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Life Cycle Assessment of Municipal Solid Waste Management Systems in the ASEAN Region: Strategies toward Environmental Sustainability

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Abstract

Rapid urbanisation and consumption patterns shift in the Association of Southeast Asian Nations (ASEAN) has rapidly increased municipal solid waste (MSW) generation, resulting in environmental challenges such as greenhouse gas emissions, resource depletion and public health risks. This study evaluates the life cycle environmental impacts of MSW management systems in ASEAN, focusing on three areas of protection, including human health, ecosystem damage, and resource depletion, and translates these impacts into monetary units. Additionally, the study investigates mitigation potentials through the integration of circular economy policies. The environmental impacts associated with managing one tonne of MSW in ASEAN countries vary across countries, with impacts on human health varying from 6.60 x 10^{-4} to 19.68 x 10^{-4} DALYs (Disability Adjusted Life Years), on ecosystem quality ranging from 1.87 x 10^{-6} to 3.31 x 10^{-6} species-years, and resource depletion costs between -0.77 and 11.08 USD_{2013}. Total environmental damage costs from managing one tonne of MSW in ASEAN countries range from 199.49 to 434.88 USD_{2023}. The environmental costs of the MSW management sector in ASEAN countries range from 29 million to 24 billion USD_{2023} in 2024 and are projected to increase, ranging from 40 million to 28 billion USD_{2023} in 2030 and from 71 million to 38 billion USD_{2023} in 2050 if current systems remain unchanged. Indonesia faces the highest environmental costs in the region, due to its substantial MSW generation volume. Singapore is the only country that avoids environmental impacts from its MSW management systems, characterised by high recycling rates, significant energy recovery, and minimal landfilling. Circular economy has the potential to reduce the environmental costs by over 60%. Therefore, comprehensive reforms, including stringent landfill regulations and incentivised recycling practices, are essential to decrease reliance on open dumping and achieve sustainable waste management.

Keywords: Life cycle assessment; municipal solid waste management; ASEAN; circular economy; environmental sustainability

Introduction

Rapid urbanisation presents a critical challenge for governments and local municipalities in managing the increase in municipal solid waste (MSW) volumes in the Association of Southeast Asian Nations (ASEAN). As urban populations grow and consumption patterns shift, the volume of MSW generated has significantly increased, resulting in adverse environmental impacts such as pollution, greenhouse gas emissions, and resource depletion. Although ASEAN countries have made efforts to address MSW management, they continue to face barriers related to technology, infrastructure, financing, policy, and stakeholder participation [1]. Current MSW management practices in ASEAN countries, which are primarily reliant on landfilling and open dumping, have demonstrated inadequate capacity to sustainably address the associated environmental challenges [1], including greenhouse gas emissions, resource depletion, and public health risks. In response, the circular economy concept has gained prominence as a transformative approach to MSW management. This model emphasises resource recovery, recycling, and the reintegration of materials back into the production cycle, thus minimising waste and environmental impacts. By adopting circular economy principles, ASEAN countries have the opportunity to mitigate the environmental impacts of their MSW management systems, promote sustainable development, and enhance their resilience against future environmental challenges.

A critical review of life cycle assessment (LCA) studies on solid waste management in Asian countries, conducted by Yadav and Samadder [2], identified landfilling as the predominant disposal method, significantly contributing to greenhouse gas emissions and leachate pollution, whereas recycling and composting demonstrated notable environmental benefits. Menikpura et al. [3] evaluating integrated solid waste management strategies in Thailand using LCA found that a system combining recycling, composting, and landfill gas recovery could reduce greenhouse gas emissions by 40% compared to the baseline scenario. Material recycling provides the most substantial environmental benefits across various impact categories, highlighting the necessity for policies that promote recycling and diversion of organic waste from landfilling and expansion of the capacity of biological treatments and animal feed for improved environmental performance of MSW management systems. Gunamantha and Sarto [4] assessed several MSW management scenarios for a region in Indonesia and concluded that increased recycling and composting could substantially reduce environmental impacts compared to landfill-dominated systems. Although incineration offered environmental benefits through energy recovery, it resulted in higher impacts in certain impact categories compared to other MSW management systems. Consequently, Gunamantha and Sarto [4] recommended implementing policies to promote waste segregation and the development of recycling infrastructure.

Rotthong et al. [5] highlighted that the utilisation of by-products is crucial for reducing the overall environmental impacts of organic waste management systems in Thailand, and that improving energy recovery efficiency in waste-to-energy systems and compost production can further mitigate environmental impacts. Budihardjo et al. [6] suggested that low-income countries in Asia should prioritise waste reduction strategies, including recycling and waste management strategies aligned with their current capacities, to effectively limit landfill MSW and mitigate environmental impacts associated with MSW management. Previous studies have demonstrated that integrated MSW management approaches incorporating recycling, composting, and advanced treatment technologies generally offer greater environmental benefits than landfill-dependent systems. While LCA has been widely applied to evaluate the environmental impacts of MSW management strategies across most individual ASEAN member countries, a significant deficiency remains in region-specific studies.

ASEAN countries, such as the Philippines and Vietnam, have recently recorded notable economic growth rates, leading to increased urbanisation and consumption patterns. Moreover, the projections of MSW generation data from the World Bank Database indicate a substantial increase in future MSW generation rates within the region [7], as detailed in **Table 1**. These trends necessitate the implementation of environmentally sound MSW management strategies to mitigate the associated environmental impacts and support long-term sustainable development in the region. The implementation of such strategies is crucial, particularly considering the income level of the country and the projected rapid increases in future MSW generation rates. A comprehensive LCA study of existing MSW management systems within the ASEAN region is essential to evaluate the environmental impacts of current MSW management systems and to identify potential strategies for their effective mitigation. This study is the first regional LCA of MSW management systems in ASEAN that (1) evaluates the environmental impacts of MSW management systems across the region, (2) translates associated environmental impacts into monetary units, and (3) assesses mitigation potentials through the integration of circular economy practices. The study provides a regional overview of the environmental impacts associated with MSW management systems and the resulting damage costs across ASEAN. Evaluating environmental impacts of the waste sector at the regional level using a consistent LCA framework enhances comparability among countries and highlights the major hotspots in the region. This study presents the comprehensive circular economy scenarios that identify opportunities to improve the environmental sustainability of MSW management systems, fostering more sustainable and environmentally conscious development in the region.

Table 1 Current and projected MSW generation in ASEAN countries (adopted from [7])

Country	Income level	Population in 2024	MSW generated (tonnes/year)		
			2024*	2030	2050
Brunei Darussalam	HIC	462,721	249,231	262,788	307,979
Cambodia	LMC	17,638,801	1,420,963	1,702,523	2,641,058
Indonesia	LMC	283,487,931	78,780,335	87,958,248	118,551,290
Lao People's Democratic Republic	LMC	7,769,819	454,156	522,053	748,378
Malaysia	UMC	35,557,673	16,586,499	18,235,817	23,733,545
Myanmar	LMC	54,500,091	8,748,499	9,315,917	11,207,310
Philippines	LMC	115,843,670	17,268,025	20,039,044	29,275,773
Singapore	HIC	6,036,860	9,073,289	9,284,685	9,989,340
Thailand	UMC	71,668,011	31,027,578	32,484,794	37,342,182
Timor-Leste	LMC	1,400,638	70,222	91,347	161,765
Vietnam	LMC	100,987,686	14,110,296	15,922,186	21,961,818

*Estimated through interpolation based on projections for the years 2030 and 2050.
MSW = municipal solid waste, ASEAN = Association of Southeast Asian Nations, HIC = high-income country, UMC = upper-middle-income country, LMC = lower-middle-income country

Materials and Methods

The environmental impacts of MSW management systems in ASEAN were assessed using the LCA framework, as outlined in the ISO 14040 and 14044 standards [8, 9].

