process (IND)	5.16E-07	0.076	0.006	0.825	Not Sig.
Power generation (ENE)	7.89E-07	0.274	0.075	0.416	Not Sig.
Agriculture waste burning (AWB)	1.76E-05	0.813	0.660	0.002**	Significant
Residential (RES)	-7.86E-06	-0.819	0.671	0.002**	Significant
Commercial (COM)	-2.27E-07	-0.813	0.660	0.002**	Significant
Refineries (REF)	-4.37E-05	-0.728	0.531	0.011*	Significant
Off-Road Transportation (TNR)	-3.51E-09	-0.291	0.085	0.386	Not Sig.
Ships (SHP)	1.10E-08	0.539	0.291	0.087	Not Sig.
Solid waste and wastewater (SWD)	-8.72E-10	-0.779	0.606	0.005**	Significant
Fugitives (FEF)	-1.01E-08	-0.550	0.303	0.080	Not Sig.

(Note: * Indicates statistical significance at $p < 0.05$, and ** indicates statistical significance at $p < 0.01$)

Table 3 Annual trend analysis of NO_x emissions by key sectors in the Central region (2014–2024).

Sector	Slope (Tg/year)	Correlation (R)	R-squared (R ²)	P-value	Significance
Road transportation (TRO)	3.25E-06	0.702	0.493	0.016*	Significant
Industrial process (IND)	3.16E-07	0.176	0.031	0.604	Not Sig.
Power generation (ENE)	2.79E-07	0.276	0.076	0.411	Not Sig.
Agriculture waste burning (AWB)	4.11E-07	0.782	0.611	0.004**	Significant
Agriculture soils (AGS)	-1.23E-07	-0.856	0.734	0.001**	Significant
Residential (RES)	-1.17E-07	-0.945	0.893	< 0.001**	Significant
Commercial (COM)	-7.80E-08	-0.921	0.848	< 0.001**	Significant
Refineries (REF)	-8.36E-08	-0.833	0.694	0.001**	Significant
Off-Road Transportation (TNR)	-2.11E-08	-0.513	0.263	0.107	Not Sig.
Agriculture livestock (AGL)	1.99E-10	0.426	0.181	0.191	Not Sig.
Ships (SHP)	3.80E-08	0.429	0.184	0.188	Not Sig.
Solid waste and wastewater (SWD)	8.91E-10	0.536	0.288	0.089	Not Sig.
Fugitives (FEF)	-3.31E-09	-0.818	0.669	0.002**	Significant

(Note: * Indicates statistical significance at $p < 0.05$, and ** indicates statistical significance at $p < 0.01$)

Table 4 Total anthropogenic CO and NO_x emissions and their sectoral contribution percentages by region in Thailand (Average 2014–2024).

Region	Average CO (Tg/year)	Top 3 CO Sectors (%)	Average NO _x (Tg/year)	Top 3 NO _x Sectors (%)
Central	4.18E-03	TRO (44.9%), REF (20.9%), AWB (20.8%)	3.37E-04	TRO (38.0%), IND (35.3%), ENE (14.5%)
Eastern	2.08E-03	TRO (40.6%), AWB (22.2%), REF (20.7%)	2.38E-04	ENE (32.6%), TRO (29.9%), IND (27.4%)
Northeastern	1.88E-03	TRO (39.0%), AWB (37.3%), REF (13.3%)	1.11E-04	TRO (48.8%), IND (23.5%), AWB (16.6%)
Northern	1.12E-03	TRO (56.9%), AWB (15.7%), REF (14.9%)	9.94E-05	TRO (41.5%), ENE (31.2%), IND (18.8%)
Southern	1.40E-03	TRO (46.7%), REF (21.8%), AWB (16.0%)	1.09E-04	TRO (47.3%), IND (35.2%), ENE (6.2%)
Western	6.80E-04	TRO (35.3%), AWB (27.6%), REF (20.5%)	7.03E-05	TRO (32.9%), ENE (31.6%), IND (22.9%)

Limitations

This study has several limitations that should be considered when interpreting the results. First, the CAMS-GLOB-ANT v6.2 dataset covers only anthropogenic emission sources and agricultural open burning, and excludes natural forest fire emissions. In Thailand, forest fires are a dominant and highly seasonal source of CO and NO_x, particularly in the Northern and Northeastern regions during the dry season. Consequently, the results presented here underestimate total national emissions during peak fire periods and are not directly comparable with studies that incorporate fire emissions. Future studies should integrate fire-

specific datasets such as FINN, GFED, or GFAS to provide a more comprehensive picture of total CO and NO_x emissions in Thailand.

Second, as a top-down global inventory, CAMS-GLOB-ANT may not fully capture fine-scale spatial heterogeneity or local emission variations that would be better represented by bottom-up national inventories [10].

Conclusions

This study investigated the spatial distribution, emission sources, and seasonal variability of anthropogenic Carbon Monoxide (CO) and Nitrogen Oxides (NO_x) emissions in Thailand from 2014 to 2024. It is important to

note that the results reflect strictly anthropogenic and agricultural open burning sources, and do not include natural forest fire emissions, which are also a major contributor to CO and NO_x in Thailand. Both pollutants exhibit similar spatial patterns, heavily concentrated in the Central and Eastern regions due to urbanization, dense transportation networks, and industrial activities. In contrast, the Northern and Northeastern regions are strongly influenced by agricultural waste burning, resulting in significant late dry-season emission peaks from March to May.

To effectively manage these precursors of secondary pollution, policy strategies must be region-specific. In the Central and Eastern economic hubs, actionable interventions should target the transportation and industrial sectors, such as accelerating the adoption of zero-emission vehicles, implementing stricter vehicle emission standards (e.g., Euro 6) [30], and enforcing continuous emission monitoring systems (CEMS) for industrial facilities. Conversely, in the Northern and Northeastern regions, mitigating agricultural waste burning through incentivizing biomass utilization or providing alternative crop residue management technologies is crucial. Finally, while this study isolated anthropogenic drivers, comprehensive air quality management in Thailand must ultimately integrate natural forest fire mitigation to address the full scope of seasonal pollutant accumulation and to better protect public health from secondary pollutants such as tropospheric ozone [5].

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A Preliminary Study on the Composition, Quantity, and Management of Solid Waste from Tourism at Kaw Kwang Beach, Koh Lanta District, Krabi Province, Thailand

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Abstract

This preliminary study explores the composition, quantity, and management of solid waste resulting from tourism activities at Kaw Kwang Beach, located in Ko Lanta District, Krabi Province, Thailand. The study area was divided into three zones: Zone A (pine forest), Zone B (central beach), and Zone C (hotel frontage). Field data were collected ten times during April–May 2024, following the International Coastal Cleanup (ICC) methodology. A total of 3,332 waste items, weighing 66.32 kilograms, were recorded. The majority of the waste was general waste, followed by recyclable and hazardous waste. Common items included wooden skewers, plastic bags, and cigarette butts, reflecting tourist behavior and coastal activities. Statistical analysis using ANOVA and Tukey HSD revealed a significant difference in waste quantity in Zone B compared to Zones A and C. The current waste management practices were found to be non-compliant with the Ministerial Regulation on Sanitation B.E. 2560 (2017), with issues such as lack of waste separation, uncovered bins, and uncontrolled landfill disposal. Despite these challenges, some waste items, such as plastic bottle caps, were creatively repurposed into flower pots by local schools. The study recommends promoting plastic reduction, enhancing community and tourist education, and improving waste management systems to protect the coastal environment and support sustainable tourism.

Keywords : Waste composition; Waste quantity; Solid waste management; Tourism; Kaw Kwang Beach

Introduction

The issue of marine debris along coastal beaches has long been a persistent environmental concern, reflecting the inefficiency of waste management policies in Thailand. Ultimately, much of this waste ends up in the ocean, carried by waves and tides, turning the sea into a vast receptacle for terrestrial waste and pollutants. This phenomenon poses serious threats to marine ecosystems, tourism activities, and the quality of life of coastal communities (Department of Marine and Coastal Resources, 2020) [1]. Thailand has been ranked among the top 10 countries contributing the most plastic waste to the ocean, with an estimated 22.8 million kilograms of plastic waste discharged into the sea as of 2021. Approximately 80% of marine debris

originates from land-based sources, while the remaining 20% is generated at sea, such as from boat-based tourism and coastal recreational activities (Office of Natural Resources and Environmental Policy and Planning, 2022) [2]. Kaw Kwang Beach, located on Koh Lanta in Krabi Province, is a tranquil coastal area popular among tourists for sunset viewing and outdoor activities. The beach is surrounded by hotels and restaurants that cater to both domestic and international visitors (Krabi Provincial Administrative Organization, 2016) [3]. Most beach users are local residents, typically visiting in family groups, with around 50–100 people per day, while foreign tourists average 30–50 per day. During festivals, the number increases significantly to over 200 people per day, still mainly locals. In the monsoon season, beach use

declines noticeably; data were collected through field surveys

A preliminary site survey revealed a significant amount of solid waste along the beach, primarily resulting from food consumption in recreational areas. One of the key issues identified was the insufficient number of waste bins, which were also placed far from popular relaxation and dining spots. This led to improper disposal of waste directly on the beach, posing a threat to marine ecosystems (Saladan Subdistrict Municipality, 2020) [4]. During the tourist season, the volume of waste increases substantially. Without effective waste management, the environmental quality deteriorates, necessitating urgent intervention. Recognizing the severity of the issue, this preliminary study aims to examine the composition and quantity of solid waste, assess current waste management practices, and explore potential reuse strategies for waste materials at Kaw Kwang Beach, Ko Lanta District, Krabi Province.

Materials and Methods

Study Area

Kaw Kwang Beach is located in Moo 1, Saladan Subdistrict, Ko Lanta District, Krabi Province, Thailand. The beach features a crescent moon shape, stretching approximately 750 meters in length, with its narrowest section measuring 300 meters in width. Uniquely, Kaw Kwang Beach offers views of the sea on both sides, and its shoreline is characterized by fine-grained sand, making it a scenic and tranquil location (Department of Marine and Coastal Resources, 2020) [1].



Figure 1 The Location of the Kaw Kwang Beach [5]

Methodology

1. Kaw Kwang Beach is located in the northwestern part of Koh Lanta Yai. Its coastline curves in a shape resembling a deer's head and antlers. Study Area Selection and Criteria The study was conducted at Kaw Kwang Beach, located in Moo 1, Saladan Subdistrict, Ko Lanta District, Krabi Province. Kaw Kwang Beach is approximately 750 meters long, with an estimated width of 30–50 meters. Using an average width of 40 meters, the total beach area is approximately 30,000 square meters. This estimation is based on the general coastal characteristics of Koh Lanta. The beach was divided into three zones:

Zone A: Pine forest area

Zone B: Central beach area

Zone C: Hotel frontage area

The site was selected based on the International Coastal Cleanup (ICC) criteria [6], which include: The area must be a sandy beach, Minimum length of 100 meters, No beach cleaning activities during the data collection period, Not located near river mouths or canals. Kaw Kwang Beach met all of these criteria.

2. Field Data Collection, A total of 10 sampling events were conducted between April and May 2024. In April, samples were collected on the 3rd, 16th, 18th, 24th, and 26th, while in May, they were collected on the 18th, 20th, 23rd, 25th, and 31st. Sampling was carried out during the lowest low tide to ensure easier access to the study area and to minimize data variability. The lowest low tide refers to the period when sea level drops to its lowest point, exposing the maximum extent of the coastal zone. [7] A total of 10 sampling events were conducted between April and May 2024 during the lowest tide periods to ensure efficient access to the sampling area. The lowest tide levels ranged from 1.04 to 1.78 meters, with the highest recorded on May 31 and the lowest on May 20. Sampling was carried out between 06:25 and 17:30 to ensure sufficient daylight. Each sampling session took approximately 2–4 hours, depending on tidal conditions and sunset time. Proper scheduling was essential for both efficiency and safety in fieldwork operations.

3. Tools and Equipment, the following tools and equipment were used for waste collection: Black garbage bags, Gloves, Face

masks, Trash pickers, Rubber boots, Weighing scale, Camera and data recording forms

4. Data Collection Process

1) Composition and Quantity of Solid Waste

(1) Waste Sampling, The beach was divided into three zones: Zone A (pine forest), Zone B (central beach), and Zone C (hotel frontage). Waste was collected using black garbage bags and sorted into three categories: General waste, Recyclable waste, Hazardous waste.

(2) Waste Measurement, each category of waste was weighed to determine its quantity and recorded using a prepared data form.

(3) Field Data Management, Field data collection and management followed the guidelines provided by the Saladan Subdistrict Municipality.

2) Local Waste Management System Analysis. The study also involved surveying and evaluating the local waste management system through collaboration with relevant agencies. The assessment focused on:

(1) Characteristics of waste containers available on the beach

(2) Waste collection procedures carried out by municipal staff

(3) Transportation methods, including the use of protective equipment and vehicles

(4) Waste disposal methods, such as incineration, landfilling, and composting

3) Waste Utilization Strategies, The study explored value-added approaches to waste utilization, including: Recycling, Upcycling or Agricultural applications

5. Data Analysis, collected data were analyzed using descriptive statistics, including percentages and averages of waste composition and quantity across zones and seasons. Additionally, ANOVA was used to examine statistical differences in waste quantities between zones. Results were presented in tables and charts to provide a clear overview of the waste situation in the study area.

Results and Discussion

Composition and Quantity of Solid Waste at Kaw Kwang Beach, Ko Lanta District, Krabi Province

Over a two-month data collection period (April–May 2024), conducted across 10 sampling sessions, a total of 3,332 waste items were collected, with a combined weight of 66.32 kilograms. These findings are consistent with the study by Sangkhana and Kamlom (2022), which reported seasonal and spatial differences in waste composition [8], and with Hardesty et al. (2016), who found significant variations in marine debris density depending on coastal zones and human activities [9]. The key findings are summarized as follows:

Types and Quantities of Waste

- General waste: 2,437 items, weighing 53.64 kg
- Recyclable waste: 797 items, weighing 14.13 kg
- Hazardous waste: 98 items, weighing 4.01 kg

These results indicate that general waste was the most prevalent category, suggesting a strong correlation with tourist behavior, particularly food consumption and recreational activities along the beach. The presence of recyclable and hazardous waste, although less in quantity, highlights the need for better waste segregation and disposal systems.

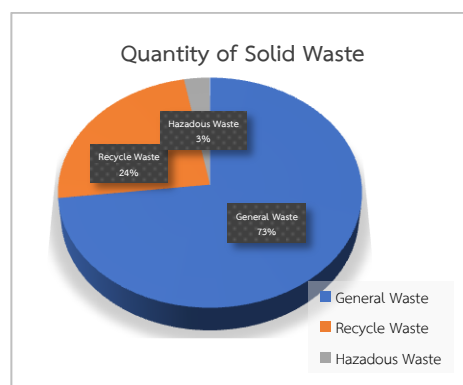


Figure 2 Quantity of Solid Waste

Waste Composition

The analysis of waste composition revealed the following:



Figure 3 Type of waste in each 3 group of waste [10]

- **General Waste:** The most frequently found item was wooden skewers, followed by plastic straws, cigarette butts, and food wrappers, respectively.

- **Recyclable Waste:** The most common item was plastic bottle caps, followed by plastic cups, plastic beverage bottles, and aluminum cans, respectively.

- **Hazardous Waste:** The most prevalent item was face masks, followed by lighters, diapers, and glass shards, respectively.

These findings indicate that the majority of waste originates from coastal recreational activities, particularly those involving food consumption and relaxation by tourists. This observation aligns with the studies conducted by Huabnarin (2017) [11] and Prasatkaew (2021) [12], which also reported similar patterns of waste types and sources in coastal areas.

Comparison by Zone

The waste data collected were analyzed based on three designated zones at Kaw Kwang Beach:

- **Zone A (Pine Forest Area)**

A total of 636 items were collected. The most common types of waste were ropes and fishing nets, which are typically associated with coastal and fishing activities. These findings are consistent with the studies by Arunsrinmorakot (2021) [13] and Pransin (2015) [14].

- **Zone B (Central Beach Area)**

This zone had the highest amount of waste, with 2,152 items recorded. The most prevalent items were wooden skewers and cigarette butts, originating from food vending, exercise activities, and tourist transportation. These results align with the findings of Pramarn et al. (2022) [15] and Bantiwivatkul (2016) [16]. The main sources are food vending, leisure activities, and tourism. This area has the highest usage intensity, resulting in the greatest amount of waste.

- **Zone C (Hotel Frontage Area)**

A total of 543 items were collected, with foam materials being the most common. The waste in this zone was linked to coastal recreation, hotel activities, fishing boats, and marine debris washed ashore. This pattern corresponds with the research of Prasatkaew (2021) [12] and Thammavicharn et al. (2014) [17]. These comparisons highlight the spatial variation in waste types and sources, emphasizing the influence of human activities and land use patterns on coastal waste accumulation.

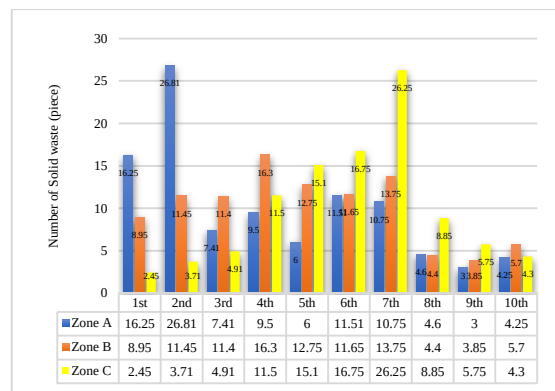


Figure 4 Waste Quantities from Sampling 1–10 in Each Zone

The data were collected over two months representing different seasons. Samples 1–5 were collected in April (summer season), and samples 6–10 were collected in May (monsoon season).

The ANOVA analysis revealed a statistically significant difference in the quantity of waste among Zones A, B, and C, with an F-statistic of 8.78 and a P-value of 0.00017. Since the P-value is less than 0.05, it can be concluded that there is a significant difference in waste quantities between the zones. To further

investigate these differences, a Tukey HSD Post-hoc Test was conducted to compare the waste quantities between each pair of zones. The results are presented in **Table 1**.

Table 1 Tukey HSD Post-hoc Test Results.

Comparison Between Zones	Mean Difference	P-value	95% Confidence Interval	Statistically Significant
A vs B	122.2	0.000	68.31 to 176.09	YES
A vs C	-1.8	0.996	-55.69 to 52.09	NO
B vs C	-124.0	0.000	-177.89 to -70.11	YES

Summary of Statistical Findings and Supporting Literature

The results of the ANOVA analysis indicated that Zone B had a statistically significant difference in waste quantity compared to both Zone A and Zone C, while Zones A and C showed no significant difference.

These findings are consistent with the study by Goldstein et al. (2013) [18], which reported high spatial variability in plastic debris across the Northeast Pacific Ocean, primarily influenced by ocean currents and human activities. Similarly, Pasternak et al. (2017) [19] found statistically significant differences ($p < 0.05$) in marine debris composition and quantity across coastal areas and seasons.

Furthermore, Galgani et al. (2015) [20] emphasized that the global distribution of marine litter varies by region and coastal characteristics, supporting the notion that marine waste management should be location-specific.

In the context of Thailand, the study by Prasatkaew (2021) [9] revealed seasonal and spatial differences in marine debris at Bang Pu seaside resort, which aligns with the current findings. The majority of waste observed in this study originated from human activities, particularly coastal recreation, tourism, and fishing. The dominant waste type was general waste, especially plastic packaging and single-use materials in summer season.