1. Goal and scope of the study

This study aims to quantify the life cycle environmental impacts of MSW management systems in ASEAN for the years 2024, 2030, and 2050. It evaluates the environmental impacts of current MSW management systems across three areas of protection (AoP) including human health, ecosystems, and resources. The study also explores future improvement potentials to mitigate environmental impacts from the waste sector in ASEAN.

The system boundary of this study encompasses all life cycle stages of MSW management within the region, starting with the collection and transport of MSW from households, followed by waste sorting and subsequent management through commonly applied MSW management systems in ASEAN countries, such as composting, incineration, recycling, landfilling, and open dumping, as shown in **Fig. 1.** Informal recycling processes are excluded from this study because their material flows and emissions are challenging to quantify, largely unregulated, and highly variable across different regions [10]. Landfills were classified into three categories: sanitary landfill equipped with landfill gas collection systems and energy recovery, controlled landfill lacking energy recovery, and unspecified landfill which lacks comprehensive or known details regarding management practices. Therefore, the unspecified landfill was considered as the unsanitary landfill based on the Doka LCI calculation tool [11], as detailed in ESM, section S1-8 [12].

The utilisation of by-products generated during the MSW management process was included. In this study, the compost produced from composting of the organic fraction of MSW is regarded as a substitute for production of organic nitrogen, phosphorus, and potassium fertilisers. Energy recovery from the incineration of MSW is also evaluated as a substitute for generation of electricity with the country's energy mix. Similarly, landfill gas collected from sanitary landfills is considered an alternative source for the generation of electricity within the country's energy mix. Additionally, materials recovered from the recyclable fractions of MSW are considered substitutes for production of virgin materials.

The units of assessment employed in this study encompass "one tonne of MSW in wet weight, managed through existing MSW management systems in ASEAN countries in 2024," as well as the "total quantity of MSW managed in ASEAN countries for the years 2024, 2030, and 2050." The assessment of one tonne of MSW is intended to identify the major contributors within MSW systems in the region, while the evaluation of the total quantity of MSW aims to estimate the overall environmental damage costs attributable to the MSW management sector during the specified years. Beyond the evaluation of environmental impacts, the study further investigates potential mitigation strategies by developing scenario-based approaches specific to different MSW management systems.

2. Scenario description

The scenarios considered in this study are presented in **Table 2**. Business-as-usual (BAU) scenarios were developed by considering the composition of MSW and the share of treatment systems in each ASEAN country, along with the current and projected amount of MSW for the years 2024, 2030, and 2050. Improvement scenarios were defined according to the proposed global waste management goals [13] which aim to provide universal access to secure, sufficient, and affordable MSW collection services, while also aiming to reduce food waste at the consumer level. These goals focus on achieving sustainable and environmentally sound MSW management by eliminating uncontrolled dumping, and diverting MSW to improve reuse, recycling, and recovery rates.

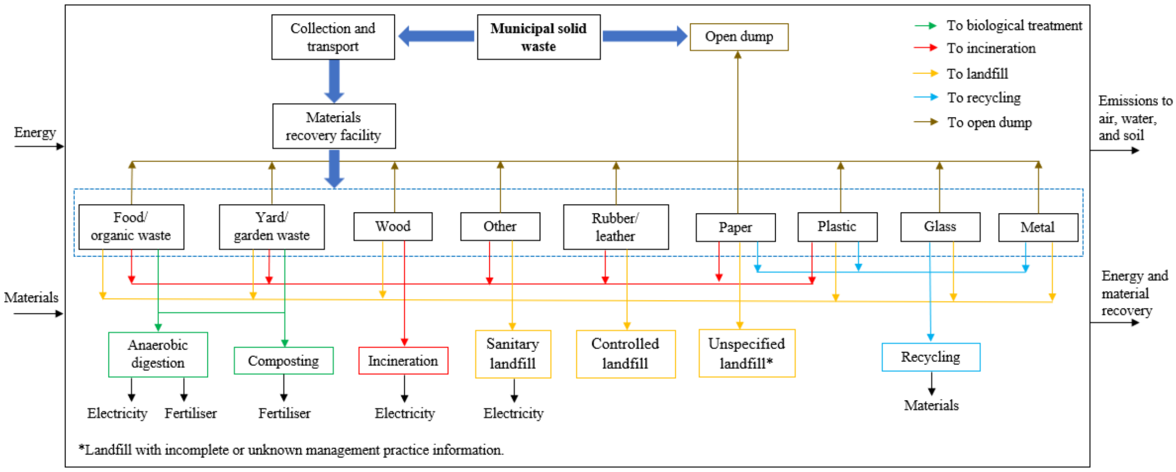

Fig. 1 System boundary of the study

Table 2 Description of scenarios

Scenario	Description
BAU 2024	Scenario reflecting current amount of MSW in 2024.
BAU 2030	Scenario reflecting projected amount of MSW in 2030.
BAU 2050	Scenario reflecting projected amount of MSW in 2050.
S1.1	Waste collection was increased from BAU level to 100%.
S1.2	Waste collection was increased from BAU level to 80%.
S2.1	Food waste was decreased from BAU level to 50%.
S2.2	Food waste was decreased from BAU level to 40%.
S3.1	Recycling was increased from BAU level to 50%.
S3.2	Recycling was increased from BAU level to 40%.
S4.1	Uncontrolled dumping was decreased from BAU level to 0%.
S4.2	Uncontrolled dumping was decreased from BAU level to 30%.
SCES	Waste collection was increased from BAU level to 80%, food waste was decreased from BAU level to 40%, recycling was increased to 40% from BAU level, and uncontrolled dumping was reduced to 30% from BAU level.

BAU = Business-as-usual, SCES = circular economy scenario

The BAU scenarios (BAU 2024, BAU 2030, and BAU 2050) represent the current and projected amounts of MSW generation in ASEAN countries for the years 2024, 2030, and 2050. BAU scenarios assumed that the proportion of MSW managed by different MSW management systems and collection coverage in each country would continue unchanged, with no improvements. In scenarios S1.1 and S1.2, MSW collection coverage was elevated from BAU level to a proposed global MSW management target of 100% [13], whereas an alternative scenario considered an increase to 80%. Countries which achieved 80% collection coverage were evaluated according to their BAU collection coverage. The increased amount of the collected MSW was proportionately diverted into the various BAU MSW management systems.

In scenarios S2.1 and S2.2, the amount of food waste was reduced from BAU level to meet the proposed global waste management target of 50%, as recommended by the United Nations Environment Programme [13], with an alternative scenario considering a reduction of the waste management target to 40%. In the recycling scenario S3.1, recycling rates were increased from BAU levels to reach the proposed global MSW management goal of 50% [13]. As an alternative, scenario S3.2 improved recycling rates from BAU levels to 40%. Countries achieving recycling rates above 50% (S3.1) or 40% (S3.2) were assessed using their existing BAU recycling rates. In the controlled disposal scenarios (S4.1 and S4.2), the quantity of uncontrolled dumping was reduced from BAU level to align with the proposed global MSW management target of 0%, as proposed by the United Nations Environment Programme [13]. An alternative scenario considered a reduction of the waste management target to 30%, followed by proportional allocation to sanitary and controlled landfills. Countries achieving uncontrolled dumping rates lower than 30% were evaluated using their existing BAU levels for uncontrolled dumping.

3. Data collection and inventory analysis

The assessment was conducted using national data on annual MSW generation and composition, as well as shares of MSW management systems from the World Bank database [7], as provided in Electronic Supplementary Material (ESM), section S1-1 [12], and the reflective life cycle inventory (LCI) data for MSW management systems related to the income levels of countries. There is currently no standardised definition of MSW and its composition across ASEAN member states [14]. Notably, countries such as Myanmar, Philippines, and Vietnam incorporate industrial waste, construction and demolition debris, as well as toxic and hazardous waste within their respective definitions of MSW [1]. Due to these inconsistencies, national data on annual MSW generation and composition were sourced from the World Bank database [7]. Specifically, the annual MSW generation data for the year 2024 has been estimated through interpolation, using projections for the years 2030 and 2050.

The LCI for MSW management systems was compiled from our published research [15], Doka inventories of waste treatment [16], and peer-reviewed literature. The relevant technological data for MSW management systems across different income levels were sourced from Oo, Prapaspongsa [15]. Waste-specific and process-specific emissions from incineration, sanitary landfills, controlled landfills, unsanitary landfills, and open dumping of MSW were calculated using the Doka LCI calculation tool [11]. Waste-specific emissions are the emissions that originate directly during the degradation or treatment of MSW, based on the input MSW composition and the application of element-specific transfer coefficients. Process-specific emissions are the emissions that are directly associated with the operations, energy consumption, and material inputs of MSW management systems, independent of the MSW composition. LCIs for anaerobic digestion, composting, and recycling were compiled from our published research [15] and peer-reviewed literature. The inventory data for each MSW management system related to different income levels are provided in ESM, sections S1-3 to S1-10 [12].

The LCI for the collection and transport of MSW, including fuel consumption and emissions, was estimated based on the fuel technology, vehicle weight, and the type of vehicles operated in ASEAN countries, is provided in ESM, section S1-2 [12]. Due to limited data availability across ASEAN countries, this study selected 12-tonne trucks as the representative vehicle type for MSW collection and transport across the region, as the Thai government data catalogue indicated a predominance of small vehicles [17], and this same pattern was also observed in Laos [18] and the Philippines [19]. According to global diesel fuel sulphur levels reported by United Nations Environment Programme [20], Euro 6 (E6) standard was considered for high-income countries (HICs), while Euro 4 (E4) standard was considered for upper-middle-income countries (UMCs) and lower-middle-income countries (LMCs). The emission factors for MSW collection and transport vehicles were derived from the Tier 2 level from the EMEP/EEA Inventory Guidebook 2023 [21] and the life cycle inventories of waste treatment services [22]. For background data, the ecoinvent version 3.10 database was used [23].

4. Life cycle impact assessment

The life cycle environmental impacts of MSW management systems in ASEAN countries were assessed using the SimaPro v9.6.01 [24]. The ReCiPe 2016 v1.1 (Hierarchist) method was applied to quantify the environmental impacts of the MSW management sector at the endpoint level, covering three areas of protection: damage to human health measured in Disability Adjusted Life Years (DALYs), damage to ecosystem diversity quantified in species.yr, and damage to resource availability expressed in USD_{2013} [25].

5. Monetary valuation

The environmental impacts at the endpoint level on human health and ecosystem damage were converted into monetary values to improve their interpretability and support informed decision-making. The budget constraint method was applied to monetise the life cycle environmental impacts based on the concept that the average annual income per capita reflects the maximum amount an individual is willing to pay for an additional year of life [26]. According to Weidema [26], Quality Adjusted Life Years (QALYs) serve as a metric for evaluating impacts on human health and are considered the reverse of Disability Adjusted Life Years (DALYs). The monetary value associated with a DALY was estimated at 74,000 EUR_{2003} with an uncertainty range of 62,000 to 84,000 EUR_{2003} [26]. For ecosystem damage, the value of a Biodiversity Adjusted Hectare Year (BAHY) was calculated relative to the monetary value of a QALY. This estimate was based on a conversion rate of 52 BAHY per QALY, resulting in a monetary value of 1,400 EUR_{2003} with an uncertainty range of 350 to 3,500 EUR_{2003} [26]. The resource scarcity is quantified as USD_{2013} in the ReCiPe 2016 method. The monetary values of human health, ecosystem damage and resource scarcity were calculated with Eq. (1) to estimate the future value of the Monetary Conversion Factors (MCFs) in 2023 for the study as it is the latest year available from the World Bank database [27]. The average inflation rate in European region from 2003 to 2023 is 2.43%, while the average inflation rate in the United States for the period from 2013 to 2023 is 2.52% [27]. MCFs of human health and ecosystem damage in EUR_{2023} are converted into USD_{2023} by using the EUR to USD exchange rate (1 EUR_{2023} ~ USD_{2023} 1.08) (International Monetary Fund, 2025).

$$\boldsymbol{MCF_{(t)} = MCF_{2003} \times (1 + r)^{t-2003}} \quad \text{(Eq.1)}$$

Where, r = average inflation rate from 2003 to 2023
t = considered year of monetary valuation (2023)

The MCFs for human health and ecosystem impacts were found to be 129,314 USD_{2023}/DALY and 59,395,017 USD_{2023}/ species.yr, respectively. The uncertainty associated with the monetary valuation approach was also examined by assessing the uncertainty ranges of DALY and BAHY. Details of MCFs are provided in ESM, section S2 [12].

6. Sensitivity analysis

A sensitivity analysis was performed to evaluate the robustness of the results of the assessment. In accordance with ISO 14040 and ISO 14044 standards, sensitivity analysis is conducted within the framework of LCA to address the uncertainty and inherent variability in the study [8, 9]. Sensitivity analysis was conducted on variations in MSW collection and transport distances, as well as on the future global renewable electricity mix. The minimum and maximum MSW collection and transport distances in East Asia and Pacific region from World Bank report [28] and the projected future global renewable energy mix for the year 2030 and 2050 [29] were applied to evaluate the influences of the changes in inputs on the results of assessment.

Results and Discussion

1. Environmental impacts from the municipal solid waste management sector in ASEAN countries

The life cycle environmental impacts of managing one tonne of MSW in ASEAN countries for the year 2024 were assessed and compared using country-specific MSW management data to identify the major contributors within MSW systems in the region. **Fig. 2** presents the environmental impacts and environmental costs of MSW management in ASEAN countries. The negative values denote the avoided burdens (environmental benefits), whereas positive values represent increasing impacts (environmental damages). The magnitude of the values presents a relative indicator of impact for each category. The net environmental impacts and damage costs per tonne of MSW management in ASEAN countries in 2024 are also provided in **Table 3**.