Table 2 the difference of type of waste in difference season

Comparison Aspect	Summer Season	Monsoon Season
Prominent Waste	Skewers, straws, cigarette butts	Plastic bottles, bottle caps, food containers
Main Sources	Beach tourists	Tourists + marine debris transported by water
Waste Characteristics	Single-use, immediate consumption waste	Packaging waste and floating plastics
Related Activities	Tourism, leisure, smoking	Tourism combined with rainwater runoff
Environmental Trend	Direct accumulation on the beach	Dispersion by water currents and rainfall

The diversity of waste across zones reflects the relationship between local activities and the types of waste generated, highlighting the need for targeted waste management strategies based on specific land use and tourist behavior.

Table 3 Clean Coast Index (CCI) Summary

Zone	Waste (items)	Area (m ²)	CCI Value	Cleanliness Level
A	639	10,000	1.28	Very Clean
B	639	10,000	1.28	Very Clean
C	635	10,000	1.27	Very Clean

The CCI values for all three zones range between 1.27 and 1.28, classified as “Very Clean.” This indicates a low density of waste per unit area on the beach. However, single-use plastic waste such as straws, plastic bags, and cigarette butts is still present. These wastes are mainly associated with tourism and recreational activities. Continuous waste management is necessary to maintain environmental quality. There is no official data on waste collection costs and frequency for Koh Lanta. The island generates about 45 tons of waste per day, mostly from tourism areas. Waste management faces high costs due to off-island transportation for disposal.

Collection is estimated to occur at least once per day, with increased frequency during peak tourist seasons. As a result, waste management on the island involves relatively high expenses compared to typical areas.

Study of Solid Waste Management at Kaw Kwang Beach, Ko Lanta District, Krabi Province

Table 4 Summary of Solid Waste Management at Kaw Kwang Beach, Ko Lanta District, Krabi Province

Aspect	Observed Practices	Regulations (Ministerial Regulation on Sanitation B.E. 2560)	Deficiencies
1. Waste Containers	Blue bins (200–240 liters), no lids, no waste separation	Must be durable, tightly sealed, and support waste separation	No lids / No separation
2. Waste Storage	Waste placed in front of houses/hotels by residents and businesses	Must have designated storage areas with structures to prevent access by animals/insects	Unsystematic / No sanitary control
3. Waste Collection	One 6-wheel truck, 4 staff members, collection starts at 00:00 hrs	Vehicles must be sealed, equipped with leachate prevention systems and warning lights	Possibly no leachate control / No warning lights
4. Protective Equipment	Staff do not wear masks or gloves; wear sandals	Must wear full PPE including gloves, masks, and closed-toe shoes	No protective equipment used
5. Waste Disposal	Landfilling without leachate control; no waste separation before disposal	Must use engineered landfills with leachate protection and proper closure systems	No groundwater protection / No waste separation

The solid waste management practices at Kaw Kwang Beach do not comply with the Ministerial Regulation on Sanitation B.E. 2560. Waste containers lack lids and are not categorized by type. There is no designated sanitary storage area for waste. The waste collection process lacks leachate control systems, and workers are not equipped with adequate protective gear. Waste disposal is

carried out through uncontrolled landfilling, without pollution prevention measures and without prior waste separation. These deficiencies pose risks to both the environment and public health.

Utilization of Solid Waste

One notable initiative involved plastic bottle caps, which were collected and donated to Lanta Rajapracha Uthit School as part of a collaborative project with the Thailand Environment Institute. The school processed the caps by melting and molding them into flower pots, demonstrating a practical approach to plastic waste recycling.

Plastic straws and plastic bags can be recycled depending on their type and cleanliness. Straws are harder to recycle due to their small size and contamination risk, while clean plastic bags are more recyclable. Effective recycling requires proper sorting, cleaning, and processing, and depends on material condition.

This initiative aligns with the work of Arunrimorakot (2020), who explored value-based design using marine debris to develop public spaces at Wonnapha Beach. Her study found that common beach litter, such as plastic bottles and bags, contributed to environmental degradation. To address this, plastic waste was thermally processed at 230°C, allowing it to be reshaped into useful products.

The ISWM-based analysis shows that waste management on Koh Lanta faces increasing pressure due to tourism. Technical issues include insufficient bins, inconsistent collection frequency, and high transport costs. Social aspects reveal improper disposal behavior and limited public participation. Policy and management lack strict enforcement and effective incentive measures.

Therefore, an integrated approach is needed to improve waste management sustainably.

These examples highlight the potential for community-based waste transformation, especially in coastal areas affected by tourism. They also emphasize the importance of creative and sustainable waste management solutions that add value while reducing environmental impact.

Hazardous Waste Risk Assessment

Hazardous waste totaled 98 items (3% of all waste collected). 4 types of hazardous

waste were identified, along with their associated risks

- 1) Face masks (21%) Risk of pathogen contamination and microplastic shedding
- 2) Lighters (10.5%) Risk of fire hazards and chemical (fuel) leakage
- 3) Diapers (7.9%) High risk, as they may harbor pathogens and contaminate leachate
- 4) Glass shards High risk, causing injury to barefoot beachgoers, particularly in Zone B

The elevated risk stems from the absence of waste segregation at the source, resulting in hazardous waste being mixed with general waste. Collection staff also lack personal protective equipment (PPE).

Recommendations include: clearly separating hazardous-waste bins, providing PPE for collection staff, conducting periodic sweeps to remove glass debris, and educating tourists on the proper disposal of these waste items.

Recommendations

It is recommended to implement source-level waste control measures, such as reducing the use of plastic and foam materials. Efforts should be made to educate tourists and local communities about proper waste management practices. Continuous support for beach cleanup activities should be encouraged, and the waste management system should be further developed to enhance its efficiency and sustainability.

Conclusions

The study found that Kaw Kwang Beach faces significant waste accumulation, especially in Zone B, due to tourism-related activities. Most waste items were general waste, such as wooden skewers and plastic bags. The waste management system was found to be inefficient and non-compliant with sanitation regulations. However, some waste, like plastic bottle caps, was successfully repurposed by local schools. The findings highlight the need for better infrastructure, public awareness, and sustainable waste management practices.

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Assessment of Air Quality Index and Potential Health Risks Using Meteorological Parameters in Chonburi Province, Thailand

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Abstract

This study assessed seasonal variations in air pollutant concentrations, air quality index (AQI), meteorological influences, and inhalation health risks in an industrially influenced area of Chonburi Province, Thailand, during 2019–2021. Monthly concentrations of NO₂, O₃, PM₁₀, and PM_{2.5} were analyzed by season. AQI was calculated as a screening-level indicator using available monitoring data, excluding SO₂ and CO because complete data were unavailable. Associations between AQI and meteorological variables were examined using Pearson correlation and regression analyses. Non-carcinogenic inhalation risk was assessed using hazard quotient (HQ) values based on a screening-level concentration-based approach. Pollutant concentrations were generally higher in January and February and lower during June–September. Winter showed the highest mean concentrations of NO₂, O₃, PM₁₀, and PM_{2.5} at 16.37 ± 1.64 ppb, 30.73 ± 3.62 ppb, 60.71 ± 11.68 µg/m³, and 31.33 ± 7.53 µg/m³, respectively. AQI was also highest in winter (73.33 ± 32.69), followed by summer (30.22 ± 5.74) and the rainy season (22.67 ± 5.49). AQI was positively correlated with atmospheric pressure ($r = 0.748$, $p < 0.01$) and negatively correlated with relative humidity ($r = -0.621$, $p < 0.01$) and rainfall ($r = -0.524$, $p < 0.01$). Multiple regression showed that atmospheric pressure was the only significant independent predictor of AQI ($B = 8.074$, $p = 0.004$), although this association should be interpreted cautiously due to possible temporal autocorrelation and COVID-19-related activity changes. The HQ results indicated that PM_{2.5} and PM₁₀ were the main contributors to potential non-carcinogenic inhalation risk, particularly during winter, when their HQ values exceeded 1.0. NO₂ and O₃ remained below 1.0 across all seasons. These findings support the need for season-specific air quality management, especially particulate matter control during winter pollution episodes in industrial communities.

Keywords : Air quality index; Meteorological factors; Seasonal variation; Inhalation health risk; Industrial area

Introduction

Air pollution is a major environmental and public health concern worldwide, particularly in rapidly urbanizing and industrializing regions [1]. Exposure to ambient air pollutants can cause a wide range of adverse health effects, from acute symptoms such as coughing, wheezing, respiratory irritation, and difficulty breathing to chronic diseases, including asthma, bronchitis, cardiovascular disease, impaired lung function, and lung cancer [2, 3]. Particulate matter with aerodynamic diameters of less than 2.5 μm and 10 μm ($\text{PM}_{2.5}$ and PM_{10}), together with ground-level ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO), are among the principal pollutants of public health concern. Fine particulate matter is particularly hazardous because it can penetrate deeply into the respiratory tract and may enter the bloodstream, thereby increasing the risks of respiratory and cardiovascular disorders [4, 5].

The Air Quality Index (AQI) is widely used to communicate ambient air-quality conditions and their potential health implications [6, 7]. It converts pollutant concentrations into a standardized scale that allows the public and regulatory agencies to identify periods of elevated pollution and associated health concerns. In standard AQI calculation, pollutant-specific averaging times are important; for example, $\text{PM}_{2.5}$ and PM_{10} are commonly assessed using 24-hour averages, whereas O_3 and NO_2 may require shorter averaging periods depending on the AQI system applied. Therefore, when only daily monitoring data are available, AQI estimates for some pollutants should be interpreted as screening-level indicators rather than exact regulatory AQI values. However, AQI levels are influenced not only by the intensity of emission sources but also by prevailing meteorological conditions [8]. Consequently, similar emission levels may produce substantially different air-quality conditions depending on atmospheric dispersion, stability, chemical transformation, and pollutant-removal processes.

Meteorological factors play an important role in controlling the concentration, movement, and persistence of air pollutants [9]. Previous studies have shown that wind speed, temperature, relative humidity, rainfall, solar radiation, and pressure-related conditions can substantially influence particulate matter and other air pollutant concentrations [10, 11]. Wind speed

generally promotes atmospheric dispersion, whereas calm conditions can lead to pollutant accumulation near emission sources. Temperature influences atmospheric stability, vertical mixing, and photochemical reactions, while atmospheric pressure may be associated with stagnant air masses and reduced pollutant dispersion. Relative humidity can affect particle growth and atmospheric chemistry, whereas rainfall can remove airborne particles and soluble gases through wet deposition. Solar radiation may also accelerate photochemical reactions that contribute to ozone formation. Because these factors vary seasonally, pollutant concentrations and AQI levels may differ considerably between dry, wet, and transitional periods [12–14].

Chonburi Province is one of Thailand's major industrial, transportation, and logistics centers and forms an important part of the Eastern Economic Corridor [15]. Rapid industrial expansion, urban development, increasing traffic density, and construction activities have introduced multiple sources of air pollution into the area. Bo Win Subdistrict is characterized by a mixture of industrial facilities, residential communities, commercial activities, and heavily trafficked roads. This combination of land uses may increase community exposure to industrial and traffic-related pollutants, particularly during meteorological conditions that limit atmospheric dispersion. In addition, the 2019–2021 study period overlapped with the COVID-19 pandemic, during which changes in traffic volume, industrial activity, and human mobility may have influenced pollutant concentrations. This factor should be considered when interpreting temporal changes in AQI and pollutant levels.

Although previous studies have examined air pollution, meteorological conditions, and health risks, several important gaps remain. Prior research has demonstrated that the relationships between $\text{PM}_{2.5}$ and meteorological variables vary across regions and seasons, highlighting the importance of season-specific analysis [16]. In Thailand, Kliengchuay, Srimanus [17] integrated meteorological parameters with $\text{PM}_{2.5}$ -related health impact assessment using AirQ+, while Vongruang, Suppoung [18] examined meteorological criteria for $\text{PM}_{2.5}$ risk classification in a coastal industrial province. However, these studies primarily focused on $\text{PM}_{2.5}$ rather than AQI as an integrated air quality indicator. In addition, age-specific health risk assessment has been

applied to PM_{2.5} exposure among children in northern Thailand [19], but less attention has been given to multiple age groups within industrially influenced communities. Therefore, this study does not claim to introduce a fundamentally new analytical method; rather, it provides a locally contextualized integrated screening assessment that combines seasonal AQI variation, meteorological associations, and age-specific inhalation health risk estimation in an industrial community of eastern Thailand.

Although previous studies in Thailand have examined PM_{2.5} variation, meteorological effects, and health risk assessment, most have focused on individual pollutants or single analytical components. The present study differs by integrating seasonal AQI characterization, meteorological association analysis, regression-based screening, and age-specific inhalation health risk assessment within the same industrially influenced community in Chonburi Province. Therefore, the contribution of this study is a locally contextualized integrated screening assessment for air-quality management in an industrial area of eastern Thailand.

Addressing this gap is important because an integrated assessment can provide a more complete understanding of how meteorological conditions influence air quality and how resulting exposure may affect different population groups. Such evidence can support the identification of high-risk seasons, vulnerable age groups, and meteorological conditions associated with elevated pollution levels. It can also strengthen local air-quality surveillance, public-health warnings, and environmental management strategies in rapidly developing industrial areas. However, source attribution was beyond the scope of this study because wind-direction analysis, back-trajectory modelling, boundary-layer information, and detailed emission inventory data were not available. Future studies should incorporate these data to better distinguish local industrial sources from regional transport and meteorologically driven accumulation.

Accordingly, this study aimed to: (1) characterize the seasonal variations in AQI and meteorological factors in Bo Win Subdistrict, Chonburi Province, during 2019–2021; (2) determine the relationships between AQI and key meteorological variables using correlation and regression analyses; and (3) assess seasonal inhalation health risks among different age groups using the U.S. EPA hazard quotient approach. The findings are expected

to provide local screening evidence for air-quality monitoring, seasonal risk communication, and environmental health management, rather than definitive source attribution or causal prediction of AQI.

Materials and Methods

Study Area and Data Collection

The study was conducted in Bowin Subdistrict, Si Racha District, Chonburi Province, Thailand (approximately 13.1°N, 101.0°E), which lies within the EEC's designated industrial promotional zone [16]. The location of the monitoring sites and the study area are presented in **Fig. 1**. The subdistrict is home to one of Thailand's largest integrated industrial estates, accommodating over 600 factories engaged in petrochemical processing, electronics manufacturing, automotive assembly, and logistics operations. The area is subject to a tropical monsoon climate with three distinct seasons: (i) the cool-dry (winter) season from November to February, dominated by the northeast monsoon with low humidity and minimal precipitation; (ii) the hot-dry (summer) season from March to May, characterised by high solar radiation and elevated temperatures; and (iii) the wet (rainy) season from June to October, driven by the southwest monsoon with high rainfall and humidity. These seasonal meteorological contrasts provide an ideal natural experiment for examining the meteorological modulation of ambient air quality. The study period covered 2019–2021, which overlapped with the COVID-19 pandemic and associated changes in traffic, industrial activity, and human mobility. Therefore, temporal variations in pollutant concentrations and AQI during 2020–2021 were interpreted cautiously, as they may reflect both meteorological effects and changes in anthropogenic emissions during the pandemic period.

Data Analysis

The data used in the analysis comprised meteorological and air pollution data. Meteorological data were obtained from the Meteorological Department, Chonburi Province, consisting of relative humidity, atmospheric pressure, rainfall, temperature, and wind speed. Air pollution data were obtained from the Bowin Subdistrict Monitoring Station, Si Racha District, Chonburi Province, operated by the Pollution Control Department. The air pollutants included in the analysis were NO₂, O₃, PM₁₀, and PM_{2.5}.

SO₂ and CO were not included because complete and consistent data for these pollutants were not available from the selected monitoring station throughout the study period. Their exclusion was therefore considered a limitation because the maximum sub-index AQI may be underestimated on days when SO₂ or CO would otherwise contribute the dominant AQI sub-index.

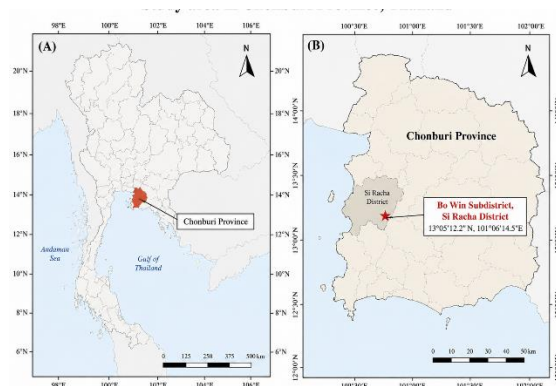


Figure 1 Location of the study area in Si Racha District, Chonburi Province, eastern Thailand

Daily average concentrations were used as the available routine monitoring dataset for the study period. However, the U.S. EPA AQI system applies pollutant-specific averaging times, including 24-hour averages for PM_{2.5} and PM₁₀, 8-hour or 1-hour averages for O₃, and 1-hour averages for NO₂. Therefore, AQI values derived from daily average NO₂ and O₃ data in this study should be interpreted as screening-level estimates rather than exact regulatory AQI values. The meteorological data and air pollution data covered the study period of 2019–2021.

Air Quality Index

The AQI was calculated for each pollutant following the U.S. EPA AQI Technical Assistance Document, using the linear interpolation formula [20]:

$$AQI^i = \frac{(AQI^{HI} - AQI^{LO}) / (Conc^{HI} - Conc^{LO})}{(Conc^i - Conc^{LO}) + AQI^{LO}} \quad (1)$$

where Concⁱ is the measured concentration of pollutant *i*; Conc^{LO} and Conc^{HI} are the lower and upper concentration breakpoints bracketing Concⁱ; and AQI^{LO} and AQI^{HI} are the corresponding AQI breakpoint values. The overall AQI was determined as the

highest pollutant-specific sub-index among the available pollutants, namely NO₂, O₃, PM₁₀, and PM_{2.5}. SO₂ and CO were excluded because complete and consistent monitoring data were not available from the selected station throughout the study period. Since the U.S. EPA AQI framework uses pollutant-specific averaging times, the AQI values calculated from daily average O₃ and NO₂ concentrations should be interpreted as screening-level estimates rather than regulatory AQI values. AQI categories were classified according to U.S. EPA standards (Table 1).

Statistical Analysis

Pearson's correlation coefficient (*r*) was used to evaluate bivariate associations between AQI and each meteorological variable. Prior to correlation analysis, data were screened for normality using the Shapiro–Wilk test. When normality assumptions were not met, Spearman's rank correlation was considered as a sensitivity analysis to confirm the direction and robustness of the associations. The strength of correlation was interpreted as: $|r| < 0.3$ (weak), $0.3 \leq |r| < 0.7$ (moderate), and $|r| \geq 0.7$ (strong). Statistical significance was set at $\alpha = 0.05$ and $\alpha = 0.01$, two-tailed.

Table 1 Air Quality Index (AQI) classification scheme

AQI Range	Category	Health Implications
0 – 50	Good	Air quality is satisfactory; poses little or no risk.
51 – 100	Moderate	Acceptable quality; some concern for unusually sensitive individuals.
101 – 150	Unhealthy for Sensitive Groups	Sensitive populations (elderly, children, asthmatics) may experience health effects.
151 – 200	Unhealthy	Everyone may begin to experience health effects.
201 – 300	Very Unhealthy	Health alert: serious effects for all population groups.

AQI Range	Category	Health Implications
301 – 500	Hazardous	Health warning of emergency conditions; entire population likely to be affected.

Correlation and regression analyses were performed using monthly mean observations for the 2019–2021 period, yielding an analytical sample size of $N = 36$. Simple linear regression models were constructed for each meteorological predictor individually to assess the independent predictive capacity of each variable:

$$AQI = \beta_0 + \beta_1 X^I + \varepsilon^I \quad (2)$$

where X^I represents each meteorological variable and ε is the random error term. Model performance was evaluated using the coefficient of determination (R^2) and p -value of the regression coefficient.