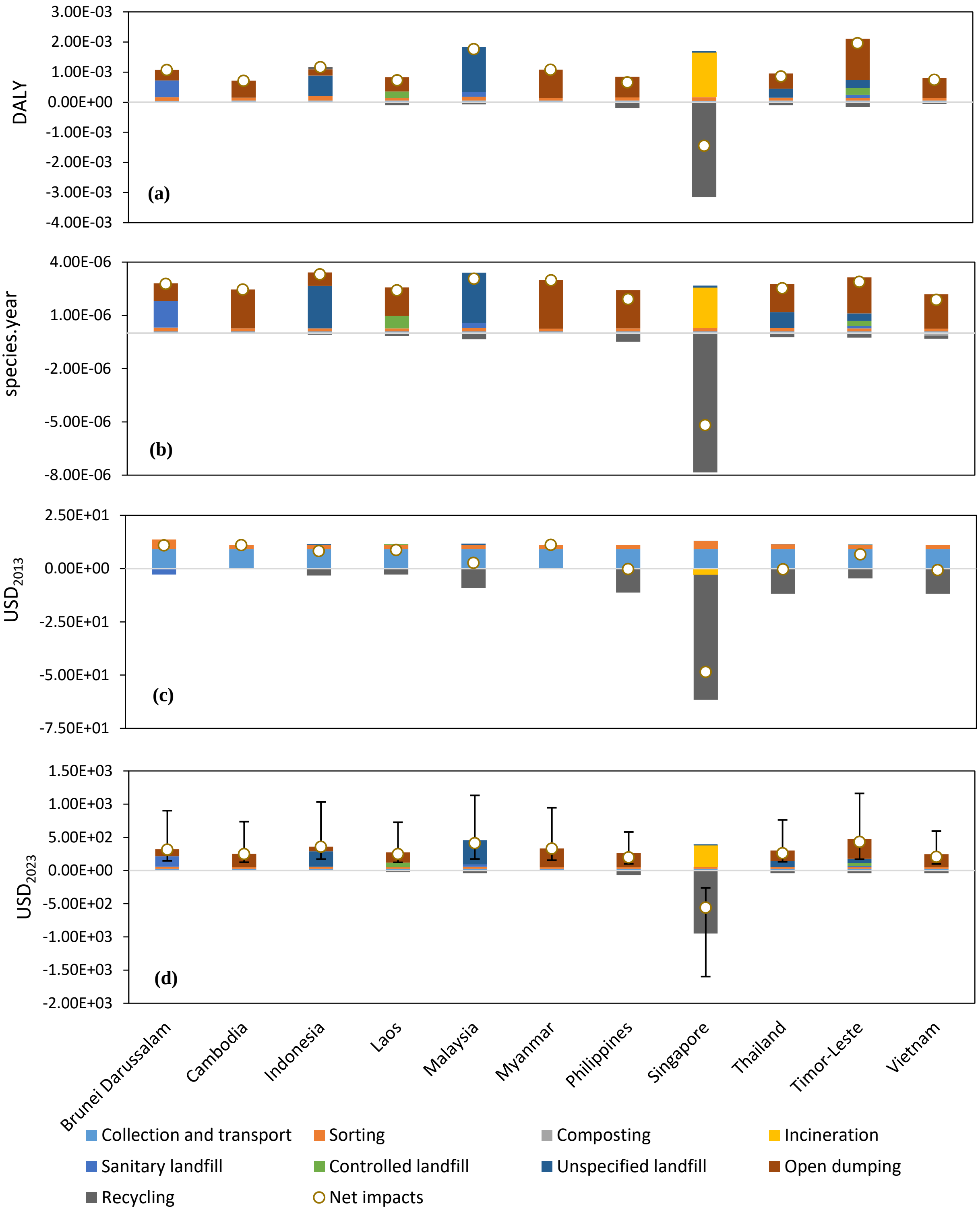

Fig. 2 Environmental impacts of one tonne of MSW management in ASEAN countries in 2024. (a) human health, (b) ecosystem quality, (c) natural resources, and (d) damage costs, the error bars denote the variation attributable to the monetary valuation.

Table 3 Net environmental impacts and damage costs per tonne of MSW management in ASEAN countries in 2024

Country	Human health (DALY)	Ecosystem damage (species.yr)	Resource scarcity (USD_{2013})	Damage costs (USD_{2023})
Brunei Darussalam	1.07E-03	2.78E-06	10.94	317.78
Cambodia	7.13E-04	2.46E-06	10.99	252.36
Indonesia	1.17E-03	3.31E-06	8.28	358.32
Laos	7.29E-04	2.42E-06	8.70	249.23
Malaysia	1.77E-03	3.07E-06	2.67	413.95
Myanmar	1.08E-03	2.98E-06	11.08	331.02
Philippines	6.60E-04	1.93E-06	-0.25	199.49
Singapore	-1.44E-03	-5.18E-06	-48.53	-555.88
Thailand	8.59E-04	2.54E-06	-0.37	261.15
Timor-Leste	1.97E-03	2.89E-06	6.70	434.88
Vietnam	7.47E-04	1.87E-06	-0.77	206.83

The assessment of environmental impacts to human health from managing one tonne of MSW in ASEAN countries ranges from 6.60×10^{-4} to 19.68×10^{-4} DALY, with the exception of Singapore, which exhibits a value of -1.44×10^{-3} DALY. Singapore is the only country that achieves substantial environmental benefits as a result of the significant proportion of MSW managed through recycling. It not only leads the region in recycling rates but also contains the highest metal fraction within its MSW, as detailed in ESM, section S1-1 [12], which contributes to environmental benefits by substituting for virgin metal production. Timor-Leste has the highest damage to human health within the region, followed in a descending order by Malaysia, Indonesia, Myanmar, Brunei Darussalam, Thailand, Vietnam, Laos, Cambodia, Philippines, and Singapore. Open dumping of MSW in ASEAN countries is the most significant contributor to human health impacts. Although higher rates of open dumping are observed in Cambodia, Myanmar, and the Philippines, Timor-Leste registers the highest impact at 1.97×10^{-3} DALY from managing one tonne of MSW. Following Timor-Leste, Malaysia records the second-highest impact in the region, with 1.77×10^{-3} DALY resulting from the unspecified landfilling of MSW. The higher impacts on human health observed in both countries are attributable to the considerable fraction of rubber waste in the MSW, which contributes to increased environmental impacts through the release of heavy metals, particularly zinc. Smolders and Degryse [30] have indicated that zinc emissions from rubber waste pose potential toxic effects on human health and aquatic ecosystems. Wik [31] has also identified zinc from waste tyres as a cause of toxicity to plants and microorganisms, which could lead to bioaccumulation and biomagnification.

The assessment of environmental impacts to ecosystem quality from managing one tonne of MSW in ASEAN countries ranges from 1.87×10^{-6} to 3.31×10^{-6} species.yr with the exception of Singapore, which exhibits a value of -5.18×10^{-6} species.yr. Indonesia has the most significant environmental impacts, followed in a decreasing order by Malaysia, Myanmar, Timor-Leste, Brunei Darussalam, Thailand, Cambodia, Laos, Philippines, Vietnam, and Singapore. The practice of unspecified landfilling within MSW management systems significantly impacts ecosystem quality in Indonesia and Malaysia, which exhibit the highest rates of unspecified landfilling practices in the region. The lack of specificity in landfill management leads to significant ecological degradation, with leachates accounting for approximately 20% of the total impacts and uncontrolled emissions of methane and carbon dioxide constituting over 70% of the total impacts, thereby adversely affecting local ecosystems. Conversely, for other ASEAN countries, with the exception of Singapore, impacts on ecosystem quality predominantly arise from open dumping practices. Open dumping, characterised by the absence of containment measures and limited regulatory oversight, exacerbates the release of pollutants into the environment, which could impact ecosystem quality. The incineration of MSW with energy recovery in Singapore results in considerable environmental impacts on ecosystems within the MSW management system. This is particularly attributable to the emissions resulting from the incineration of the plastic fraction of MSW, which accounts for over 35% of the total impacts, and the rubber fraction of MSW, which contributes approximately 20% of the total impacts. The major contributor to environmental impacts on ecosystems resulting from MSW incineration is carbon dioxide emissions, which account for approximately 50% of the total impacts.

The assessment of environmental impacts to resource scarcity from managing one tonne of MSW in ASEAN countries ranges from -0.77 to 11.08 USD_{2013} with the exception of Singapore, which exhibits a value of -48.53 USD_{2013}. Myanmar experiences the most significant impacts, followed by Cambodia, Brunei Darussalam, Laos, Indonesia, Timor-Leste, Malaysia, Philippines, Thailand, Vietnam, and Singapore, in decreasing order. The significant impacts on resource scarcity observed in the region are associated with the consumption of fossil fuels during the collection and transport of MSW and its sorting. Some ASEAN countries benefit from the byproducts generated from MSW management systems, including recycling, composting, incineration, and sanitary landfilling. For instance, Thailand and Philippines derive higher benefits from recycling within the region, following Singapore. Brunei Darussalam benefits predominantly from energy recovery through sanitary landfilling, supported by the highest sanitary landfill rate in the region. Additionally, Vietnam derives greater benefits from composting, reflecting its highest composting rate within the region. These systems facilitate resource conservation by reclaiming valuable materials and energy, thereby mitigating the impacts associated with resource scarcity. For example, recycling MSW in these countries can decrease the demand for virgin material extraction, while energy recovery from incineration reduces dependence on non-renewable energy sources.

The assessment of environmental impacts in terms of environmental damage costs from managing one tonne of MSW in ASEAN countries varies from 199.49 to 434.88 USD_{2023} with the exception of Singapore, which exhibits a value of -555.88 USD_{2023}. Timor-Leste has the highest environmental management costs per tonne of MSW management in the region, followed in a descending order by Malaysia, Indonesia, Myanmar, Brunei Darussalam, Thailand, Cambodia, Lao, Vietnam, Philippines, and Singapore. Notably, the prevalent practice of open dumping of MSW in Timor-Leste, particularly in cases where rubber waste with elevated levels of heavy metals, such as zinc, constitutes a substantial fraction of MSW, contributes significantly to increased environmental damage costs. This is primarily driven by the adverse impacts on human health resulting from the leaching and dissemination of toxic substances into the surrounding environment. Singapore is the only country in the region that avoids the environmental impacts of the MSW management sector, primarily due to its highest recycling rates in the region and the absence of landfilling of MSW.

2. Future status of environmental impacts from the municipal solid waste management sector in ASEAN countries

The environmental costs of the MSW management sector in ASEAN countries for the year 2024 range from approximately 29 million to 24 billion USD_{2023}, depending on MSW composition, management systems and annual generation rates in each country, apart from Singapore, which avoids the environmental damage costs of about 5 billion USD_{2023}. Without the implementation of improvements or reforms in current MSW management systems, these costs are projected to escalate, ranging from 40 million to 28 billion USD_{2023} in 2030 and from 71 million to 38 billion USD_{2023} in 2050, as shown in **Fig. 3.** Indonesia suffers the highest environmental costs from the MSW management sector among ASEAN countries, despite ranking the third highest in costs per tonne of MSW. This result can be explained by the fact that Indonesia has the highest population among ASEAN countries, as shown in **Table 1**, which primarily drives its substantial MSW generation volume and amplifies the overall environmental impacts despite relatively moderate per-tonne costs. The annual MSW generation in Indonesia accounts for over 40% of the region's total, significantly contributing to its elevated environmental costs.

Timor-Leste has the lowest environmental costs from the MSW management sector among ASEAN countries, despite having the highest environmental costs per tonne of managed MSW within the region. This result is primarily due to its low annual MSW generation rate, as Timor-Leste has the second lowest population among ASEAN countries. MSW generation rate in Timor-Leste is the lowest in the region, accounting for less than 1% of the total MSW generated regionally. Brunei Darussalam has the lowest population in the region; however, its annual MSW generation rate is approximately 3.5 times higher than that of Timor-Leste, as shown in **Table 1**. This highlights the critical importance of MSW reduction strategies to mitigate the environmental damage costs associated with high MSW volumes, despite treatment costs per tonne. Implementing effective MSW reduction strategies is essential for reducing the overall environmental damage costs across the region.

Singapore is the only country in the region that avoids significant environmental impacts from its MSW management sector, primarily due to its high recycling rate, with 61% of collected MSW being recycled and 37% processed through energy recovery via incineration. The landfilling of only 2% of the total collected MSW results in minimal environmental impacts typically associated with landfilling, such as methane emissions and leachate production. This integrated approach allows Singapore to achieve environmental benefits through resource recovery and waste diversion.

3. Mitigation potential of environmental impacts from the municipal solid waste management sector in ASEAN countries in 2030 and 2050

The mitigation potential of total environmental damage costs from MSW management systems in ASEAN countries in 2030 and 2050 were assessed through improvement potentials and a circular economy scenario as shown in **Fig. 4**. The potential reductions in the total percentage of environmental costs associated with MSW management systems are also presented in **Fig. 5**. According to scenarios S1.1 and S1.2, increasing the waste collection rate alone does not inherently lead to a reduction in environmental damage costs, primarily due to the continued prevalence of unsanitary landfilling and open dumping practices within the current MSW management systems of ASEAN countries. These unmanaged disposal methods, along with increased exhaust emissions generated from MSW collection and transport and its sorting, significantly contribute to higher environmental impacts. Such impacts frequently outweigh the environmental benefits associated with merely increasing MSW collection efforts. This underscores the necessity of adopting more comprehensive MSW management strategies that focus not only on collection but also on reducing disposal impacts through proper treatment, resource recovery, and waste minimisation initiatives, in order to achieve environmental sustainability.

The environmental costs associated primarily with MSW collection and transport processes are also influenced by the type of fuel used in each country. High-income countries employing higher-quality fuels, such as Euro 6, can mitigate environmental impacts. In contrast, lower-income countries experience high environmental costs due to the use of lower-quality fuels, such as Euro 4. Therefore, transitioning to better fuel quality through supportive policies and international collaboration is essential for enhancing the environmental sustainability of the MSW collection and transport sector, thereby achieving broader environmental and public health benefits.

In the food waste reduction scenarios S2.1 and S2.2, environmental damage costs in the ASEAN countries could be reduced by up to 23% with a 50% reduction in food waste (S2.1), and by about 18% with a 40% reduction in food waste (S2.2). Environmental costs per tonne of MSW management in ASEAN countries could be reduced by approximately 5% to 21% with S2.1, and by 4% to over 16% with S2.2, depending on the proportion of food waste fraction in the MSW. Cambodia could achieve the highest reduction due to its substantial food waste fraction in the MSW stream in the region. Conversely, Singapore could attain an approximately 1% reduction in environmental costs per tonne of MSW under both the current global waste management target and the alternative scenario, reflecting its low proportion of food waste in the overall MSW composition.