A multiple linear regression (MLR) model was subsequently developed incorporating all meteorological predictors simultaneously to assess their joint influence on AQI:

$$AQI = \beta_0 + \beta_1 Ra + \beta_2 T + \beta_3 RH + \beta_4 Pa + \beta_5 Ws + \varepsilon \quad (3)$$

where Ra is rainfall, T is temperature, RH is relative humidity, Pa is atmospheric pressure, and Ws is wind speed. Before interpreting the regression results, model assumptions were examined. Multicollinearity among predictors was assessed using the variance inflation factor (VIF), and VIF values were reported to evaluate the stability of regression coefficients, particularly because relative humidity, rainfall, and atmospheric pressure may be intercorrelated. VIF values were reported to evaluate the stability of regression coefficients, particularly because relative humidity, rainfall, and pressure may be intercorrelated. Model assumptions (normality of residuals, homoscedasticity, linearity) were verified through residual diagnostic plots [21]. Because monthly AQI data may exhibit temporal dependence, the Durbin–Watson statistic was also used to assess residual autocorrelation. Regression results were interpreted as statistical associations rather than causal effects. All analyses were performed using SPSS Statistics version 28.0.

Health Risk Assessment

Health risk from exposure to air pollutants through inhalation was assessed using the hazard quotient (HQ), which is commonly applied to evaluate potential non-carcinogenic health effects. The HQ represents the ratio between the estimated exposure concentration and the reference concentration for inhalation exposure [22]. An HQ value less than or equal to 1 indicates that the estimated exposure is within an acceptable level and that adverse non-carcinogenic health effects are unlikely to occur. In contrast, an HQ value greater than 1 suggests that the exposure level exceeds the reference threshold, indicating a potential health concern from inhalation exposure [19]. The non-carcinogenic hazard quotient for inhalation exposure was calculated as follows:

$$HQ = \frac{EC}{Rfc} \quad (4)$$

where HQ is the hazard quotient, EC is the exposure concentration of the pollutant in air ($\mu\text{g}/\text{m}^3$) and RfC is the pollutant-specific inhalation reference concentration ($\mu\text{g}/\text{m}^3$). The exposure concentration was estimated using the following equation:

$$EC = \frac{C \times ET \times EF \times ED}{AT} \quad (5)$$

where C is the measured concentration of the air pollutant ($\mu\text{g}/\text{m}^3$), ET is the exposure time (h/day)(h/day)(h/day), EF is the exposure frequency (days/year), ED is the exposure duration (years), and AT is the averaging time (h). Exposure was assumed to occur for 24 h/day and 350 days/year, representing a long-term residential exposure scenario in the study area. For non-carcinogenic risk assessment, AT was calculated as $ED \times 365 \times 24$. Under this formulation, the exposure duration term is cancelled algebraically by the averaging time; therefore, the HQ values were interpreted as overall pollutant-specific screening estimates rather than age-specific dose-based risk estimates.

Prior to HQ calculation, NO_2 and O_3 concentrations reported in ppb were converted to $\mu\text{g}/\text{m}^3$, while PM_{10} and $\text{PM}_{2.5}$ concentrations were directly used in $\mu\text{g}/\text{m}^3$. The RfC values used in this study were 57, 120, 25, and 50 $\mu\text{g}/\text{m}^3$ for NO_2 , O_3 , $\text{PM}_{2.5}$, and PM_{10} , respectively.

Results and Discussion

Seasonal Meteorological Characteristics

Table 2 presents the mean meteorological parameters disaggregated by season across the 2019–2021 study period. The winter season was distinguished by the lowest mean rainfall (20.75 mm), the lowest relative humidity (66.65%), the highest atmospheric pressure (1002.84 hPa), and the lowest wind speed (4.15 knots). These meteorological conditions are characteristic of the prevailing northeast monsoon, which delivers continental air masses with low moisture content and suppresses vertical atmospheric mixing through high-pressure subsidence. In contrast, the rainy season recorded the highest rainfall (156.19 mm), the greatest relative humidity (77.12%), the lowest atmospheric pressure (999.20 hPa), and the highest wind speed (5.22 knots)—conditions that collectively facilitate the dispersion and wet deposition of air pollutants. The summer season represented an intermediate regime with the highest temperature (30.39°C) and moderate precipitation.

Air Pollutant and Air Quality Index

Monthly concentrations of NO₂, O₃, PM₁₀, and PM_{2.5} showed a clear temporal pattern (**Figure 2**). The highest concentrations were generally observed in January and February. In January, NO₂, O₃, PM₁₀, and PM_{2.5} concentrations were 18.56 ppb, 32.44 ppb, 70.62 µg/m³, and 40.00 µg/m³, respectively.

Similarly, high concentrations were observed in February, with values of 15.38 ppb, 32.56 ppb, 68.67 µg/m³, and 34.33 µg/m³, respectively. In contrast, lower concentrations were generally recorded during June–September, with minimum values observed for NO₂ in August (8.00 ppb), O₃ in August (15.00 ppb), PM₁₀ in June (31.34 µg/m³), and PM_{2.5} in August (11.33 µg/m³).

When grouped by season, winter showed the highest average concentrations for all pollutants (**Table 3**). The mean concentrations of NO₂, O₃, PM₁₀, and PM_{2.5} during winter were 16.37 ppb, 30.73 ppb, 60.71 µg/m³, and 31.33 µg/m³, respectively. These values decreased during summer to 12.10 ppb, 22.53 ppb, 40.47 µg/m³, and 17.89 µg/m³, respectively, and were lowest during the rainy season at 10.21 ppb, 17.61 ppb, 33.30 µg/m³, and 13.28 µg/m³, respectively. This seasonal pattern indicates that winter was the most critical period for air pollution in the study area, particularly for particulate matter.

The higher pollutant concentrations during winter may be associated with stable atmospheric conditions, reduced vertical mixing, and limited rainfall, which can promote pollutant accumulation near the ground surface. Conversely, the lower concentrations during the rainy season may reflect the effect of atmospheric washout and wet deposition.

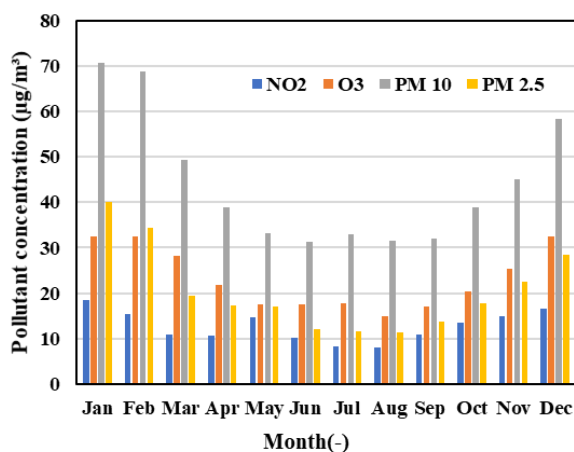


Figure 2 Monthly variation in NO₂, O₃, PM₁₀, and PM_{2.5} concentrations during the study period

Table 2 Seasonal mean meteorological parameters at Bowin Subdistrict, Chonburi Province

Season	Ws (knot)	Ra (mm)	T(°C)	Pa (hPa)	RH (%)
Winter	4.15	20.75	28.88	1002.84	66.65
Summer	4.93	87.16	30.39	1000.72	73.53
Rainy	5.22	156.19	29.40	999.20	77.12

Table 3 Seasonal variation in air pollutant concentrations in the study area

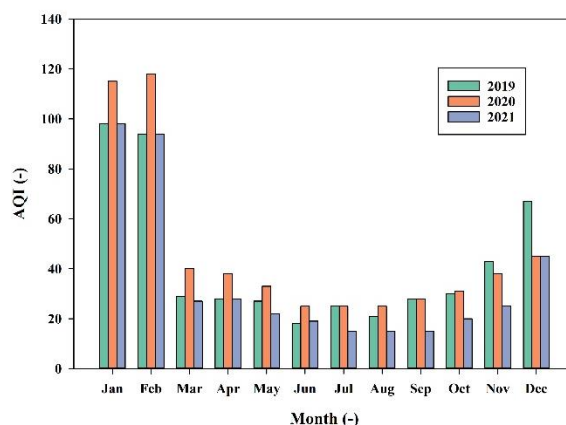
Season	NO ₂ (ppb)	O ₃ (ppb)	PM ₁₀ (µg/m ³)	PM _{2.5} (µg/m ³)
Winter	16.37 ± 1.64	30.73 ± 3.62	60.71 ± 11.68	31.33 ± 7.53
Summer	12.10 ± 2.23	22.53 ± 5.43	40.47 ± 8.23	17.89 ± 1.26
Rainy	10.21 ± 2.23	17.61 ± 1.97	33.30 ± 3.12	13.28 ± 2.65
Overall Mean ± SD	12.74 ± 3.36	23.21 ± 6.73	44.23 ± 14.49	20.45 ± 9.30

This finding is consistent with Watcharaviton, Chio [23], who reported clear monthly and seasonal variations of PM₁₀, NO₂, SO₂, and O₃ in Bangkok, with higher concentrations during winter and lower levels during the rainy period. Similarly, Li, Shao [24] found that PM_{2.5}, PM₁₀, and NO₂ were generally higher during the winter/heating period in Beijing, reflecting the influence of seasonal emissions and meteorological conditions. Shelton, Liyanage [25] also demonstrated that urban air pollutants, including PM_{2.5}, PM₁₀, NO₂, SO₂, and O₃, varied seasonally and were associated with meteorological parameters. Therefore, the monthly pollutant concentrations were subsequently converted into AQI values to provide an integrated indicator of air quality and to support health-risk interpretation in the following section.

Figure 3 illustrates the temporal variation in monthly AQI during 2019–2021. The results revealed pronounced seasonal fluctuations in air quality across the study area. Overall, AQI values ranged from 15 to 118, indicating that air quality varied from good conditions to levels that may affect sensitive population groups. The annual mean AQI values were 42.33 ± 28.12 , 46.75 ± 33.23 , and 35.25 ± 29.56 in 2019, 2020, and 2021, respectively. Although the mean AQI values generally remained within the good air quality category, substantial monthly fluctuations were observed, suggesting that short-term meteorological and emission-related factors played an important role in determining air quality conditions.

A distinct increase in AQI was observed during December to February in each year, with the highest AQI recorded in January 2020. This peak value of 118 indicates a level of air pollution that may pose health risks to sensitive groups, particularly children, older adults, and individuals with respiratory diseases. The elevated AQI during this period may be

attributed to the combined influence of seasonal meteorological conditions and local emission sources. During the winter season, relatively stable atmospheric conditions, lower mixing height, reduced rainfall, and weaker pollutant dispersion can promote the accumulation of air pollutants near the ground surface. These conditions may be particularly relevant in areas influenced by industrial activities, transportation networks, and urban expansion.

**Figure 3** Monthly Air Quality Index analysis from 2019 to 2021

In contrast, the lowest AQI values were recorded from June to September 2021, with a minimum value of 15, reflecting good air quality and minimal health risk. This period corresponds largely to the rainy season, during which frequent rainfall and higher atmospheric moisture can enhance pollutant removal through wet deposition and reduce the resuspension of particulate matter. Rainfall can also improve atmospheric cleansing by washing out airborne particles and soluble pollutants, thereby contributing to lower AQI levels.

Seasonal comparison further confirmed that winter was the most critical period for air quality deterioration (see **Table 4**). The mean

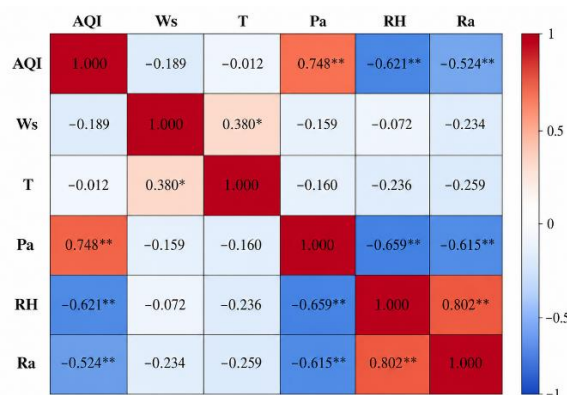
AQI during winter was 73.33 ± 32.69 , which was approximately 2.43 times higher than that observed in summer and 3.23 times higher than that observed in the rainy season. These findings indicate that seasonal meteorological conditions strongly influenced AQI variation in the study area. Although summer and rainy seasons were both classified as good air quality periods, the rainy season showed the lowest mean AQI, supporting the role of precipitation in reducing ambient pollutant concentrations.

Table 4 Seasonal AQI variation (2019–2021)

Season	AQI (Mean $\pm$ SD)	Degree
Winter	73.33 ± 32.69	Moderate
Summer	30.22 ± 5.74	Good
Rainy	22.67 ± 5.49	Good

Correlation Between AQI and Meteorological

Pearson's correlation analysis was performed to evaluate the relationships between AQI and meteorological factors. As presented in **Figure 4**, atmospheric pressure showed the strongest positive association with AQI ($r = 0.748$, $p < 0.01$). This result indicates that periods of higher atmospheric pressure tended to coincide with higher AQI values. High-pressure conditions are generally associated with greater atmospheric stability, weaker vertical mixing, and limited pollutant dispersion, which may promote the accumulation of pollutants near the ground.



* Correlation significant at $p < 0.05$ (two-tailed); ** Correlation significant at $p < 0.01$ (two-tailed).

Figure 4 Heatmap of Pearson correlation coefficients between AQI and meteorological variables

Relative humidity exhibited a strong and statistically significant negative correlation with AQI ($r = -0.621$, $p < 0.01$). Rainfall also demonstrated a significant inverse association with AQI ($r = -0.524$, $p < 0.01$). These findings suggest that higher relative humidity and greater rainfall were generally associated with lower AQI values. Rainfall may reduce atmospheric pollutant concentrations through wet deposition, while humid and rainy conditions may also suppress the resuspension of road dust and enhance atmospheric cleansing.

Wind speed showed a weak negative correlation with AQI, but the relationship was not statistically significant ($r = -0.189$, $p > 0.05$). Although the direction of the relationship is consistent with the dispersive effect of wind, its weak magnitude suggests that wind speed alone did not substantially explain AQI variability during the study period. This may be related to the limited variability of wind speed, differences in wind direction, local topographic conditions, or the influence of nearby industrial and traffic-related emission sources.

Temperature showed almost no relationship with AQI ($r = -0.012$, $p > 0.05$), indicating that temperature alone was not an important determinant of AQI during the study period. This negligible association may reflect competing atmospheric processes, as higher temperatures can enhance vertical mixing while also promoting photochemical reactions and secondary pollutant formation. The influence of temperature may therefore vary according to pollutant type, season, solar radiation, and its interaction with other meteorological variables.

The correlation matrix also revealed significant relationships among the meteorological variables. Wind speed was positively correlated with temperature ($r = 0.380$, $p < 0.05$). Atmospheric pressure was negatively correlated with relative humidity ($r = -0.659$, $p < 0.01$) and rainfall ($r = -0.615$, $p < 0.01$), whereas relative humidity was strongly positively correlated with rainfall ($r = 0.802$, $p < 0.01$). The significant interrelationships among meteorological variables indicate that these factors did not operate independently. Therefore, multiple linear regression analysis was subsequently performed to evaluate the independent contribution of each meteorological variable to AQI after simultaneous adjustment for the other variables. This analytical approach

is important because the observed bivariate associations may partly reflect shared meteorological processes, such as atmospheric stability, moisture conditions, and precipitation-related pollutant removal.

These findings are consistent with previous studies showing that meteorological conditions can jointly influence air pollutant dispersion, accumulation, and removal. Zhang, Zhang [26] reported that $PM_{2.5}$ concentrations were negatively associated with wind speed, suggesting that stronger winds enhance pollutant dispersion. Wang, Cao [27] found that particulate matter concentrations were closely related to wind speed, surface pressure, and relative humidity. Similarly, Yu, Zhong [28] demonstrated that AQI was associated with wind speed, relative humidity, and precipitation, with wind and rainfall contributing to lower AQI through atmospheric dispersion and pollutant washout.

Simple and Multiple Linear Regression Models:

Following Pearson's correlation analysis, simple linear regression was conducted to quantify the individual effects of meteorological variables on AQI. The regression results were consistent with the correlation analysis (see **Table 5**). Atmospheric pressure was the strongest individual predictor of AQI and explained 55.9% of its variability ($R^2 = 0.559$, $p < 0.001$). Relative humidity also showed a significant inverse association with AQI and

explained 38.6% of the variability ($R^2 = 0.386$, $p < 0.001$). Rainfall was likewise significantly and negatively associated with AQI, accounting for 27.4% of the variability ($R^2 = 0.274$, $p = 0.002$). In contrast, wind speed ($R^2 = 0.036$, $p = 0.293$) and temperature ($R^2 < 0.001$, $p = 0.945$) were not statistically significant predictors of AQI. The use of simple linear regression and the coefficient of determination (R^2) in the present study is consistent with previous air quality studies that applied regression-based approaches to explain or predict AQI. Bortnick, Coutant [29] used regression models to relate continuous $PM_{2.5}$ monitoring data to AQI reporting and demonstrated that simple linear regression could provide strong model fit, with (r^2) values of 0.96 and 0.86 across different metropolitan areas. Similarly, Alruwaili [30] applied simple linear regression to examine the relationship between traffic volume and AQI, reporting an (R^2) value of 0.71 for AQI. More recently, Ajaj, Awad [31] used linear regression models to predict AQI during severe dust periods in Iraq based on $PM_{2.5}$ concentrations and reported high explanatory performance, with monthly (R^2) values up to 0.85 and validation (R^2) values exceeding 0.90. These studies support the use of simple linear regression and (R^2) as appropriate statistical tools for evaluating the explanatory contribution of individual environmental or meteorological predictors to AQI variability.

Table 5 Simple linear regression models between meteorological variables and AQI

Predictor	Regression model	<i>r</i>	R^2	p-value
Wind speed (Ws)	$AQI = 61.016 - 4.588Ws$	-0.189	0.036	0.293
Temperature (T)	$AQI = 45.576 - 0.298T$	-0.012	<0.001	0.945
Atmospheric pressure (Pa)	$AQI = -10,027.097 + 10.057Pa$	0.748	0.559	<0.001
Relative humidity (RH)	$AQI = 234.794 - 2.710RH$	-0.621	0.386	<0.001
Rainfall (Ra)	$AQI = 51.367 - 0.143Ra$	-0.524	0.274	0.002

Multiple linear regression was performed to evaluate the independent effects of meteorological variables on AQI, as presented in **Table 6**. The model was statistically significant and explained 60.7% of AQI variability ($R^2 = 0.607$, adjusted $R^2 = 0.534$, $p < 0.001$), indicating that meteorological conditions substantially contributed to changes in air quality during the study period. Among the predictors, atmospheric pressure was the only significant independent factor associated with AQI

($B = 8.074$, $\beta = 0.600$, $p = 0.004$). This finding suggests that higher atmospheric pressure may promote pollutant accumulation, likely due to more stable atmospheric conditions, reduced vertical mixing, and limited pollutant dispersion. Such conditions can increase near-surface pollutant concentrations, particularly in areas influenced by industrial activities and traffic emissions. Although relative humidity and rainfall were significantly associated with AQI in the correlation analysis, they were no longer

significant in the adjusted model. This may reflect overlapping effects among meteorological variables, particularly the interrelationships between atmospheric pressure, humidity, and rainfall. Similarly, wind speed and temperature were not significant predictors after adjustment, suggesting that their effects on AQI may depend on other factors such as wind direction, emission sources, atmospheric stability, and seasonal conditions.

The present findings are consistent with previous studies indicating that meteorological conditions play an important role in regulating air pollution levels. Kliengchuay, Cooper Meeyai [32] reported that meteorological variables, including relative humidity, temperature, and atmospheric pressure, were associated with PM₁₀ concentrations in Mae Hong Son Province, Thailand. Similarly, Lv, Li [33] found that wind speed was negatively associated with PM_{2.5} and NO₂ concentrations, while rainfall contributed to the reduction of several air pollutants. In addition, Wang, Cui [34] demonstrated that precipitation generally reduced AQI and PM_{2.5} concentrations

through atmospheric washout and wet deposition. These findings support the results of the present study, in which atmospheric pressure was the dominant independent predictor of AQI, while relative humidity and rainfall showed inverse associations with AQI in the bivariate analysis.

Human Health Risk Assessment:

Table 6 summarizes the results of the inhalation health risk assessment based on the screening-level concentration-based approach. The HQ values varied by pollutant and season, with the highest values generally observed during winter. Among the pollutants, PM_{2.5} and PM₁₀ were the dominant contributors to potential non-carcinogenic inhalation risk. The highest HQ value was observed for PM_{2.5} during winter (HQ = 1.202), followed by PM₁₀ during winter (HQ = 1.164). Both values exceeded the benchmark value of 1.0, indicating potential non-carcinogenic health concerns associated with particulate matter exposure during the winter season.

Table 6 Multiple linear regression analysis of meteorological variables associated with AQI

Predictor	B	SE	Standardized β	t	p	95% CI for B
Constant	-8012.901	2630.886	—	-3.046	0.005	-13,411.034 to -2614.768
Ws	-3.349	3.386	-0.138	-0.989	0.331	-10.296 to 3.597
T	2.100	3.501	0.087	0.600	0.554	-5.084 to 9.284
Pa	8.074	2.554	0.600	3.161	0.004	2.834 to 13.314
RH	-1.019	0.976	-0.233	-1.043	0.306	-3.022 to 0.985
Ra	0.006	0.061	0.023	0.103	0.919	-0.119 to 0.131

In contrast, NO₂ and O₃ showed HQ values below 1.0 across all seasons. The HQ values for NO₂ ranged from 0.323 in the rainy season to 0.518 in winter, while those for O₃ ranged from 0.276 in the rainy season to 0.482 in winter. PM₁₀ and PM_{2.5} also showed lower HQ values during summer and the rainy season, with values below 1.0. These findings indicate that particulate matter, particularly PM_{2.5} and PM₁₀ during winter, represented the main contributors to potential inhalation health risk in the study area. The results should be interpreted as screening-level pollutant-specific risk estimates rather than age-specific dose-based risk estimates.

Seasonal differences were evident, with HQ values generally highest in winter and

lowest during the rainy season. This pattern may reflect increased pollutant accumulation under stable winter meteorological conditions, reduced vertical mixing, and limited atmospheric dispersion. In contrast, lower values during the rainy season may be partly associated with atmospheric washout and wet deposition, which reduce particulate concentrations in ambient air.

These findings are consistent with previous studies reporting seasonal differences in particulate matter exposure and health risk. Wu, Lu [35] found that PM_{2.5} and associated heavy metal concentrations were highest in winter, and that non-carcinogenic health risks increased during periods of elevated particulate pollution in Ningbo, China. Duan, Yan [36] similarly reported seasonal variations in

PM_{2.5}-bound trace metals and source-specific health risks in an industrial city in China. Roy, Singh [37] also demonstrated that PM₁₀-

and PM_{2.5}-bound metals contributed to non-carcinogenic risks among both adults and children in a polluted mining area.

Table 6 Seasonal hazard quotient values for non-carcinogenic inhalation risk

Pollutant	Winter	Summer	Rainy
NO ₂	0.518	0.383	0.323
O ₃	0.482	0.353	0.276
PM ₁₀	1.164	0.776	0.639
PM _{2.5}	1.202	0.686	0.509

Note: NO₂ and O₃ concentrations reported in ppb were converted to µg/m³ prior to HQ calculation.

Limitations and Future Directions:

This study has several limitations. First, the analysis was based on monitoring data from a single industrially influenced area during 2019–2021, which may limit generalization to areas with different emission sources, land-use characteristics, and meteorological conditions. Second, the statistical analyses focused mainly on seasonal patterns and linear associations between AQI and meteorological variables; therefore, short-term fluctuations, nonlinear relationships, lag effects, and temporal autocorrelation may not have been fully captured. The study period also overlapped with the COVID-19 pandemic, during which changes in traffic and industrial activity may have influenced air quality patterns.

Third, AQI was calculated using available pollutants, including NO₂, O₃, PM₁₀, and PM_{2.5}, while SO₂ and CO were excluded due to incomplete data. In addition, daily average O₃ and NO₂ concentrations were used; therefore, the AQI values should be interpreted as screening-level estimates rather than exact regulatory AQI values. Fourth, the health risk assessment was based on a screening-level concentration-based approach using pollutant-specific reference concentrations. Thus, HQ values should be interpreted as pollutant-specific screening estimates rather than individual clinical risk or age-specific dose-based risk estimates.

Future studies should include longer monitoring periods, additional monitoring sites, SO₂ and CO data, pollutant-specific time-series models, nonlinear and lag-effect analyses, and threshold-based approaches. Incorporating wind direction, boundary layer height, source apportionment, emission inventory data, personal

exposure monitoring, and health-outcome data would strengthen causal interpretation and improve the design of targeted air quality management strategies.

Conclusions

This study assessed seasonal AQI variation, meteorological influences, and inhalation health risks in the study area. The results showed that AQI varied by season, with higher levels during winter and lower levels during the rainy season. Pearson's correlation and simple linear regression indicated that atmospheric pressure was positively associated with AQI, whereas relative humidity and rainfall were negatively associated with AQI. In the multiple linear regression model, atmospheric pressure remained the only significant independent predictor, suggesting that high-pressure or stable atmospheric conditions may be associated with pollutant accumulation. However, this finding should be interpreted cautiously because the analysis was based on monthly time-series observations and may be influenced by autocorrelation, multicollinearity among meteorological variables, and changes in anthropogenic activity during the COVID-19 period.

The inhalation health risk assessment showed that potential non-carcinogenic risk varied by pollutant and season. PM_{2.5} and PM₁₀ were the dominant contributors to the estimated risk, particularly during winter, when their HQ values exceeded the benchmark value of 1.0. In contrast, NO₂ and O₃ showed HQ values below 1.0 across all seasons. Since the assessment was based on a screening-level

concentration-based approach, the HQ results should be interpreted as pollutant-specific screening estimates rather than age-specific dose-based risk estimates. These findings highlight the importance of season-specific air quality management, particularly during winter pollution episodes, with priority attention to particulate matter control.

Future studies should incorporate longer-term air quality monitoring, pollutant-specific source apportionment, wind direction, boundary layer height, emission inventory data, and spatial exposure assessment. The integration of personal exposure monitoring and age-specific activity patterns would also improve the accuracy of inhalation health risk estimation. In addition, advanced statistical or machine-learning models could be applied to better predict AQI variation and identify key drivers of air pollution in industrially influenced communities. Future work should also include SO₂ and CO where complete data are available, apply pollutant-specific AQI averaging conventions, and evaluate threshold-based prediction models, such as logistic regression or ROC analysis, to identify meteorological conditions associated with unhealthy AQI levels.

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Legal Development Guidelines for Strengthening the Role of Citizens in Household Waste Management in Thailand

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Abstract

This research addresses the critical environmental crisis of household waste in Thailand, where existing legal frameworks fail to regulate public behavior at the source. Although the government has designated waste management as a national agenda, overall waste volume continues to rise due to shifting socio-economic conditions and the lack of mandatory waste segregation. This study aims to examine legal concepts and theories, conduct a comparative analysis of legal measures in the United Kingdom, Sweden, and Japan, analyze impediments within the Thai legal system, and propose developmental pathways to enhance the civic role in waste management. The findings reveal significant structural gaps in Thai law, which primarily focuses on "end-of-pipe" solutions, lacks specific duties for individual households, and relies on inefficient flat-rate fee structures. Comparative evidence suggests that success in developed nations stems from the exercise of state power through "Command and Control" mechanisms alongside economic incentives. Consequently, this research recommends a comprehensive legal reform, including the enactment of a specialized "Lex Specialis" for household waste. Key proposals include transposing constitutional duties into statutory obligations, transitioning to a "Pay-As-You-Throw" (PAYT) fee model, and implementing Extended Producer Responsibility (EPR) and Deposit-Refund Systems (DRS). These reforms are essential to transform citizens from passive service recipients into active environmental stakeholders, ensuring sustainable resource recovery and social equity.

Keywords : Legal Development Guidelines; Civic Duty and Responsibility; Circular Economy; Household Waste Management

Introduction

The challenges surrounding household waste management constitute a significant environmental crisis with profound ramifications for contemporary Thailand. Notwithstanding the endeavors of the government and state authorities to address these exigencies and designate household waste management as a National Agenda [1], statistical data regarding municipal solid waste—encompassing household refuse—indicates a consistent upward trajectory. This trend is inextricably linked to shifting socio-economic dynamics and evolving consumption modalities. The primary impediment to effective management resides in public behavior at the

source, specifically the lack of conscientious waste segregation. Such neglect leads to the cross-contamination of diverse waste categories, thereby diminishing their economic viability and impeding efficient resource recovery. Consequently, this imposes an immense fiscal burden on the public sector regarding logistics and disposal, while simultaneously engendering deleterious effects on public health and well-being [2]. These systemic failures underscore the inadequacies of the extant legal framework in effectively regulating behavioral patterns or incentivizing the role of citizens as stakeholders obligated to mitigate the environmental impacts derived from household waste.

Legal factors constitute both a primary cause and a significant impediment contributing to the persistent failure in regulating public conduct regarding household waste management. This is evident across various contexts, including the Constitution and related statutes. For instance:

First, the issue of ambiguity regarding the role of citizens and their duty to preserve the environment. Although the current Constitution of the Kingdom of Thailand, 2017 [3], under Chapter 5: Duties of the Thai People, stipulates in Section 50 (8) that “A person shall have a duty to cooperate and support the conservation and protection of the environment...”, such a provision remains merely a general principle. It requires the enactment of supplementary legislation to establish concrete enforcement mechanisms over public behavior. Consequently, an examination of various extant Thai laws reveals significant inconsistencies and regulatory gaps in enforcing and organizing public conduct regarding environmental preservation. This issue is directly pertinent to the challenges of household waste management by citizens themselves.

Second, the legal challenges arising from a regulatory framework that prioritizes the control of large-scale pollution sources while neglecting the household sector. This disparity is evident in the Enhancement and Conservation of National Environmental Quality Act, 1992 [4], particularly within the various provisions of Part 7: Monitoring and Control. Although the 'Polluter Pays Principle' (PPP) was adopted as a foundational tenet for environmental protection, the legislative intent remains focused on regulating industrial point sources. There is a discernible lack of provisions establishing a standard of conduct or a legal duty for individual citizens as small-scale generators of household waste. Consequently, the public's legal responsibility for environmental conservation is not effectively applied to household waste management. This regulatory gap inhibits public awareness of their status as stakeholders and their legal obligation to manage the waste they generate, ultimately resulting in negative externalities that adversely affect the broader public interest.

Third, the legal problems stemming from a framework that prioritizes "end-of-pipe" solutions for household waste management rather than

addressing the problem at its source. This is illustrated by the Public Health Act, 1992 [5] in section 20 which empowers the state to provide public services for the collection, transportation, and disposal of waste. Such provisions reflect a reactive approach, as the legislative intent is primarily focused on the collection of fees and the prohibition of waste disposal in public areas. Crucially, the Act fails to mandate "waste segregation" at the household level in a concrete manner. Consequently, citizens are positioned merely as passive recipients of state services, shifting the entirety of the management burden onto the public sector. This imbalance precludes active public participation and cooperation in managing household waste at the point of origin.

Finally, the legal problems arising from a regulatory focus on urban cleanliness and public order rather than systematic household waste management. This is exemplified by the Maintenance of Cleanliness and Orderliness of the Country Act, 1992 [6], which is intended to preserve the sanitation and aesthetics of public spaces. The Act primarily functions as a prohibitive law, restraining citizens from actions that disturb public order—such as the prohibition against disposing of filth or waste in public places, as stipulated in Sections 29 to 34 of Chapter 2. However, it fails to impose a legal duty on citizens to manage waste within their households. This creates a legal loophole whereby citizens may commingle all types of household waste without penalty, provided that the disposal occurs within state-provided receptacles or designated areas. Consequently, the scope of this Act is limited to the regulation of public spaces and fails to govern public conduct regarding waste management at the source. Furthermore, the Act prescribes a "flat-rate" fee for waste management. This results in an inequitable situation where individuals who generate minimal waste or practice diligent segregation bear the same financial burden as those who generate excessive waste or fail to segregate entirely. Such a fee structure lacks the necessary incentives to motivate behavioral changes toward more sustainable household waste management.

In light of the aforementioned circumstances and legal exigencies, conducting research to identify pathways for legal development—with an emphasis on empowering citizens to actively collaborate with state authorities in household

waste management—is a critical endeavor. Such research serves to establish a equilibrium between the rights and duties of citizens and the exercise of state power, ultimately transforming Thailand into a society characterized by sustainable waste management and environmental preservation throughout the entire lifecycle. Research Contributions: for academic dimension, this research provides profound insights into the limitations of Thai legal system regarding the regulation of public conduct in household waste management, which directly impacts the creation of a sustainable environment. For the legal development dimension, his study serves as a framework for the legislature to formulate or amend relevant statutes, incorporating provisions that clearly define the duties of citizens in household waste management while establishing concrete enforcement mechanisms. Moreover, for the social dimension, this research establishes a legal system that fosters public awareness of environmental duties and responsibilities, leading to a sustainable reduction in waste volume and an increase in recycling rates at the source.

Research Gap and Unique Contribution

This study bridges a critical research gap by shifting the focus from "end-of-pipe" technologies to analyzing the regulatory vacuum at the point of origin (the household sector) and the legal constraints of state power regarding domestic privacy. The unique contribution is the conceptualization of a standalone statute (*Lex Specialis*) grounded in Law and Economics and Circular Economy principles. By pioneering a Dual-Track Approach, the framework harmonizes mandatory enforcement (e.g., "No Sort, No Collect") with fiscal and tax incentives (PAYT/EPR/DRS), legally redefining passive citizens into active, obligated stakeholders in resource recovery.

Objective and Methodology

This study aims to examine the relevant conceptual and theoretical framework: legal concepts, theories, and principles; conduct a comparative analysis of legal measures and experiences from the United Kingdom, Sweden, and Japan; analyze the current legal impediments within the Thai context; and

propose recommendations for legal reform that prioritize the enhancement of the public's role as a key partner in household waste management alongside the government. This study constitutes legal research primarily employing a Documentary Research methodology. The operational procedures are categorized as follows: Data Collection involves the comprehensive gathering and review of legal statutes, judicial precedents (where applicable), pollution situation reports, dissertations, and academic articles pertaining to household waste management from both domestic and international sources. Data Analysis is conducted through Content Analysis to evaluate the efficacy of Thai legal measures against international standards, supplemented by Comparative Legal Analysis to identify legal frameworks appropriate for the Thai socio-cultural context. Finally, Data Synthesis involves the integration of findings to propose legal reforms, encompassing both Mandatory Measures and Incentive Measures.

Furthermore, the scope of this research is directed towards the examination of legal provisions that impact the role of citizens in household waste management. The primary statutes under review include the Constitution of the Kingdom of Thailand, 2017; the Enhancement and Conservation of National Environmental Quality Act, 1992; the Public Health Act, 1992; and the Maintenance of Cleanliness and Order of the Country Act, 1992, as well as relevant subordinate legislation pertaining to fee collection structures and waste segregation mandates. The comparative jurisdictional scope further encompasses the legal systems of the United Kingdom, noted for its civil penalty measures; Sweden, distinguished by its mandatory food waste segregation; and Japan, characterized by its robust social discipline and local government ordinances.

Results and Discussion

Conceptual and Theoretical Framework

Regarding the relevant legal concepts, theories, and principles, it is found that enhancing the role of citizens in effective and sustainable household waste management—thereby establishing the legitimacy of state power in regulating or limiting individual liberties and creating a system conducive to

behavioral shifts—incorporates the following frameworks:

1. Right to a Healthy Environment and Civic Duty

The concept of the right to a healthy environment is a fundamental right aimed at ensuring that individuals can live in conditions conducive to health and safety. However, within the realm of public law, 'rights' are invariably intertwined with 'duties.' [7] In the context of household waste, while citizens possess the right to demand efficient public waste collection services from the state, they simultaneously bear a 'fundamental duty' to refrain from polluting and to actively preserve environmental quality [8]. Imposing a legal duty on households to segregate waste prior to disposal is, therefore, not merely a restriction of liberty; rather, it is an exercise of state power to protect the collective environmental rights of the public. Transforming the status of citizens from 'passive receivers' of services to 'active contributors' with shared responsibilities constitutes a vital foundation for the modern development of household waste management legislation.

2. Law and Economics and Behavioral Control

The field of Law and Economics analyzes how legal frameworks should be designed to achieve maximum efficiency in resource allocation. In the context of household waste, this theory posits that citizens are "Rational Actors" who make decisions regarding waste disposal or segregation based on a cost-benefit analysis. If the law mandates a flat-rate fee for waste services, the "marginal cost" of disposing of additional waste effectively becomes zero for the individual, thereby eliminating any incentive for waste reduction. Applying Law and Economics to legal reform focuses on the utilization of Economic Instruments, such as the Pay-As-You-Throw (PAYT) system, to internalize social costs into private costs. Under this mechanism, if individuals generate more waste, they must bear higher costs, whereas diligent segregation of recyclables leads to reduced fees. Such legal mechanisms compel individuals to automatically adjust their behavior through the imposition of financial burdens [9]. Recent studies demonstrate that purely command-and-control frameworks

are insufficient to alter household behavior without functional economic instruments. Their legal and economic analyses of the Pay-As-You-Throw (PAYT) mechanism in developed jurisdictions show that replacing flat-rate schemes with unit-based pricing models leads to an average of over 30% reduction in municipal solid waste destined for landfills, reinforcing the argument that financial accountability directly catalyzes household source segregation [10, 11].

3. Circular Economy Principle

The Circular Economy principle shifts the perspective on household waste from "refuse requiring disposal" to "resources for recovery" (Resource Recovery). This concept relates to household waste management through the establishment of legal standards that mandate the Waste Hierarchy, which prioritizes waste reduction (Reduce), reuse (Reuse), and recycling (Recycle). Legislation supporting this principle does not merely regulate disposal; it encompasses mandatory public participation in returning recyclable materials to the system. This participation is fundamental to preserving the value of materials, preventing them from becoming useless landfill waste, and ensuring they can be reutilized as resources [12].

4. Polluter Pays Principle (PPP)

The Polluter Pays Principle (PPP) serves as a fundamental tenet of international environmental law, stipulating that those responsible for producing pollution must bear the costs of remediation or management [13]. At the household level, every citizen is essentially a "polluter" through the consumption of goods and the generation of solid waste. The integration of this principle into waste management aims to establish legal equity. When the law authorizes the state to collect fees that reflect the actual costs of waste management, it is not merely a revenue-generating exercise; rather, it is a legal instrument to compel individuals to acknowledge the burden they impose on society and the environment. Failure to impose appropriate fees on waste generators constitutes an unjust shifting of externalities onto the state and the public.

5. Extended Producer Responsibility (EPR) Principle

The Extended Producer Responsibility (EPR) principle extends the scope of a producer's responsibility to encompass the post-consumer stage of a product's lifecycle. Although this principle primarily focuses on the private sector, it is inextricably linked to household waste management, as the vast majority of domestic refuse consists of "packaging" generated by producers. Legislation implementing EPR establishes a take-back system that directly engages the public. Under this framework, citizens are legally mandated to segregate packaging waste, while producers are obligated to provide collection points or subsidize the costs of recycling. The synergy between laws regulating producers and those governing household behavior under the EPR framework facilitates a comprehensive "closed-loop" waste management system, effectively minimizing the burden of waste management at its point of origin [14]. Successful Circular Economy outcomes rely heavily on statutory synchronization, where recent expansions of Extended Producer Responsibility (EPR) and Deposit-Refund Systems (DRS) globally underscore that legislation must simultaneously mandate source segregation for citizens and take-back structures for producers, achieving resource recovery rates of up to 80-90% for household packaging components [15, 16].