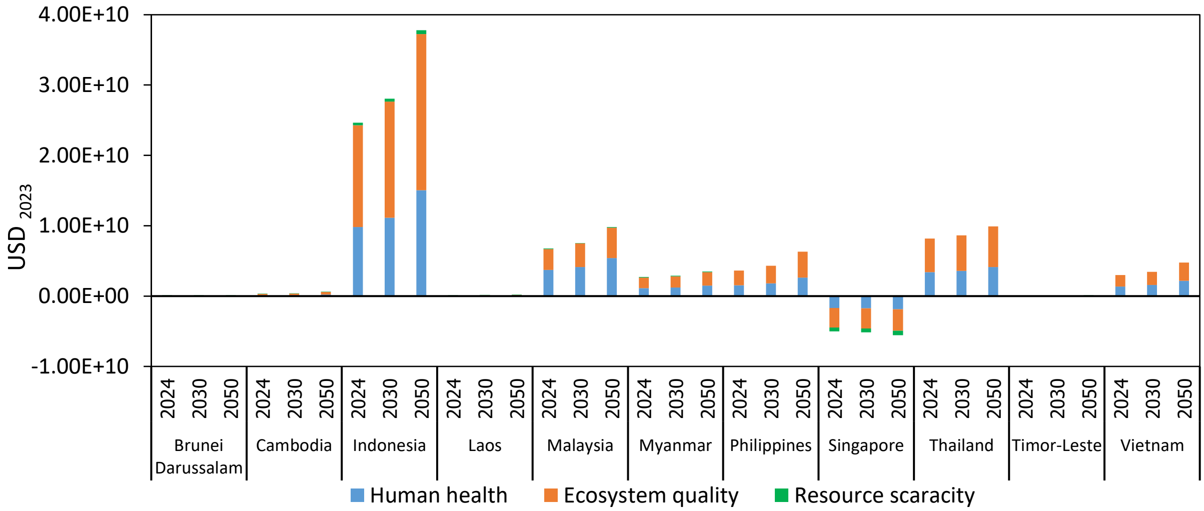

Fig. 3 Projected environmental costs associated with MSW management in ASEAN countries for 2024, 2030 and 2050

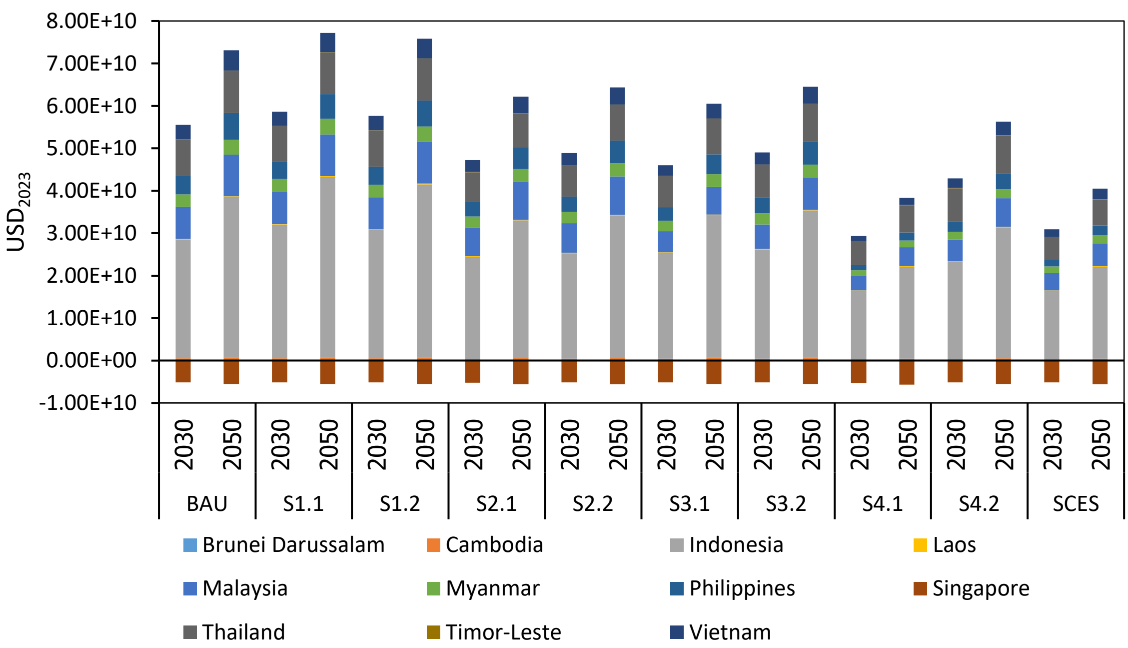

Fig. 4 Improvement potentials of MSW management systems in ASEAN countries in the year 2030 and 2050

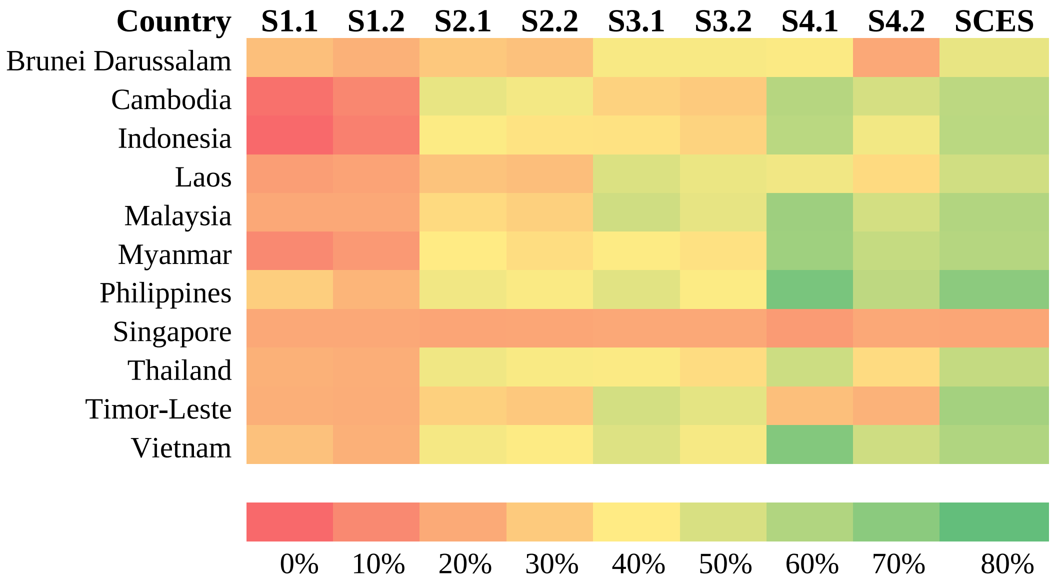

Fig. 5 Potential reductions in the total percentage of environmental costs associated with MSW management systems in ASEAN countries

In the scenarios with increased recycling rates, S3.1 and S3.2, the total environmental damage costs in the ASEAN countries, excluding Singapore, could be reduced by up to 23% and 34% by increasing recycling to 40% (S3.2) and 50% (S3.1), respectively. Singapore could not gain additional environmental benefits under scenarios S3.1 and S3.2, as its existing BAU recycling rate of 61% already exceeds the proposed targets in these scenarios. Environmental costs per tonne of MSW management in ASEAN countries, excluding Singapore, could be reduced by approximately 15% to 77% with S3.1, and from 12% to 60% with S3.2, depending on the initial composition of recyclable materials. Timor-Leste could achieve the highest environmental cost reduction due to the higher percentage of recyclable fractions in its MSW, particularly the metal waste fraction, which is the second highest in the region after Singapore.