Comparative Analysis of International Legislation and Experiences in Household Waste Management

A comparative study of foreign legislation demonstrates that success in waste management does not rely solely on the provision of public services by the state. Rather, it depends on the exercise of state power through legal mechanisms to "mandate duties" and "restrict liberties" regarding public disposal practices. The specific measures and their impacts are detailed as follows:

1. The United Kingdom: Enforcement through Statutory Notices and Civil Penalties
The United Kingdom exercises state power to regulate public behavior through the Environmental Protection Act 1990, which functions as a clear "Command and Control" mechanism at the household level.

1.1 Legal Measures: Under Section 46, local authorities are empowered to issue "Statutory Notices" mandating that citizens place waste in designated receptacles, segregate waste types as specified, and present waste on certain days and times [17]. Non-compliance allows authorized officers to issue "Fixed Penalty Notices (FPNs)"—a form of civil sanction—immediately without the need for court proceedings [18].

1.2 Impact on the Public: These measures impose a "Legal Burden" on citizens as waste generators. Individual liberty to dispose of waste indiscriminately is curtailed, and citizens must bear the financial cost of penalties if they lack discipline. However, the positive outcome is that citizens receive clean and orderly services, representing a trade-off between the acceptance of legal duties and the enjoyment of a high-quality environment [19].

2. Sweden: Economic Incentives and Mandatory Bio-waste Segregation.

Sweden emphasizes the application of the Polluter Pays Principle (PPP) and the Law and Economics framework to create mechanisms that compel an automatic shift in public behavior.

2.1 Legal Measures: The Swedish Environmental Code mandates the segregation of bio-waste (organic waste) as an 'absolute duty' for households, specifically for energy production purposes [20]. Furthermore, Sweden has also implemented a 'weight-based billing' system, where waste fees are collected based on the actual weight of the waste dumped. This represents a rigorous application of the Polluter Pays Principle (PPP) at the individual level.
Impact on the Public: Citizens are confronted with "marginal costs" for excessive waste generation, which incentivizes source reduction and mindful consumption patterns. Although citizens must dedicate time to meticulous waste segregation, they receive reciprocal benefits in the form of reduced service fees and access to affordable energy derived from the Waste-to-Energy process.

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service fees and access to affordable energy derived from the Waste-to-Energy process [21].

3. Japan: Behavioral Control through Local Ordinances and Social Pressure.

Japan serves as a preeminent model for the integrated exercise of "State Power and Social Power" to regulate individual conduct under the Basic Act on Establishing a Sound Material-Cycle Society.

3.1 Legal Measures: Japanese law empowers local governments to implement a "Standardized Garbage Bag System" (Financial Incentive), where bags are priced higher to incorporate disposal costs (Pay-As-You-Throw). Furthermore, the "No Sort, No Collect" policy is enforced, granting sanitation workers the legal authority to refuse non-segregated waste and affix a non-compliance sticker [22]. In certain jurisdictions, regulations require citizens to write their names on waste bags to ensure traceability to the polluter.

3.2 Impact on the Public: These measures impact the Right to Privacy to a certain extent but are widely accepted as a fundamental civic duty. Citizens bear a significant "Social Pressure" (Social Sanction), as non-compliance can lead to social stigmatization within the community. This legal framework transforms waste management into a matter of personal discipline that is subject to continuous state and social oversight.

Legal Challenges and Impediments to Household Waste Management in Thailand

Based on an analysis of the situation in Thailand in conjunction with international legal principles and experiences, it is found that the primary obstacle to successful household waste management in Thailand does not reside in disposal technology. Rather, it lies within the limitations of the legal structure, which adversely impacts the regulation of public behavior, as detailed below:

1. Absence of Substantive Provisions Mandating "Civic Duty in Waste Segregation".

Although the Constitution of Thailand stipulates the environmental duties of citizens, existing enforcement statutes—specifically the Maintenance of Cleanliness and Order of the Country Act, 1992 and the Public Health Act, 1992—contain no provisions designating "source segregation" as a mandatory duty that citizens must perform prior to disposal. In the

absence of a mandatory legal framework, the state's authority is limited to "requesting cooperation," which lacks legal sanctions. This contrasts sharply with the legal systems of Japan or Sweden, where duties are explicitly defined by law [23]. This regulatory vacuum leads citizens to perceive the commingling of waste in a single bag as a legally permissible action, as it does not constitute a statutory offense.

2. Limitations on the Exercise of State Power over Domestic Conduct.

A significant obstacle to enforcing waste discipline in Thailand is the tension between the exercise of state power for the public interest and the protection of the Right to Privacy. While authorities in the United Kingdom utilize powers under Section 46 to inspect waste receptacles and issue immediate fines, Thai officials frequently encounter legal constraints when attempting to inspect the "contents within waste bags" or identify individual household polluters. Opening waste bags to monitor behavior may be challenged as an infringement of personal privacy or an ultra vires exercise of power, as current Thai statutes primarily authorize state action only for the maintenance of external cleanliness in public spaces [24].

3. Failure to Implement Economic Instruments for Behavioral Control.

According to the Law and Economics framework, behavioral modification necessitates a functional price mechanism. However, Thailand's current subordinate legislation remains tethered to a "Flat-rate" fee structure [25]. The prevailing fee rates do not authentically reflect the Polluter Pays Principle (PPP). Households that diligently endeavor to reduce or segregate waste are burdened with the same financial costs as those generating excessive volumes of refuse. This legal disparity results in a lack of both "positive incentives" and "negative pressures" within Thai law to compel citizens to segregate waste, unlike the Pay-As-You-Throw (PAYT) systems successfully implemented in Japan or Sweden.

4. Absence of Legislation on Extended Producer Responsibility (EPR) Linked to Households.

Thailand has yet to enact a primary statute (Act of Parliament) that effectively mandates the Extended Producer Responsibility

(EPR) principle. In the absence of mandatory EPR legislation requiring producers to facilitate the take-back of packaging, the entire burden of managing product residues falls directly upon citizens and the state. Citizens lack convenient, legally-supported channels to return packaging waste to producers. Consequently, such packaging is discarded as co-mingled household waste, which is difficult to manage and constitutes a significant barrier to the achievement of Circular Economy objectives [26].

5. The Existence of Multiple related Laws Leads to Conflict and Lack of Unity.

Household waste management in Thailand is governed by several laws, each with different primary objectives (the National Environmental

Quality Act focuses on policy frameworks, the Public Health Act focuses on disease prevention, and the National Cleanliness and Orderliness Act focuses on urban aesthetics). The distribution of legal authority across multiple laws with conflicting legal intent results in a lack of unified enforcement regarding household waste management. Various agencies tend to prioritize prosecuting "littering" (illegally dumping garbage in public areas) under the Cleanliness Act because it is a more straightforward procedure than enforcing environmental waste separation principles [27]. This lack of legal unity hinders the public's ability to clearly understand their legal roles and responsibilities toward the state.

Table 1 Comparative Matrix of Statutory Frameworks and Household Behavioral Regimes

Country / Comparative Dimensions	The United Kingdom (UK)	Sweden	Japan	Thailand
Primary Statutory Instruments	<i>Environmental Protection Act 1990</i>	<i>Swedish Environmental Code (Miljöbalken)</i>	<i>Basic Act for Establishing a Sound Material-Cycle Society</i>	<i>Public Health Act B.E. 2535, Maintenance of Cleanliness Act B.E. 2535, and NEQA B.E. 2535</i>
Statutory Duty and Source Segregation Mandate	Legally enforceable mandate driven by municipal Statutory Notices.	Absolute statutory obligation with a strict focus on 100% organic/bio-waste separation.	Enforceable civic obligation codified through specific local government ordinances.	Absence of substantive mandates; limited to "voluntary cooperation," allowing legal commingling.
Fiscal Instruments / Economic Regimes	Fixed public service levies coupled with prompt non-compliance civil penalties.	Weight-based billing systems, strictly executing the Polluter Pays Principle (PPP).	Pay-As-You-Throw (PAYT) via standardized, pre-paid municipal refuse bags.	Flat-rate monthly fee structure; minimal rates that strip away waste-minimization incentives.
Behavioral Enforcement Mechanism	Civil and administrative sanctions via Fixed Penalty Notices (FPNs) bypassing court delays.	Marginal cost mechanisms compelling households to minimize waste to lower utility levies.	"No Sort, No Collect" policy enforced via statutory non-compliance stickers and name traceability.	End-of-pipe reactive approach; limits enforcement to visible littering in open public spaces.

Statutory Justification over Domestic Privacy	Legitimate public power under Section 46 to inspect refuse contents and issue fines.	Accepted limitation of liberties in exchange for heavily subsidized, waste-derived green energy.	Justifiable restriction of privacy driven by robust communal and social oversight.	Severe regulatory hurdles; lacks statutory entry or inspection rights, risking privacy torts.
Extended Producer Responsibility (EPR / DRS)	Closed-loop networks reinforced by strict producer take-back civil frameworks.	Nationwide Deposit-Refund System (DRS/Pant) granting immediate cash or vouchers.	Integrated product-specific recycling statutes binding producers and community depots.	Absence of mandatory primary EPR statutes, shifting all fiscal burdens to municipalities.
Regulatory Architecture and Ideology	Command-and-control approach with streamlined local administrative authority.	Market-based instruments blending environmental mandates with energy infrastructure.	Decentralized governance leveraging formal laws with informal social sanctions.	There are many laws with conflicting intentions, leading to a lack of unity.
Legal Status of the Citizen	Active contributors operating within a legally balanced regime of rights and duties.	Co-producers of green energy bound to return material value to closed loops.	Communal stewards subject to continuous state and localized social peer review.	Passive recipients shifting the entire logistical and financial burden onto the public sector.

Conclusions and Recommendations

The evolution of household waste legislation must transcend the perception of waste as mere refuse, moving toward a framework where waste is redefined as a resource that every individual is legally obligated to manage in collaboration with the state. The exercise of state power to restrict the liberty of indiscriminate disposal—whether through the amendment of existing statutes or the enactment of a new specific Act dedicated to household waste management—serves as a pivotal instrument in establishing a sustainable 'Civic Role in Environmental Stewardship' that aligns with international standards. An analysis of the legal nexus between state authority and civic duties reveals that surmounting Thailand’s legal impediments necessitates a structural legal reform. This reform must be grounded in theoretical principles and successful international experiences, adapted to the Thai context. Accordingly, the recommendations for developing household

waste management legislation to further enhance the role of the public are as follows:

1. Transposing Constitutional Duties into Statutory Obligations

To address the lack of enforceable provisions regarding "civic duty" at the operational level, the State must utilize the Constitution of the Kingdom of Thailand, 2017, Section 50 (8), as a legal basis for the Parliament to enact a primary statute (Act of Parliament). This legislation should explicitly mandate "source segregation of solid waste" as a mandatory duty for all households. Furthermore, a clear definition of "environmental civic duty" should be established within the household waste management law. This would provide the State with the legitimate authority to intervene in waste management behaviors within private domestic spaces—analogueous to the powers granted under Section 46 of the UK’s Environmental Protection Act. Such a legal framework would prevent individuals from invoking the right to privacy as an impediment to

waste segregation practices intended for the public interest.

2. Reforming Existing Statutes to Establish Behavioral Enforcement Mechanisms

It is proposed that the lack of coordination among the three primary statutes be addressed through the following legal reforms:

2.1 Enhancement and Conservation of National Environmental Quality Act 1992: Provisions should be incorporated to empower the State to issue "Household Waste Management Standards" and implement Economic Instruments at the individual level. This ensures that the Polluter Pays Principle (PPP) and Law and Economics frameworks possess concrete enforceability rather than remaining mere policy principles without practical effect.

2.2 Public Health Act: The waste collection fee system must be reformed, transitioning from a flat-rate structure to a variable-rate system based on the actual weight or volume of household waste generated (Pay-As-You-Throw). By adopting Japan's standardized garbage bag model, the fee will function as a 'behavioral control instrument' rather than merely a service fee for waste transportation provided by the state to the public.

2.3 Maintenance of Cleanliness and Order of the Country Act 1992: The underlying philosophy of the Act must shift from an emphasis on "aesthetics" to "environmental discipline." Provisions should be added mandating the duty of owners or occupiers of dwellings to segregate household waste. Sanctions, such as administrative fines, should be prescribed for non-compliance with state-defined sorting standards. Furthermore, a "No Sort, No Collect" provision should be enacted, legally empowering officials to refuse the collection of unsegregated waste, thereby creating social enforcement similar to the Japanese model.

3. The enactment of a new primary statute as a specialized law (Lex Specialis) dedicated specifically to household waste management

Beyond the amendment of existing legislation, an alternative approach involves drafting a new, standalone primary law to serve as a specific and centralized framework for

household waste management. The essential substantive provisions of this proposed Act are as follows:

3.1 The Act shall stipulate a comprehensive national policy framework and management plan for household waste, aligned with the National Economic and Social Development Plan. This framework is to be grounded in the principles of the Circular Economy and the Right to a Healthy Environment, emphasizing civic duties and active cooperation with the state.

3.2 The Act shall mandate the establishment of household waste collection and disposal fees, administered by the public sector, utilizing a variable-rate structure based on the actual weight or volume of waste disposed of by citizens. This entails the abolition of the current flat-rate system to ensure that fees function effectively as a behavioral control instrument, incentivizing public compliance with the state's waste management objectives.

3.3 The Act shall stipulate the Extended Producer Responsibility (EPR) principle, mandating that producers establish comprehensive systems for the take-back of packaging from households. This mechanism serves to alleviate the statutory duties of both citizens and the public sector in managing household waste that is difficult to recycle. Furthermore, it utilizes price mechanisms to compel producers to internalize environmental costs, thereby incentivizing the design of products and packaging that are more environmentally friendly.

3.4 The Act shall provide for the implementation of a Deposit-Refund System (DRS), established as a mandatory price-based mechanism for specific categories of packaging within household waste, modeled after the Swedish system. This initiative aims to transform public behavior from the role of 'disposers' to 'returners,' thereby reintegrating resources into the production cycle or facilitating reuse. Under the DRS, a small deposit fee is added to the product price at the point of purchase—such as for plastic bottles or aluminum cans. Upon consumption, citizens may return these containers to redeem the deposit in the form of cash or cash-equivalent vouchers. Furthermore, the operational and financial

management of this deposit-refund mechanism may be administered through the Environmental Fund.

3.5 The Act shall stipulate tax incentives and social welfare measures by granting benefits to citizens who consistently perform waste segregation. Such incentives may include reductions in waste collection fees or discounts on local taxes, such as the Land and Buildings Tax. These measures are designed to encourage voluntary public participation in household waste management, facilitating alignment with state-defined guidelines through positive reinforcement.

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Green Chemistry Synthesis of Ag/ZnO (ashwater) Using Bark Ash Water and Mango Extract for Enhanced Photocatalytic Degradation of Rhodamine B

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Abstract

Ag/ZnO (BAW) was synthesized via a green chemical precipitation method and evaluated as a visible-light photocatalyst for Rhodamine B (RhB) degradation. X-ray diffraction (XRD) analysis confirmed the coexistence of hexagonal wurtzite ZnO and metallic Ag phases, while energy-dispersive X-ray spectroscopy (EDX) verified the presence of Zn, O, and Ag. Scanning electron microscopy (SEM) revealed mixed rod-like and short tubular morphologies. UV-Vis diffuse reflectance spectroscopy demonstrated enhanced visible-light absorption of Ag/ZnO (BAW) compared with ZnO (BAW), and Tauc plot analysis showed a reduction in the optical band gap from 3.16 to 3.10 eV after Ag incorporation. Under visible-light irradiation, Ag/ZnO (BAW) achieved 99.69% RhB degradation within 120 min, compared with 89.51% for ZnO (BAW). The degradation followed a pseudo-first-order kinetic model, with Ag/ZnO (BAW) exhibiting an apparent rate constant of 0.0428 min^{-1} , approximately 2.6 times higher than that of ZnO (BAW) (0.0165 min^{-1}). The addition of 1,4-benzoquinone (BQ) markedly suppressed RhB degradation, suggesting the involvement of superoxide radicals ($\text{O}_2^{\bullet-}$) in the photocatalytic mechanism. However, the possible contributions of other reactive species cannot be excluded. The enhanced photocatalytic activity of Ag/ZnO (BAW) is associated with improved light absorption and enhanced photoinduced charge-carrier separation induced by Ag incorporation. These findings demonstrate the potential of Ag/ZnO (BAW) as an efficient and environmentally friendly photocatalyst for dye degradation under visible-light irradiation.

Keywords : Ag/ZnO; Green synthesis; Photocatalysis; Rhodamine B; Pseudo-first-order

Introduction

Rhodamine B (RhB) is widely utilized as a synthetic dye, particularly applied in the textile industry and the manufacturing of various commercial products, including ballpoint pens, paints, leather goods, dye lasers, carbon paper, stamp pad inks, fireworks, and explosive materials [1]. In the case of Rhodamine utilization, it has raised serious environmental concerns that RhB has been reported to induce mutagenic and oncogenic effects in living organisms [2, 3]. Consequently, effective RhB removal is essential for environmental

remediation and human health protection. Metal oxide photocatalysts have attracted considerable attention for dye degradation because they can utilize UV and visible light to generate reactive species that decompose pollutants. Among them, ZnO has been widely studied due to its excellent electrical, optical, and catalytic properties, showing significant potential for the removal of persistent synthetic dyes from wastewater. There are various synthesis methods of ZnO, such as thermal decomposition, hydrothermal treatment, sol-gel processing, and chemical precipitation, have been used. Among these methods, the chemical precipitation

method is widely employed because of its simplicity, cost-effectiveness, and controllability of material particle size and morphology. To handle posing environmental problems, a green synthesis method has been chosen instead of previous approaches avoiding hazardous chemicals and by products generated during the process. The green method has started by using plant extracts or waste-derived precursors for reducing and stabilizing agents. This method decreases dangerous chemicals created in the process, reduces production costs, and aligns with principles of sustain-able chemistry [4].

Recent studies of the potential capability of ZnO nanoparticles in the dye degradation process. ZnO has been synthesized using Hibiscus rosa-sinensis leaf extract and has shown effective RhB degradation under sunlight [5]. In addition, polysaccharide is applied for ZnO nanoparticles synthesis using *Sechium edule* showing high photocatalytic performance under visible light irradiation [6]. Moreover, ZnO nanoparticles synthesized from *Cyanometra remiflora* leaf extract illustrated comparable activity, confirming the capability of green synthesis methods. Despite this capability, the wide band gap of ZnO (about 3.2 eV) restricts its excitation mainly to UV light, limiting its efficiency under natural sunlight, which is dominated by visible light. To overcome these challenges, surface modification and metal nanoparticle doping have been extensively studied to enhance visible-light-driven photocatalysis. Ag particle added into the process has shown remarkable effectiveness in reducing the band gap, extending the adsorption, and improving separation efficiency. The silver on nanoparticles are helpful to transfer and suppress electron hole recombination, leading to a higher stage of photocatalytic activity [7]. Hybrid photocatalysts, such as Ag-modified Al-doped ZnO (AZO), have demonstrated excellent performance in both hydrogen production and dye degradation under UV and visible light irradiation [8]. The improvement of photocatalytic activity is primarily controlled by the efficiency of charge transfer (CT) at the interface between metals, such as Ag, and semiconductor materials, such as ZnO. These interfacial interactions play a major role in supporting the rapid migration of photogenerated electron-hole pairs leading to restrain their

recombination and significantly improving light adsorption capability.