In the scenarios of diverting uncontrolled dumping, S4.1 and S4.2, environmental damage costs in the ASEAN countries could be reduced by up to 71% by diverting all uncontrolled dumping of MSW to controlled disposal (S4.1), and by about 41% by redirecting over 30% of uncontrolled dumping from the BAU level to controlled disposal (S4.2). Environmental costs per tonne of MSW management in ASEAN countries, excluding Singapore, could be reduced by approximately 11% to over 82% with S4.1, and by 4% to over 64% with S4.2. Singapore may not gain additional environmental benefits under scenarios S4.1 and S4.2 and Brunei Darussalam under S4.2, as their existing BAU levels of uncontrolled dumping, at 2% and 28% respectively, have already met the proposed targets in these scenarios. The Philippines with the second highest recycling rate in the ASEAN region after Singapore, could achieve the most significant reduction in environmental costs.

In the circular economy scenario (SCES), environmental costs in the ASEAN countries could be reduced by up to 62% by increasing the MSW collection rate from the BAU level to 80%, reducing food waste from the BAU level to 40%, increasing recycling from the BAU level to 40%, and decreasing uncontrolled dumping from the BAU level to 30%. By implementing the circular economy scenario, environmental costs in ASEAN countries, excluding Singapore, for the years 2030 and 2050 can be reduced by approximately 23% to 62%, depending on existing MSW systems. Singapore, having already met all the proposed targets in this scenario, would not experience additional environmental benefits. Singapore, with high recycling rates, minimal landfilling, and a low proportion of food waste in its overall MSW composition, could serve as a role model for other ASEAN countries aiming to mitigate the environmental costs associated with MSW management. However, its replicability in the region is impeded by factors such as weaker regulatory capacity, limited enforcement, financial constraints, and larger land areas. These challenges often result in landfilling or open dumping, leading to diminishing incentives for investments in alternative treatment systems. Timor-Leste, which has the highest environmental costs per tonne of MSW in the region, could achieve over 60% reduction in environmental costs by implementing SCES in its MSW management systems.

4. Sensitivity analysis

The sensitivity analysis examined variations in the minimum and maximum MSW collection and transport distances (SS1.1 and SS1.2) and demonstrated that the environmental costs per tonne of MSW management fluctuate by approximately 4% to 10%, depending on these distances (**Fig. 6, a**). Therefore, optimising the MSW collection and transport distances is important for reducing the overall environmental costs of the waste sector. One potential approach to further enhance the MSW management sector is the electrification of MSW collection and transport, which would not only lead to substantial improvements in operational efficiency, such as reduced fuel consumption and lower operational costs, but also contribute to significant reductions in environmental costs. By effectively managing MSW collection and transport processes, ASEAN countries can achieve more sustainable MSW management practices, minimising environmental impact and fostering environmental responsibility.

When applying future renewable energy mixes for the years 2030 and 2050 (scenarios SS2.1 and SS2.2), it is estimated that the environmental costs per tonne of MSW management could be reduced by approximately 1% to 28% in 2030 and 2% to 30% in 2050, depending on the existing energy mix in each country (**Fig. 6, b**). Countries like Myanmar would experience the smallest reductions in environmental costs with the adoption of future renewable energy mixes, given that its current electricity mix is already significantly composed of hydroelectric power (54%) and natural gas (33%) [23]. Indonesia stands to achieve the highest reductions in environmental costs through the adoption of renewable energy mixes, as its current electricity mix is heavily reliant on lignite-fired power plants at 64% [23]. The transition to a renewable energy mix can lead to a substantial decrease in greenhouse gas emissions and other environmental impacts associated with MSW management. The shift from lignite to renewable sources in Indonesia promises substantial environmental benefits, highlighting the critical role of energy source in national waste management strategies. Such shifts not only address climate change mitigation but also foster cleaner air and more resilient energy systems, aligning with broader sustainability goals across ASEAN countries.

5. Limitations of the study

National data on MSW collection and transport vehicles are sparse across the ASEAN region. Therefore, the limited information available from Thailand, Laos, and the Philippines was applied across the ASEAN region. This approach constitutes a study limitation, as country-specific vehicle data for the region were unavailable for most of the countries in the region. To address this limitation, consistent and representative national vehicle data on MSW collection and transport from all ASEAN countries are required for the analysis.

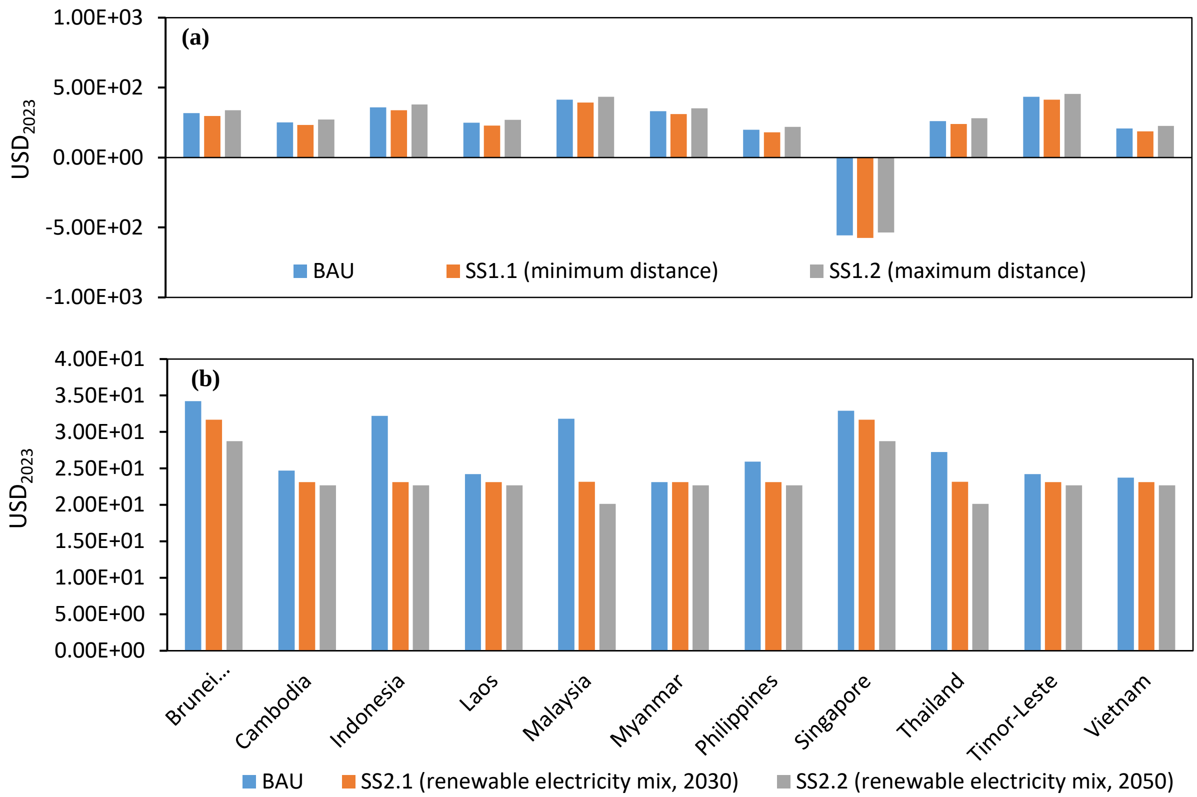

Fig. 6 Environmental costs per tonne of MSW management sector based on the BAU and sensitivity scenarios (a) minimum and maximum waste collection and transport distances, (b) electricity consumption in MSW sorting with BAU and the future global renewable electricity generation mix data in 2030 and 2050.