In term of these considerations, the current study focuses on the green synthesis of Ag/ZnO (BAW) photo catalysts. ZnO (BAW) is prepared by using bark ash water as a natural precursor, while Ag is extracted through mango extract [9] through a simple precipitation method. The photocatalytic efficiency of the synthesized Ag/ZnO (BAW) is subsequently studied and compared with the pure bark ash water. As a result, their performance in the RhB dye degradation is particularly emphasized under light irradiation.

Objectives

To study the synthesis of Ag/ZnO (BAW) through a green chemical method using bark ash water as a main precursor as well as mango extract as a reducing and stabilizing agent, and to evaluate its photocatalytic capability efficiency in the RhB degradation compared with the bark ash water.

Methods

1. Synthesis of Zinc Oxide from Bark Ash Water using the Co-precipitation method

Zinc oxide (ZnO) was synthesized from Bark Ash Water using a co-precipitation method adapted from Phongarthit et al. (2019). Briefly, 2.19 g. of zinc acetate ($\text{Zn}(\text{CH}_3\text{COO})_2$) was dissolved in 20 ml. of deionized water under stable stirring. Consequently, 50 ml. of Bark Ash Water with pH value 12 was added into the solution over 3 minutes with continuous stirring. The mixture was heated to 80 degrees Celsius and stirred for an hour before finishing and allowing precipitation to occur. The precipitated material was repeatedly washed with deionized water and ethanol to remove residual impurities, followed by filtration and drying at 100 degrees Celsius for an hour. The dried material was ground into a fine powder and subsequently calcined in a high temperature furnace at 900 degrees Celsius for an hour to obtain ZnO derived from Bark Ash Water (ZnO (BAW)). The final obtained product was ground again after calcination to achieve equal particlesize

2. Preparation of Ag/ZnO

To prepare the Ag/ZnO (BAW) composite material, 0.1 g of calcined ZnO (BAW) powder was dispersed in 50 ml of a silver nanoparticle solution synthesized from mango extract. Fresh mango fruits were washed thoroughly, peeled, rinsed with deionized water, and cut into small pieces. A 2.5 g portion of the mango flesh was mixed with 100 mL of deionized water and heated at 50 °C for 1 h. After cooling to room temperature, the extract was filtered through Whatman No. 1 filter paper. The preparation of the mango extract and the synthesis of silver nanoparticles (AgNPs) were performed according to the method reported by Ninaksorn et al. [2023]. The extract was added into the ZnO suspension under continuous stirring for an hour to ensure homogeneous deposition of Ag on the ZnO surface. The result of the precipitation was collected by filtration, thoroughly rinsed with deionized water to remove residual impurities, and subsequently dried in a hot-air oven for an hour. The dried material was finely ground into powder to be the Ag/ZnO (BAW) composite, which was used for photocatalytic efficiency testing in the degradation of Rhodamine B (RhB).

3. Characterization of Ag/ZnO (BAW)

SEM-EDS analysis confirmed the formation and elemental distribution of the Ag/ZnO (BAW) composite. The optical properties were evaluated by UV-Vis diffuse reflectance spectroscopy, and XRD analysis verified the hexagonal wurtzite ZnO structure with additional peaks attributed to metallic Ag, confirming the successful formation of Ag/ZnO (BAW).

4. Photocatalytic Study

The photocatalytic activity of Ag/ZnO (BAW), synthesized using ZnO (BAW) prepared from Bark Ash Water, was examined based on its performance to degrade Rhodamine B (RhB) dye under visible light irradiation. RhB solution with concentration of 1.0×10^{-5} M was prepared as the prototype pollutant. For each experiment, 0.1 g of the Ag/ZnO (BAW) catalyst was added to 250 ml beaker containing 150 ml. of the RhB solution. The suspension was first stirred in the dark for 30 minutes to generate adsorption-desorption equilibrium, after which it was allowed to settle for 2 minutes.

Then, a 3 ml. aliquot of the supernatant was subsequently withdrawn and centrifuged at 3,000 rpm for 3 minutes to remove any residual catalyst particles, and the result of clear solution was retained for further analysis. Following this step, The suspension was irradiated under visible light using a 25 W xenon lamp fitted with a 420 nm long-pass optical filter to exclude ultraviolet irradiation. The distance between the light source and the reaction vessel was fixed at 16 cm, and the suspension was continuously stirred throughout the photocatalytic reaction. At predetermined irradiation times (10, 20, 30, 45, 60, 90, and 120 min), aliquots were withdrawn, allowed to settle, and subsequently centrifuged before UV-Vis spectrophotometric analysis. The absorbance of each sample was then measured using a UV-Vis spectrophotometer. The photocatalytic degradation efficiency of RhB was calculated from the absorbance values at different time intervals using Equation (1):

$$\%D.E. = (C_0 - C_t) / C_0 \times 100 \quad (1)$$

where C_0 and C_t represent the initial concentration and the concentration of Rhodamine B at irradiation time t , respectively. According to the Beer-Lambert law, the absorbance of Rhodamine B is directly proportional to its concentration under the experimental conditions employed. Therefore, the concentration ratio (C_t/C_0) was determined from the corresponding absorbance ratio (A_t/A_0).

Results and Discussion

The synthesized Ag/ZnO (BAW) was characterized using Energy-dispersive X-ray spectroscopy (EDX) to determine its elemental composition and to confirm the successful incorporation of Ag on the ZnO (BAW) surface. As illustrated in **Figure 1 (a)**, The EDX analysis confirmed the presence of Zn, O, and Ag, indicating the successful formation of the Ag/ZnO (BAW) composite. The Ag loading was estimated to be 14.3 wt%, demonstrating the effective deposition of Ag onto the ZnO (BAW) surface. The deposited Ag nanoparticles are expected to form a metal-semiconductor (Schottky) junction with ZnO (BAW), which promotes interfacial electron transfer, suppresses the recombination of photogenerated electron-hole pairs, and consequently enhances the

photocatalytic activity under visible-light irradiation. The morphological characteristics of the composite were further investigated by

Scanning Electron Microscopy (SEM), as shown in **Figure 1(b)**, revealing a mixture of rod-like and short tubular structures.

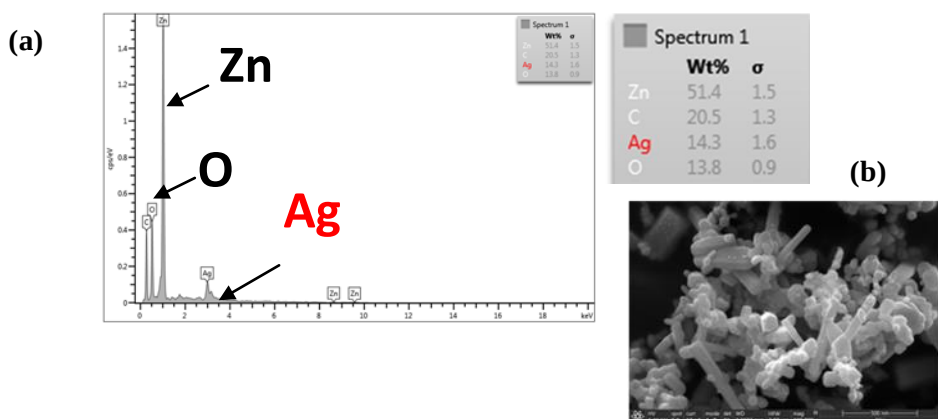


Figure 1 EDX spectrum of Ag/ZnO (BAW) (a) and morphology of Ag/ZnO (BAW) synthesized via the coprecipitation method (b)

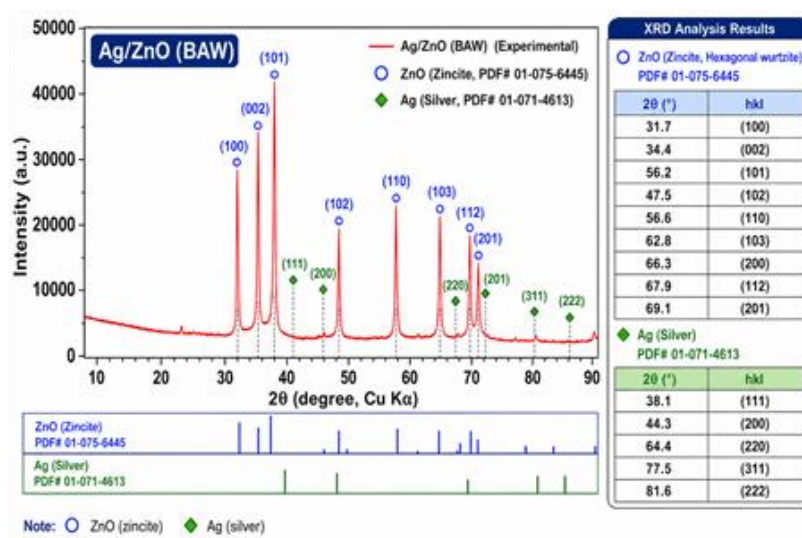


Figure 2 XRD pattern of Ag/ZnO (BAW), showing the characteristic diffraction peaks of hexagonal wurtzite ZnO and metallic Ag. The observed peaks agree well with the standard reference patterns PDF# 01-075-6445 for ZnO and PDF# 01-071-4613 for Ag, confirming the formation of the Ag/ZnO (BAW) composite

From **Figure 2** The XRD pattern confirmed that the synthesized Ag/ZnO (BAW) composite predominantly exhibited the hexagonal wurtzite crystal structure of ZnO (BAW). In addition, characteristic diffraction peaks corresponding to metallic Ag were observed, confirming the successful formation of the Ag/ZnO (BAW)

composite. The absence of any noticeable structural changes in the ZnO (BAW) diffraction pattern indicates that the incorporation of Ag did not alter the crystal structure of ZnO

Figure 3 (c) presents the UV-Vis diffuse reflectance (UV-Vis DR) spectra of the samples. The strong absorption observed at wavelengths

below 400 nm is attributed to the electron transition from the valence band to the conduction band of ZnO (BAW). Significantly, an additional absorption band emerges at wavelengths above 400 nm in the visible region. Notably, the spectrum of Ag/ZnO (BAW) displays a importantly broader absorption band in the visible range compared to that the pure ZnO (BAW). The Tauc plot analysis in **Figure 3 (d)** revealed that the estimated band-gap energy decreased from approximately 3.18 eV for ZnO (BAW) to 3.10 eV for Ag/ZnO (BAW). This slight reduction in the apparent band-gap energy is associated with the modification of the ZnO (BAW) surface by Ag nanoparticles. In addition, Ag nanoparticles enhance visible-light absorption through their surface plasmon resonance (SPR) effect, enabling the photocatalyst to harvest a broader portion of the visible-light spectrum. These effects facilitate the separation of photogenerated electron-hole pairs and contribute to the enhanced photocatalytic degradation of Rhodamine B under visible-light irradiation.

Figure 4 (e) shows the time-dependent degradation spectra of Rhodamine B (RhB), with the characteristic absorption peak at 554 nm gradually decreasing during visible-light irradiation, confirming the photocatalytic activity of Ag/ZnO (BAW). **Figure 4 (f)** compares the photocatalytic degradation of RhB over ZnO (BAW), Ag/ZnO (BAW), and Ag/ZnO (BAW) in the presence of 1,4-benzoquinone (BQ). After 120 min, Ag/ZnO (BAW) achieved

99.69% degradation, compared with 89.51% for ZnO (BAW), whereas the addition of BQ reduced the degradation efficiency to 25.38%. These results demonstrate the enhanced photocatalytic performance of Ag/ZnO (BAW) and suggest the involvement of superoxide radicals ($O_2^{\bullet-}$) in the RhB degradation mechanism, although the possible contributions of other reactive species cannot be excluded.

The photocatalytic degradation kinetics were evaluated using the pseudo-first-order model. As shown in **Figure 5**, the approximately linear relationship between $\ln(C_0/C_t)$ and irradiation time indicates pseudo-first-order behavior. Ag/ZnO (BAW) exhibited an apparent rate constant (k) of 0.0428 min^{-1} , approximately 2.6 times higher than that of ZnO (BAW) (0.0165 min^{-1}), demonstrating its enhanced photocatalytic activity. In the presence of 1,4-benzoquinone (BQ), the rate constant decreased markedly to 0.0021 min^{-1} , suggesting the involvement of superoxide radicals ($O_2^{\bullet-}$) in RhB degradation.

This was demonstrated by the addition of 1,4-benzoquinone a well-established scavenger for superoxide radicals, to the Rhodamine B solution containing the Ag/ZnO (BAW) photocatalyst. Under these conditions, the degradation efficiency decreased significantly, indicating that superoxide radicals play an important role in the photocatalytic degradation process. The experimental results, presented in **Figure 6**.

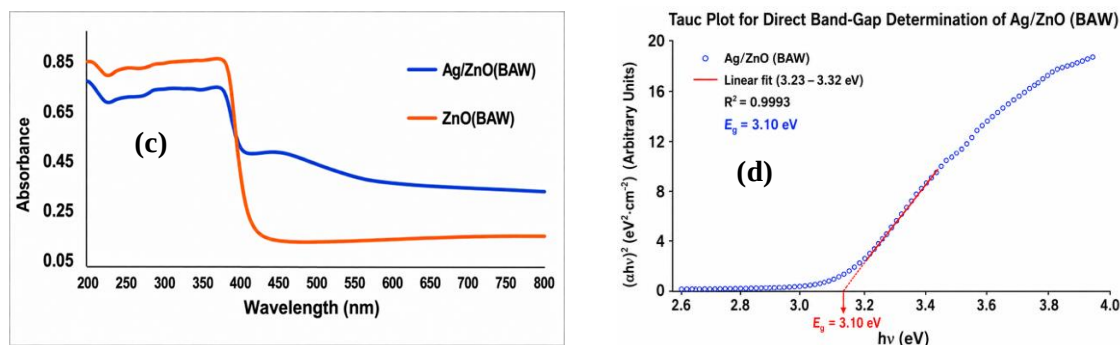


Figure 3 (c) UV-vis DR spectra of Ag/ZnO (BAW) compared with ZnO (BAW)
(d) Tauc Plot for Direct Band-Gap Determination of Ag/ZnO (BAW)

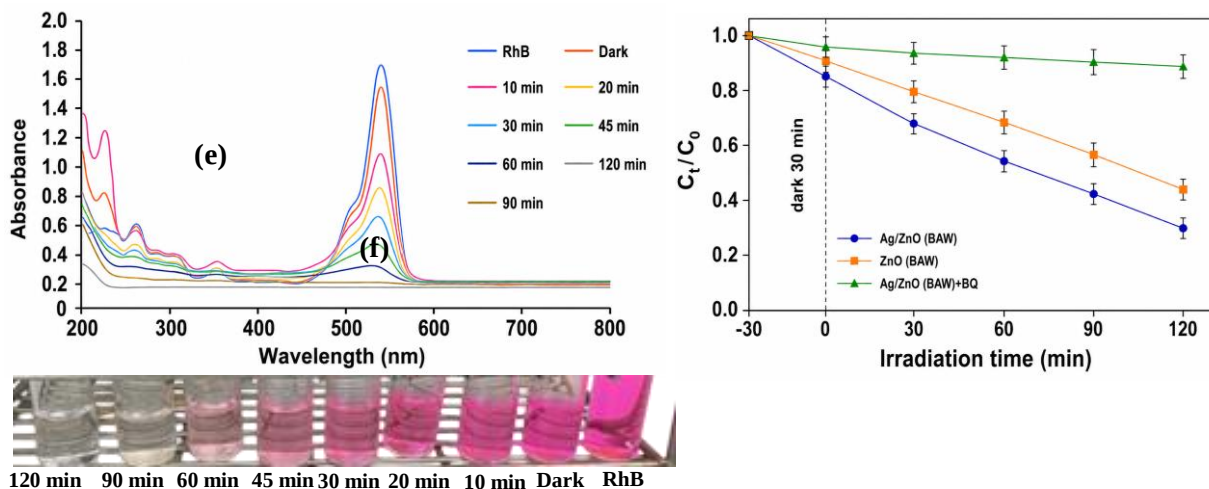


Figure 4 (e) Time-dependent UV–Vis absorption spectra of RhB over Ag/ZnO (BAW) (f) Photocatalytic degradation of Rhodamine B over ZnO (BAW), Ag/ZnO (BAW), and Ag/ZnO (BAW) with 1,4-benzoquinone (BQ) under visible-light irradiation. Prior to irradiation, the suspension was equilibrated in the dark for 30 min. Error bars represent mean $\pm$ SD (n = 3).

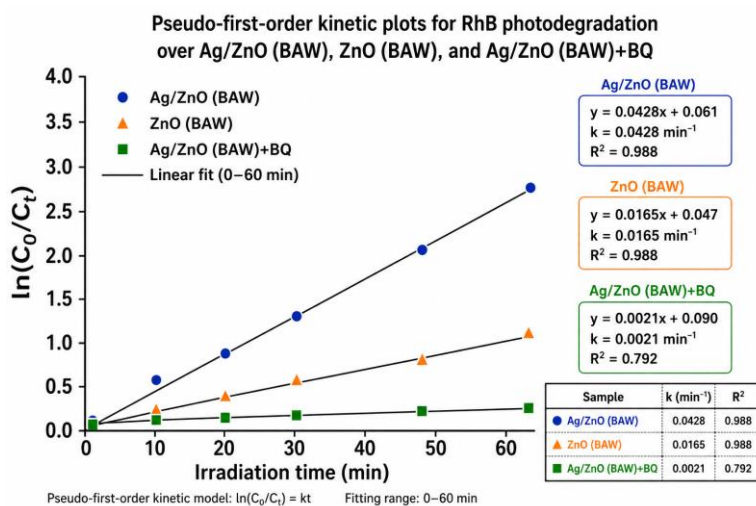


Figure 5 Pseudo-first-order kinetic plots for the photocatalytic degradation of Rhodamine B over ZnO (BAW), Ag/ZnO (BAW), and Ag/ZnO (BAW) in the presence of (BQ) benzoquinone under visible-light irradiation.

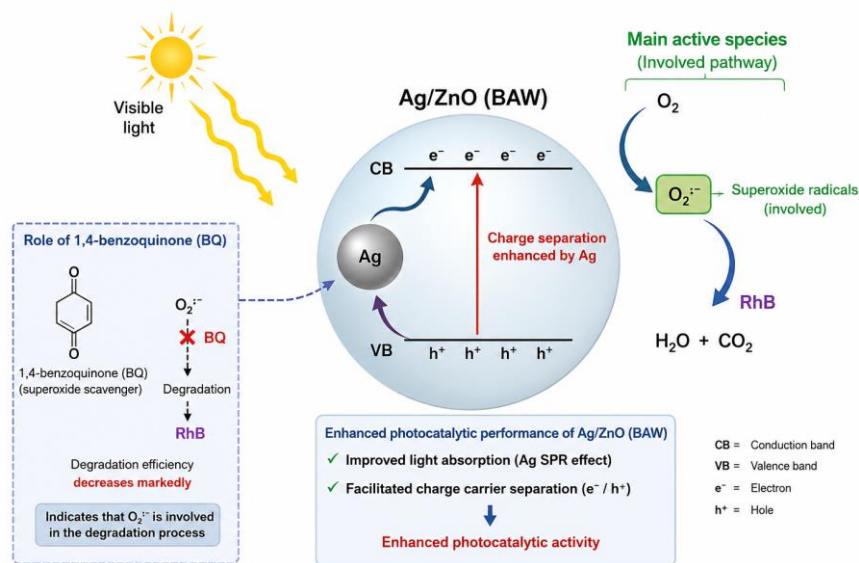


Figure 6 Possible scheme for charge-carrier transfer process in a visible light-irradiated Ag/ZnO (BAW) system

Table 1 Comparison of the photocatalytic performance of Ag/ZnO (BAW) with previously reported ZnO-based photocatalysts

Reference	Photocatalyst	Pollutant	Light Source	Time (min)	Degradation (%)	Band Gap (eV)	Rate Constant, k (min^{-1})
Chai et al. (2019)	Green synthesized ZnO NPs (using <i>Hibiscus rosa-sinensis</i>)	Palm Oil Mill Effluent (POME)	UV Pen-Ray Lamp (254 nm)	240	82% (COD removal)	3.34	Not Specified
Hadi & Jasim (2025)	Ag/ZnO nanocomposites	Brilliant Blue (BB) dye	UV light (UVA LED)	60	99.87% (at 10 mg/L)	~3.37 (for ZnO)	Not Specified
Phongarthit et al. (2020)	AgCl/ZnO (Green approach)	Rhodamine B (RhB), Reactive Orange (RO), Bisphenol A (BPA)	Visible Light (25W Xe lamp, >420 nm)	60	>90% (RhB and BPA)	~3.2	0.07318 (RhB)
Bharathi et al. (2022)	Green synthesized ZnO NPs (using <i>Sechium edule</i>)	Rhodamine B (RhB)	Visible Light (Tungsten halogen)	75	95%	3.08	Not Specified
Trang et al. (2020)	AZO-20 (Ag@ZnO hybrid nanostructure)	Rhodamine B (RhB)	UV and Visible Light	120	97% (UV) / 82% (Visible)	3.07	0.025 (UV) / 0.014 (Visible)
This work	Ag/ZnO (BAW)	Rhodamine B (RhB)	RhB Visible	120	99.69%	3.10	0.0428 (RhB)

As shown in Table 1, the photocatalytic performance of Ag/ZnO (BAW) was compared with previously reported ZnO and Ag/ZnO-based photocatalysts. The present Ag/ZnO (BAW) exhibited a high RhB degradation efficiency of 99.69% within 120 min under visible-light irradiation, with an optical band gap of 3.10 eV and an apparent rate constant of 0.0428 min^{-1} . Although direct comparison among studies should be made with caution because of differences in photocatalyst composition, pollutant type and concentration, catalyst dosage, light source, and experimental conditions, these results demonstrate the competitive photocatalytic performance of Ag/ZnO (BAW) relative to previously reported ZnO-based systems.

Conclusions

This study successfully synthesized Ag/ZnO (BAW) via a coprecipitation method. XRD and EDX analyses confirmed the coexistence of hexagonal wurtzite ZnO (BAW) and metallic Ag, while SEM revealed rod-like and short tubular morphologies. UV-Vis DR and Tauc plot analyses showed enhanced visible-light absorption and a reduced band gap from 3.16 eV for ZnO (BAW) to 3.10 eV for Ag/ZnO (BAW). Ag/ZnO (BAW) achieved 99.69% Rhodamine B degradation within 120 min, compared with 89.51% for ZnO (BAW). The degradation followed pseudo-first-order kinetics, with Ag/ZnO (BAW) exhibiting a rate constant of 0.0428 min^{-1} , approximately 2.6 times higher than ZnO (BAW) (0.0165 min^{-1}). The scavenger experiment using 1,4-benzoquinone (BQ), a well-established scavenger for superoxide radicals, indicated that superoxide radicals ($\text{O}_2^{\cdot-}$) are involved in the photocatalytic degradation of Rhodamine B, as the degradation efficiency decreased markedly after the addition of BQ. The enhanced performance of the Ag/ZnO (BAW) composite is attributed to the presence of silver, which improves light absorption and facilitates charge carrier separation, thereby enhancing photocatalytic activity. Overall, Ag incorporation enhanced light absorption and photocatalytic activity, demonstrating the potential of Ag/ZnO (BAW) for efficient dye degradation.

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Low- H_2 Used Cooking Oil Deoxygenation over a Multifunctional Catalyst: Product-Window Redistribution under H_2 /Formic Acid Assistance

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Abstract

The catalytic conversion of used cooking oil (UCO) to green diesel is not only a conversion problem but also a pathway-control and product-window optimization problem. UCO-derived triglycerides and fatty acids can undergo hydrodeoxygenation (HDO), decarbonylation (DCO), decarboxylation (DCO_2), cracking, and secondary redistribution reactions. In this study, a multifunctional Ni-MgO-Ce_{0.6}Zr_{0.4}O₂/γ-Al₂O₃ catalyst was applied for UCO deoxygenation under four hydrogen-supply modes: Catalyst (C), C+H₂, C+FA (formic acid), and combined C+H₂+FA operation. The reactions were compared at 320°C and 350°C, and the products were analyzed by GC-TCD, GC-FID, and DGC/SimDist. The 320°C condition served as a lower-severity reference, where diesel-range products were generally better preserved, whereas 350°C promoted stronger liquid-phase upgrading, higher distillable-product formation, and more effective residue suppression. At 350°C, the distillable fraction below 370°C increased from 78.3% in the catalyst (C) mode to 98.6% in the C+H₂+FA mode, while residue decreased from 21.7% to 1.4%. However, this improvement was accompanied by product lightening, with the diesel-range fraction decreasing from 42.3% to 22.4% and the naphtha-range fraction increasing from 23.8% to 56.8%. Gas analysis showed CO-rich products in the catalyst (C) mode, supporting a strong DCO tendency even without external H₂, while FA-containing modes increased CO_x formation due to both UCO deoxygenation and possible FA decomposition. In the closed reactor, FA-derived gas formation may also have increased internal pressure and contributed to higher reaction severity and product lightening. Overall, the catalyst shows promise for controlled low- H_2 deoxygenation, but secondary cracking and excessive light-product formation must be controlled.

Keywords : used cooking oil; multifunctional catalyst; deoxygenation; formic acid; low H_2

Introduction

Green diesel is an important renewable hydrocarbon fuel because its properties are closer to petroleum diesel than conventional fatty acid methyl ester biodiesel. It contains negligible oxygen and is mainly composed of paraffinic hydrocarbons, giving improved oxidative stability, higher cetane quality, and good compatibility with existing diesel engines and fuel infrastructure [1-3]. Used cooking oil (UCO) is a promising lipid-based feedstock because it is inexpensive, widely available as a waste resource, and can reduce both environmental burdens and competition with edible oils [4, 5]. Therefore, converting UCO into diesel-range hydrocarbons is a relevant pathway for circular renewable fuel production.

Catalytic deoxygenation of UCO mainly proceeds through hydrodeoxygenation (HDO), decarboxylation (DCO_2), and decarbonylation (DCO) [1, 3, 6]. These pathways differ in hydrogen demand and carbon efficiency. HDO removes oxygen mainly as H_2O and generally preserves the original fatty-acid carbon number, whereas DCO_2 and DCO remove oxygen as CO_2 and CO and usually shorten the hydrocarbon chain by one carbon atom [6, 7]. Although HDO can retain more carbon in the liquid product, it requires substantial external H_2 , commonly under elevated pressure. In contrast, DCO_2 /DCO can reduce direct H_2 consumption but may lower liquid carbon recovery. Thus, low- H_2 green diesel production requires pathway control rather than simple conversion maximization.

The dependence on external H_2 remains a major technical and economic limitation of green diesel production because high-pressure H_2 increases process complexity, equipment cost, and safety requirements [1, 4, 5]. For this reason, recent studies have explored H_2 -lean, H_2 -free, and donor-assisted systems as alternatives to fully hydrogen-rich operation [8-10]. H_2 -free deoxygenation over Ni/MgO- Al_2O_3 has shown that green diesel-like hydrocarbons can be produced from fatty-acid model compounds without direct gaseous H_2 , although pathway selectivity and carbon loss remain key challenges [9, 10]. Other Ni-based H_2 -free systems have also been proposed

for biomass upgrading through in situ hydrogen generation or transfer-hydrogenation-related mechanisms [11].

Nickel-based catalysts are attractive for reduced- H_2 deoxygenation because Ni is cheaper than noble metals and can promote hydrogenation, C–O bond cleavage, and deoxygenation reactions [8, 9, 12]. However, Ni may also promote cracking, methanation, coke formation, or excessive DCO/ DCO_2 [8, 12]. Accordingly, the present catalyst was designed by combining several complementary catalytic functions reported in previous studies. MgO was incorporated to introduce basic sites, which have been enhanced decarboxylation-related activity and moderation of the acidic character of alumina [9, 10]. CeO_2 – ZrO_2 -based oxides were selected because of their redox properties, oxygen-storage/transport capability [15, 16]. γ - Al_2O_3 was used as a high-surface-area structural support to disperse the active phases and provide mechanical stability. By integrating metallic Ni, basic MgO, redox-active $\text{Ce}_{0.6}\text{Zr}_{0.4}\text{O}_2$, and γ - Al_2O_3 within a single catalyst, therefore the Ni–MgO– $\text{Ce}_{0.6}\text{Zr}_{0.4}\text{O}_2$ / γ - Al_2O_3 formulation was selected as a multifunctional system for investigating pathway control under reduced- H_2 UCO deoxygenation.

In addition to Ni/ Al_2O_3 -based systems, bimetallic Ni, Co-based, Ni–W, phosphide, and carbide catalysts have also been investigated for green diesel production. These studies demonstrate that catalyst composition strongly influences deoxygenation activity and the resulting diesel-, kerosene-, and gasoline-range product distribution [5, 12-14, 17, 18].

Hydrogen-donor-assisted operation is another strategy for reducing direct H_2 dependence. Alcohols, glycerol-derived compounds, water-assisted systems, and other hydrogen-transfer media have been investigated as possible sources of in situ hydrogen or hydrogen-transfer species [11]. Formic acid (FA) is an attractive hydrogen donor because it can serve as an in-situ hydrogen source while also generating CO and CO_2 , potentially reducing external H_2 demand and modifying the reaction environment during deoxygenation. However, donor-assisted operation complicates pathway interpretation because

donor decomposition may generate H_2 , CO , CO_2 , or oxygenated intermediates. Therefore, gas-phase CO and CO_2 should not be interpreted only as direct indicators of UCO-derived DCO/DCO₂, but should be considered together with liquid yield, carbon-number distribution, and boiling-range redistribution.

In this study, a multifunctional catalyst was applied for UCO deoxygenation under four hydrogen-supply modes, comparing reactions at 320°C and 350°C.

Materials and Methods

Catalyst Preparation

The experiments were carried out using a multifunctional $Ni-MgO-Ce_{0.6}Zr_{0.4}O_2/\gamma-Al_2O_3$ catalyst. The catalyst was synthesized by a sequential incipient wetness impregnation method. In the preparation sequence, the Ce–Zr oxide phase was first deposited on the $\gamma-Al_2O_3$ support, followed by MgO modification and subsequent Ni loading. Before use in the catalytic reaction, the catalyst was pre-reduced under flowing H_2 at 30 mL min⁻¹. The temperature was increased to 500°C [8] at a heating rate of 2°C min⁻¹ and maintained at this temperature for 2 h.

UCO Collection and Preparation

Used cooking oil (UCO) was employed as the renewable lipid feedstock. The UCO was collected from palm oil used for deep-frying Chinese fried dough sticks over a seven-day period, during which approximately half of the oil was periodically replaced with fresh oil. Prior to catalytic testing, the collected UCO was filtered to remove suspended particles and then heated at 60°C for 30 min to reduce residual moisture. The moisture content of the prepared UCO, determined by a gravimetric method, was 0.058 wt%. For each experiment, 6.0 g of UCO and 0.6 g of catalyst were loaded into a 70 mL cylindrical batch reactor fitted with a gas-tight cover. The catalyst amount corresponded to 10 wt% relative to the UCO feed. The reaction was conducted in an electrically heated reactor system equipped with oscillatory mixing at 1.6 cycles min⁻¹ (Figure 1). All experiments were performed at

320°C and 350°C with a holding time of 1 h after reaching the target temperature.

Experimental Conditions and Run

In this study, four hydrogen-supply modes (as defined in Table 1) were designed to compare the effect of hydrogen management on UCO deoxygenation. The first mode, Catalyst (C), contained neither external H_2 nor formic acid (FA). The C+ H_2 mode, employed the catalyst together with gaseous H_2 . The C+FA mode, employed the catalyst with FA as the hydrogen donor without external H_2 . The C+ H_2 +FA mode, combined the catalyst, external H_2 , and FA. For the C+ H_2 and C+ H_2 +FA modes, the reactor was initially charged with H_2 to 0.9 MPa. In the C+ H_2 mode, the hydrogen input was equivalent to 3 mol H_2 per mol UCO. In the C+FA mode, 2.2 g of FA was added, corresponding to 6 mol FA per mol UCO. In the C+ H_2 +FA mode, the reactor was charged with H_2 at 3 mol H_2 per mol UCO together with 1.1 g of FA, corresponding to 3 mol FA per mol UCO. This experimental design allowed direct comparison among C, C+ H_2 , C+FA, and C+ H_2 +FA modes under the same reaction temperature and residence time.

For each experiment, 6.0 g of UCO and 0.6 g of catalyst were loaded into a 70 mL cylindrical batch reactor fitted with a gas-tight cover. The catalyst amount corresponded to 10 wt% relative to the UCO feed. The reaction was conducted in an electrically heated reactor system equipped with oscillatory mixing at 1.6 cycles min⁻¹ (Figure 1). All experiments were performed at 320°C and 350°C with a holding time of 1 h after reaching the target temperature.

Analytical Techniques

After reaction, the gas and liquid products were separately analyzed. The gas phase was analyzed directly by GC-TCD (Model Agilent technology, GC7820A), with emphasis on H_2 , CO , CO_2 , and other permanent gases. The liquid phase was characterized by GC-FID and simulated distillation (SimDist) (Model Agilent technology, GC7820A). GC-FID was used to evaluate the hydrocarbon carbon-number distribution of the liquid products, while SimDist was applied to determine the boiling-range distribution.

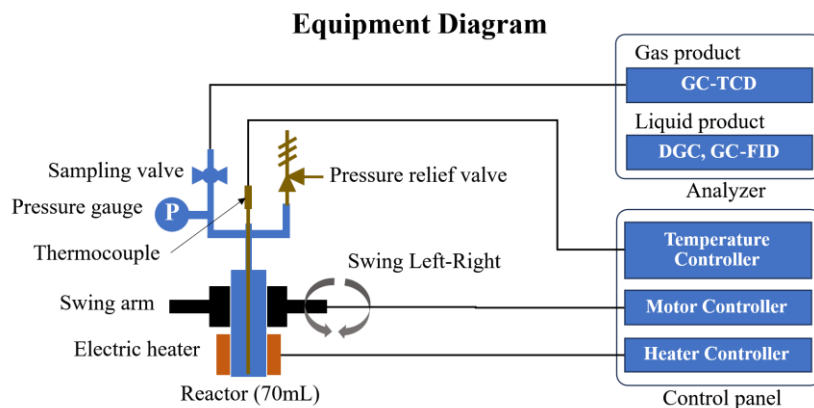


Figure 1 Equipment diagram of oscillatory mixing reactor

Table 1 Reaction conditions under different hydrogen-supply modes

H ₂ Supply Mode	UCO (g)	Catalyst (g)	Temperature (°C)	Holding time (h)	Initial H ₂ pressure (MPa)	H ₂ input/mol UCO	FA added (g)
Catalyst (C)	6.0	0.6	320/350	1	0.0	None	0
C+H ₂	6.0	0.6	320/350	1	0.9	3 mol H ₂	0
C+FA	6.0	0.6	320/350	1	0.0	None	2.2
C+H ₂ +FA	6.0	0.6	320/350	1	0.9	3 mol H ₂	1.1

The amount of gas produced was estimated using an overall mass-balance approach. The reactor and its contents were weighed before and after reaction, and the gas mass was calculated from the difference after considering the recovered liquid and solid fractions. Therefore, the reported gas yield should be interpreted as a mass-balance-based estimate rather than a direct gas-collection measurement. This value was used as a comparative indicator of gas formation among the different hydrogen-supply modes.

Catalytic performance was evaluated from recovered liquid yield, boiling-range distribution, hydrocarbon carbon-number distribution, and gas composition. SimDist classified the liquid products into naphtha (IBP–200°C), kerosene (200–250°C), diesel (250–370°C), and residue (>370°C), while GC-FID and GC-TCD were used for carbon-number distribution and gas-phase composition, respectively. CO and CO₂ were used only as supporting pathway indicators because FA decomposition can also generate these gases.

Results and Discussion

Liquid Yield and Temperature Effect

The effect of reaction temperature was first evaluated by comparing the liquid products obtained at 320°C and 350°C under the four hydrogen-supply modes (

Table 2) Overall, increasing the reaction temperature from 320°C to 350°C improved the extent of liquid-phase upgrading, particularly in terms of distillable product formation and residue suppression. In the C mode, the recovered product yield increased from 38.78% to 53.32%. Similar improvements were observed in the C+H₂ and C+FA modes as display in

Table 2, Although the C+H₂+FA mode showed a slightly lower gravimetric product yield at 350°C than at 320°C, the residue was almost completely suppressed, decreasing from 0.52 g to 0.04 g.

Table 2 Gravimetric recovered liquid yield and fraction weights under different modes

Liquid	H ₂ Supply Mode							
	Catalyst (C)		C+H ₂		C+FA		C+H ₂ +FA	
	320°C	350°C	320°C	350°C	320°C	350°C	320°C	350°C
UCO (g)	6.02	6.08	6.02	6.02	6.02	6.02	6.00	6.09
Product (g)	2.33	3.24	2.87	3.31	2.58	3.21	3.22	3.09
Naphtha (g)	0.54	0.99	0.86	1.33	0.91	1.52	1.40	1.78
Kerosene (g)	0.32	0.51	0.50	0.61	0.56	0.64	0.65	0.61
Diesel (g)	1.47	1.75	1.51	1.38	1.10	1.05	1.16	0.70
Product yield (%)	38.78%	53.32%	47.60%	55.07%	42.78%	53.37%	53.67%	50.68%
Residue (g)	1.16	0.90	1.20	0.58	0.53	0.29	0.52	0.04
Total yield (%)	57.97%	68.09%	67.61%	64.78%	51.66%	58.14%	62.33%	51.40%

The SimDist results in **Table 3** further support the stronger upgrading effect at 350°C. For all reaction modes, the distillable product fraction increased when the temperature was raised from 320°C to 350°C. The product yield calculated from the SimDist boiling-range distribution increased from 66.90% to 78.30% in the C mode, and also the same trend in other modes. Especially in C+H₂+FA mode, increased from 86.10% to 98.60%.

At the same time, the residue fraction decreased markedly at 350°C, suggesting enhanced conversion of heavy oxygenated or partially converted intermediates. Previous studies have shown that increasing temperature promotes further conversion of triglyceride-derived and oxygenated species and, under more severe conditions, secondary cracking toward lighter hydrocarbons [1, 2]. Accordingly, the lower residue accompanied by increased naphtha-range products observed at 350°C suggests that the higher temperature promoted not only deeper conversion but also secondary product lightening.

Liquid Yield and Product Distribution

Based on the gravimetric results in **Table 3** increasing the reaction temperature from 320°C to 350°C generally improved the liquid product yield in the C, C+H₂, and C+FA

modes. This suggests that the higher temperature promoted the conversion of UCO-derived heavy intermediates into liquid-phase products. However, the C+H₂+FA mode did not follow this trend, showing a slightly lower liquid yield at 350°C than at 320°C. This result suggests that the combined C+H₂+FA condition may have increased the reaction severity beyond liquid-product stabilization. In the closed reactor, FA-derived gas formation and the resulting pressure build-up may have further promoted conversion of liquid intermediates into lighter volatile or gaseous products.

At 350°C, the C, C+H₂, and C+FA modes produced comparable liquid product yields of 53.32%, 55.07%, and 53.37%, respectively. Therefore, hydrogen supply did not strongly increase total liquid production under the present conditions. Instead, the main difference among the modes was observed in the distribution of liquid fractions. The C mode retained the largest diesel-range product mass, whereas C+H₂ and C+FA shifted part of the liquid toward lighter fractions. The C+H₂+FA mode showed the strongest naphtha formation and the lowest diesel-range product mass, indicating a more severe redistribution of the liquid product.

Table 3 SimDist-derived boiling-range distribution of liquid products under different H₂-supply modes

Liquid	H ₂ Supply Mode							
	Catalyst (C)		C+H ₂		C+FA		C+H ₂ +FA	
	320°C	350°C	320°C	350°C	320°C	350°C	320°C	350°C
Naphtha	15.40	23.80	21.20	34.10	29.30	43.50	37.50	56.80
Kerosene	9.30	12.20	12.20	15.60	18.00	18.40	17.50	19.40
Diesel	42.20	42.30	37.00	35.30	35.50	29.90	31.10	22.40
Residue	33.10	21.70	29.60	15.00	17.20	8.20	13.90	1.40
Product yield	66.90	78.30	70.40	85.00	82.80	91.80	86.10	98.60

Boiling-range Shift, Residue Reduction

SimDist analysis further clarifies how temperature and hydrogen-supply mode affected the boiling-range distribution of the liquid products. Compared with 320°C, operation at 350°C consistently increased the distillable fraction below 370°C and reduced the residue fraction in all reaction modes. This indicates that the higher temperature promoted the conversion of heavy oxygenated or partially converted compounds into lower-boiling liquid fractions. The effect was most pronounced in the C+H₂+FA mode, where the residue fraction decreased from 13.9% at 320°C to only 1.4% at 350°C.

At 350°C, the C mode retained the highest diesel-range fraction but also showed the largest residue fraction, indicating partial upgrading with limited heavy-fraction conversion. H₂ addition reduced the residue fraction and increased the distillable product fraction, but did not improve diesel-range preservation. FA-containing modes produced a stronger shift toward lower-boiling products. In particular, the C+H₂+FA mode gave the highest distillable fraction of 98.6% and showed the strongest increase in naphtha-range products. This strong light-fraction formation may be partly associated with the higher effective severity created by FA decomposition. In a closed reactor, the formation of H₂, CO₂, and CO can increase the internal pressure and alter the vapor–liquid–solid reaction environment, thereby promoting further conversion of heavy intermediates toward lower-boiling products.

Overall, the SimDist results reveal a clear trade-off between residue suppression and diesel-range preservation. Higher temperature and

FA-assisted operation enhanced heavy-fraction conversion, but this improvement was accompanied by product lightening. Therefore, the key optimization target should not be maximum conversion alone, but controlled redistribution toward the most valuable product window.

Carbon-number Distribution

GC-FID analysis was used to evaluate whether the liquid products retained the carbon-number range expected from UCO-derived fatty acids. The original UCO feed was dominated by C₁₈ and C₁₆ fatty-acid species, mainly oleic acid (C18:1), palmitic acid (C16:0), linoleic acid (C18:2), and stearic acid (C18:0). Therefore, if deoxygenation proceeded mainly through HDO, DCO₂, or DCO with limited secondary cracking, the hydrocarbon products would be expected to remain largely in the C₁₅–C₁₈ range.

However, **Figure 2** shows that the liquid products were distributed over a lighter carbon-number region. At 350°C, the C mode produced hydrocarbons mainly in the C₆–C₁₆ range, while the C+H₂, C+FA, and C+H₂+FA modes showed stronger contributions of lighter hydrocarbons. This indicates that oxygen removal was accompanied by carbon-chain cleavage, especially under H₂- and FA-assisted conditions.

The 320°C results provide a useful comparison for interpreting this trend. At the lower temperature, the shift toward lighter hydrocarbons were less pronounced, suggesting that secondary cracking was less severe. Therefore, the lighter carbon-number distribution observed at 350°C was not only a

result of hydrogen-source selection, but also reflected the higher reaction severity caused by temperature.

Overall, the GC-FID results support the SimDist interpretation that the reaction did not simply preserve C_{16}/C_{18} -derived hydrocarbons in the diesel-relevant C_{15} – C_{18} range, but shifted toward lighter hydrocarbons, especially under FA-assisted operation. Therefore, the substantial formation of hydrocarbons below C_{15} observed in this study cannot be explained by deoxygenation alone and indicates additional C–C bond cleavage or secondary cracking. Similar formation of lighter hydrocarbons at increased reaction severity has been reported for Ni-based deoxygenation systems [1, 12].

Product-window Shift, Diesel Retention

From a product-window perspective (**Figure 3**), the temperature comparison shows a clear trade-off between stronger upgrading and diesel-range preservation. At 320°C, the diesel-range fraction was generally better retained, whereas increasing the temperature to 350°C promoted a stronger shift toward lighter fractions. This indicates that higher reaction severity improved heavy-fraction conversion but reduced the ability to preserve the diesel product window.

At 350°C, the diesel-range fraction decreased progressively from 42.3% in the C mode to 35.3% in C+H₂ mode, 29.9% in C+FA mode, and 22.4% in C+H₂+FA mode. In the same sequence, the naphtha-range fraction

increased from 23.8% to 56.8%. This trend shows that H₂ and FA did not enhance diesel-range preservation under the present conditions. Instead, they redirected the product slate toward lighter hydrocarbon fractions. For the C+FA and C+H₂+FA modes, this product-window shift may not be caused by hydrogen-donor chemistry alone. FA decomposition also generated gaseous products, which increased the internal pressure under the closed batch condition. This pressure build-up may have intensified the reaction environment and contributed to secondary cracking or redistribution toward naphtha-range products.

The moderate increase in kerosene-range products also suggests some movement toward middle-distillate formation. However, the dominant redistribution was toward the naphtha range rather than selective kerosene formation. Therefore, the main limitation of the current operating window was not insufficient conversion of heavy material, but excessive light-product formation and insufficient diesel retention.

Overall, the results indicate that future optimization should focus on moderating reaction severity rather than simply increasing conversion. For diesel-oriented production, lower temperature or reduced donor severity may be beneficial. However, if the target is broadened to include kerosene- and naphtha-range renewable products, the lighter fractions may also be considered as part of the overall product value.

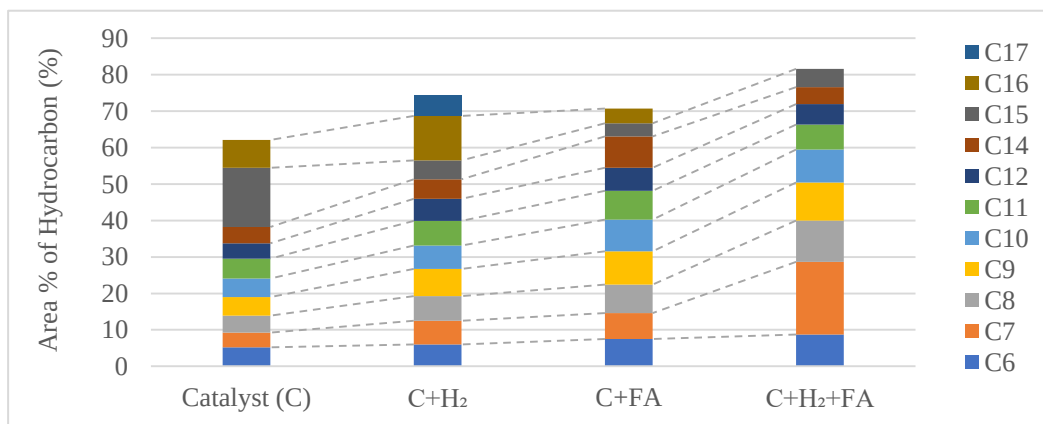


Figure 2 GC-FID-derived hydrocarbon distribution of liquid products at 350°C under different modes

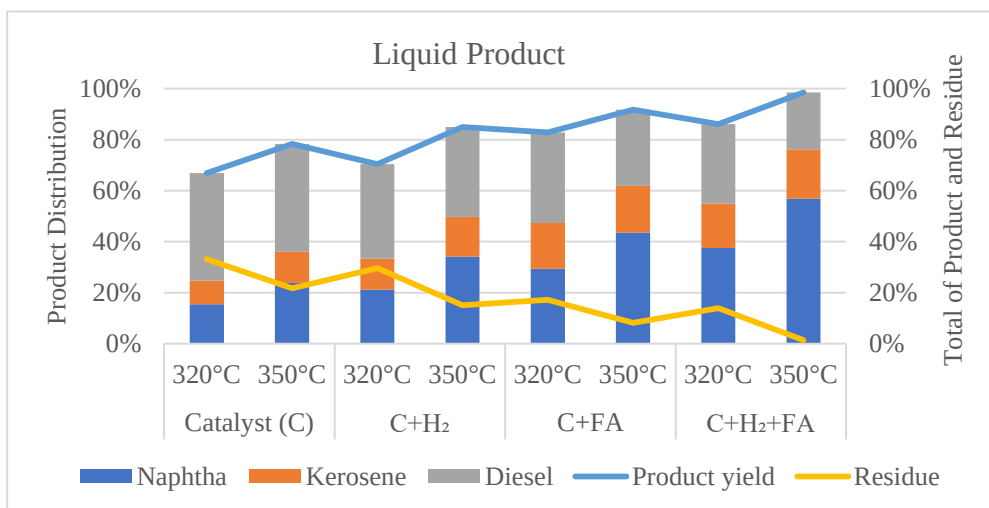


Figure 3 Hydrocarbon distribution of liquid products under different H₂-supply modes

Note: The product name refers from the range of boiling point

Gas-phase and Pathway Interpretation

Gas-phase analysis (**Figure 4**) provides additional evidence for interpreting the liquid-product trends discussed above. Compared with 320°C, the 350°C condition generally produced stronger CO and CO₂ formation, indicating that the higher temperature intensified oxygen-removal and gas-forming reactions.

At 350°C, the C mode produced CO-rich gas even without external H₂ or formic acid. This result suggests that the multifunctional catalyst itself promoted CO-forming deoxygenation pathways, particularly decarbonylation. The low CO₂/CO ratio in this mode further indicates that DCO was more dominant than CO₂-forming decarboxylation under catalyst-only operation.

The occurrence of CO-rich gas under H₂-free conditions is consistent with previous studies showing that Ni/MgO–Al₂O₃-type catalysts can promote non-hydrogenative deoxygenation of fatty acids through DCO/DCO₂ pathways [9, 10]. In the present catalyst, the predominance of CO over CO₂ suggests that the reaction network was more strongly biased toward CO-forming pathways under the C mode condition.

When H₂ was introduced in the C+H₂ mode, CO formation was not fully suppressed. This indicates that the available H₂ under the present condition was insufficient to shift the

reaction network completely toward hydrodeoxygenation. Therefore, DCO remained an important pathway even in the presence of external H₂. This result supports the concept that the present system should be interpreted as controlled low-H₂ deoxygenation rather than HDO-dominant conversion.

For FA-containing modes, both CO and CO₂ increased markedly at 350°C. However, these gases cannot be assigned only to UCO-derived deoxygenation because formic acid can decompose through two competing routes: dehydrogenation to H₂ and CO₂, and dehydration to CO and H₂O. Therefore, CO and CO₂ in the C+FA and C+H₂+FA modes may originate from both UCO conversion and FA decomposition. This makes the CO₂/CO ratio useful as a supporting indicator, but not as a direct quantitative measure of DCO₂/DCO selectivity. In addition to changing the chemical pathway, FA decomposition may also have changed the physical reaction environment. The generation of gaseous products in the closed batch reactor caused pressure build-up, which may have increased the effective reaction severity. This pressure-assisted severity could promote further transformation of heavy oxygenated intermediates and partially converted liquid products, leading to stronger residue suppression but also greater formation of naphtha-range hydrocarbons.

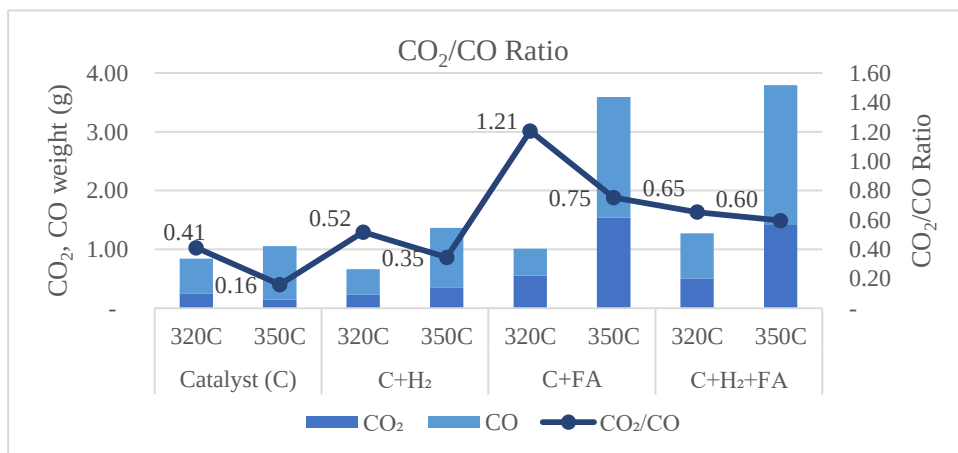


Figure 4 Gas-phase composition determined by GC-TCD, pathway-related indicators.

Note: Total gas yield was estimated separately by overall mass difference

Overall, the gas results are consistent with the liquid-product analysis. The 320°C data represent a lower-severity reference, whereas the 350°C data more clearly show intensified CO_x formation, stronger residue suppression, and greater product lightening. Thus, the gas-phase evidence supports the interpretation that donor-assisted operation promoted deeper conversion not only through chemical donor effects, but also through pressure-related reaction severity and secondary redistribution of the liquid products.

Product-value Implication

In term of product value, it should be interpreted a redistribution of renewable hydrocarbon fractions with different potential downstream applications. Beyond maximizing diesel-range selectivity, the liquid product should be evaluated from an overall product-value perspective. UCO-derived liquid hydrocarbons can potentially be fractionated into diesel-range hydrocarbons for renewable diesel, kerosene-range hydrocarbons as SAF-relevant intermediates or blending-oriented fractions, and naphtha-range hydrocarbons as renewable feedstock for petrochemical or circular plastic applications.

This perspective may become increasingly important in the future as biogenic kerosene- and naphtha-range hydrocarbons gain more relevance in low-carbon fuel and circular carbon markets. Aviation fuel development is

moving toward certified low-carbon and biogenic components under frameworks such as ICAO/CORSIA, while the petrochemical sector is also seeking renewable and circular carbon feedstocks for plastics and chemical production. If properly separated, upgraded, and certified, these fractions may become value-added renewable product streams.

Thus, future optimization should not focus only on maximizing diesel yield, but should also consider product-window allocation. Depending on market demand and downstream upgrading options, the optimal operating condition may be the one that provides the highest overall value from a controlled balance of renewable diesel, SAF-relevant kerosene, and renewable naphtha, rather than the highest diesel fraction alone.

Conclusions

The multifunctional Ni-MgO-Ce_{0.6}Zr_{0.4}O₂/γ-Al₂O₃ catalyst was applied for UCO deoxygenation under different hydrogen-supply modes at 320°C and 350°C. The comparison between the two temperatures showed that 320°C provided a lower-severity reference, where diesel-range products were generally better preserved, while 350°C promoted stronger liquid-phase upgrading, higher distillable-product formation, and more effective residue suppression. Therefore, the temperature effect revealed a clear trade-off

between diesel-range preservation and heavy-fraction conversion.

At 350°C, H₂- and FA-assisted modes increased the distillable liquid fraction and strongly reduced residue. However, this improvement was accompanied by a shift of the product distribution toward lighter naphtha- and kerosene-range fractions. The diesel-range fraction decreased from the C mode to the C+H₂+FA mode, indicating that the current donor-assisted condition increased reaction severity but did not preserve the diesel product window. GC-FID carbon-number distribution further confirmed that the products were not simply retained in the C₁₅–C₁₈ diesel-relevant range, but were shifted toward lighter hydrocarbons.

Gas-phase analysis supported the interpretation of CO- and CO₂-forming pathways. The catalyst mode produced CO-rich gas even without external H₂ or FA, suggesting that the catalyst can promote decarbonylation under low-H₂ conditions. Moreover, FA-derived gas formation may have increased the internal reactor pressure, thereby contributing to higher reaction severity, residue suppression, and product lightening. Therefore, gas-phase indicators should be interpreted together with liquid yield, boiling-range distribution, and carbon-number distribution.

Overall, the results show that DCO/DCO₂ can be useful low-H₂ deoxygenation pathways, but only if secondary cracking and excessive light-product formation are controlled. The optimization target should therefore not be limited to maximum conversion or maximum diesel yield alone. Future process development should consider product-window allocation and overall product value, including renewable diesel-range hydrocarbons, SAF-relevant kerosene-range fractions, and renewable naphtha for circular petrochemical applications.

Further work should focus on reaction control and analytical validation. Key variables include reaction temperature, residence time, catalyst loading, H₂ pressure, FA dosage, and H₂:FA ratio. Additional GC-MS analysis, oxygenate quantification, and improved gas quantification are required to confirm pathway contribution and product stability. A more selective reduced-H₂ window should balance

residue suppression, diesel retention, and the total value of fractionated renewable products.

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- [1] Inthorn, D., Sidtitoon, N., Silapanuntakul, S. and Incharoensakdi, A. 2002. Sorption of mercury, cadmium and lead in aqueous solution by the use of microalgae. *Science Asia*. 28(3): 253-261.

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- [1] Inthorn, D., Singhakarn, C. and Khan, E. Decolorization of reactive dyes by pre-treated Flute reed (phragmites karka (Retz)). At 34th Mid-Atlantic Industrial & Hazardous Conference, Annual Mid Atlantic Industrial and Hazardous Waste Conference at Rutgers University, New Jersey, USA on September 20-21, 2002.

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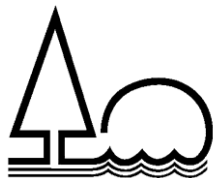
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- [1] Inthorn, D. Heavy metal removal. In: Kojima, H. and Lee, Y.K. *Photosynthetic Microorganisms in Environmental Biotechnology*, Springer-Verlag, 2001; 111-135.

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Estimation of Biomass Carbon Storage and Ecological Values of Urban Forest at Chulalongkorn University and its Implications for Carbon Management <i>Nay Linn Oo, Win Trivitayanurak and Kanokwalee Suteethorn</i>	1-14
Assessment of Pollutant Dispersion in Emergency Scenarios at an Oil Terminal: A Case Study Using the ALOHA Model <i>Ruengwith Artvichai and Pichnaree Lalitaporn</i>	15-33
Anthropogenic CO and NO _x Emission Inventory in Thailand <i>Karnthida Swetarat, Sirapong Sooktawee and Pichnaree Lalitaporn</i>	35-48
A Preliminary Study on the Composition, Quantity, and Management of Solid Waste from Tourism at Kaw Kwang Beach, Koh Lanta District, Krabi Province, Thailand <i>Tidarat Kumlom, Pornphan Chuchuenchit and Nisarin Panwang</i>	49-56
Assessment of Air Quality Index and Potential Health Risks Using Meteorological Parameters in Chonburi Province, Thailand <i>Teeranun Nakyai, Mattana Santasnachok, Nantaporn Phatrabuddha and Pitsanu Pannaracha</i>	57-70
Legal Development Guidelines for Strengthening the Role of Citizens in Household Waste Management in Thailand <i>Uthen Thatsaringkharnsakun</i>	71-81
Green Chemistry Synthesis of Ag/ZnO (ashwater) Using Bark Ash Water and Mango Extract for Enhanced Photocatalytic Degradation of Rhodamine B <i>Kanitta Phongarhit, Rabiab Suwanpetch and Chanun Phongarhit</i>	83-91
Low-H ₂ Used Cooking Oil Deoxygenation over a Multifunctional Catalyst: Product-Window Redistribution under H ₂ /Formic Acid Assistance <i>Tassanai Siripala, Maneerat Khemkhao and Tharapong Vitidsant</i>	93-103