The monetary valuations of DALY and BAHY were derived from global estimates expressed in euros. These figures were adjusted using the average inflation rate for the European region and subsequently converted to USD. This conversion was performed to present environmental impacts of MSW management systems at the national level across ASEAN. It was implemented because USD is widely used in ASEAN countries, serving as the principal currency for international trade, cross-border financial transactions, and foreign reserve holdings across the region [32]. This approach aims to facilitate the presentation of environmental impacts from the waste sector at the regional level. However, it introduces a limitation to the study, as it may misrepresent region-specific economic conditions in ASEAN countries by relying on European inflation dynamics, which differ from ASEAN inflation trends and exchange-rate volatility. Nonetheless, this study remains comprehensive, incorporating mitigation potential through the integration of circular economy practices to provide a holistic LCA of the MSW management systems across ASEAN and enhancing interpretability and supporting informed decision-making.

6. Policy recommendations

Based on the improvement scenarios, most ASEAN countries require comprehensive MSW management reforms, including the development and enforcement of stringent regulations for landfill diversion and incentivising recycling initiatives to reduce dependency on open dumping. Implementing such measures could mitigate over 60% of environmental costs, enhance ecosystem quality and promote sustainable development within the region. The adoption of environmentally sound MSW strategies that suit to local MSW composition, alongside economic and environmental factors, is crucial.

High-income countries in ASEAN, such as Brunei Darussalam and Singapore, possess greater financial resources for advanced MSW treatment and the capacity to implement gradual landfill taxes to encourage landfill diversion. We recommend establishing suitable infrastructure and legislation, including investment in advanced MSW management systems, landfill diversion targets, and integrated landfill taxes and bans, which have been effective in reducing landfill rates in the European Union [33]. Other ASEAN countries face budget constraints, limited technical capacity for advanced MSW treatment, and prevalent open dumping with weak enforcement. Uncontrolled open dumping of MSW, particularly with a high fraction of food waste, poses significant environmental and health risks. Therefore, prioritising investments in transitioning from open dumps to sanitary or controlled landfills is essential. A step-by-step approach can achieve progressive improvements, transitioning from open dumps to controlled landfills and, ultimately, sanitary landfills. Landfill mining is an alternative strategy that may be implemented once the waste within a landfill achieves physical, chemical, and biological stability. This approach has the potential to extend the operational lifespan of landfills and aligns with sustainable development goals. Landfill mining contributes to environmental benefits by enabling the recovery of valuable materials and reducing greenhouse gas emissions from landfills [34].

The recycling scenarios (S3.1 and S3.2) provide environmental benefits by substituting virgin material production. Therefore, ASEAN countries should establish national recycling targets to improve recycling rates. The ambitious targets have been shown to enhance recycling performance significantly, while additional standards for recycled materials are critical for maintaining quality, safety, and supply chain confidence within the European Union. High-income ASEAN countries possess the capacity to design, implement, and enforce economic policies such as deposit-return schemes and extended producer responsibility (EPR) regulations and to coordinate regionally. We recommend mandating EPR for key packaging sectors, ensuring robust monitoring, and harmonising standards across the region to enhance effectiveness and efficiency. Conversely, other ASEAN countries face limited industry structures, weak enforcement, and insufficient recycling infrastructure. Therefore, a phased approach involving voluntary EPR, data collection, and pilot collection schemes for materials such as plastics and beverage containers integrated with industry is recommended. This foundation can be progressively expanded toward mandatory EPR systems, supported by regional cooperation and donor funding. International aid and cooperation can support infrastructure development and capacity building in the region. Partnerships with international organisations, such as the Asian Development Bank and the World Bank, and engagements with high-income countries as co-investors and donors can mobilise investments and grants to support regional research and pilot projects.

The organic fraction, primarily composed of food waste, constitutes a significant portion of MSW in the region. This organic waste can be either composted or processed via anaerobic digestion to produce biogas. Despite the region's favourable climate for such biological treatments, these methods are not extensively implemented in most ASEAN countries. This limited application is mainly due to inadequate source separation and the contamination of MSW with hazardous waste, which impede efficient biological processing. To address these challenges, the introduction of source separation practices is required, accompanied by educational campaigns aimed at raising public awareness across diverse demographic groups. Furthermore, authorities should consider implementing market incentives and penalties, along with the appropriate allocation of financial resources, to enhance the effectiveness and sustainability of MSW management sector. Policies for MSW management in the region should include direct subsidies or tax incentives for commercial composting and anaerobic digestion and should promote compost utilisation in the agricultural sector. Household and community composting should be incentivised via small grants, technical assistance, and market development. Decentralised pilot facilities in densely populated urban areas, funded by donors or public-private partnerships, can enhance the efficiency and sustainability of MSW management systems. These measures are crucial for optimising the potential benefits of organic waste treatment and promoting environmentally sustainable MSW management systems within the region.

Conclusions

This study aims to quantify the life cycle environmental impacts of MSW management systems in ASEAN countries for the years 2024, 2030, and 2050, and explores mitigation potentials through the integration of circular economy practices. Environmental damage costs from managing one tonne of MSW in ASEAN countries, excluding Singapore, range from 199.49 to 434.88 USD_{2023}, with Timor-Leste incurring the highest management costs in the region. Singapore has the lowest environmental costs from managing one tonne of MSW among ASEAN countries, with total environmental damage costs of -555.88 USD_{2023}. The integrated approach with high recycling rates, significant energy recovery, and minimal landfilling allows Singapore to achieve environmental benefits through resource recovery and waste diversion. The estimated environmental damage costs from the MSW management sector in ASEAN countries range from 29 million to 24 billion USD_{2023} in 2024. If no improvements are made to existing systems, these costs are projected to increase, ranging from 40 million to 28 billion USD_{2023} in 2030 and from 71 million to 38 billion USD_{2023} in 2050. Indonesia incurs the highest overall environmental costs in the region, primarily due to its large MSW generation volume, which significantly amplifies total impacts despite moderate per-tonne costs.

According to the improvement scenarios, increasing MSW collection rates alone does not reduce environmental damage costs in ASEAN countries due to ongoing open dumping and landfilling. Food waste reduction scenarios could potentially decrease the environmental damage costs in ASEAN countries by approximately 18% to 23%, depending on the proportion of food waste fraction in the MSW. Increasing recycling scenarios could decrease environmental costs in ASEAN countries by approximately 23% to 34%, with Timor-Leste achieving the greatest benefits due to its high recyclable waste fractions. Diverting uncontrolled dumping scenarios could reduce the environmental costs in ASEAN countries by up to 41% to 71%, with the Philippines achieving notable reductions due to its high recycling rates. The circular economy scenario could reduce the environmental costs in ASEAN countries by approximately 62%.

Sensitivity analysis showed that optimising MSW collection and transport distances can reduce environmental costs by 4% to 10%. Therefore, reducing MSW collection and transport distances could enhance efficiency and environmental sustainability in the MSW management sector of ASEAN countries. Applying future renewable energy mixes could reduce environmental costs of MSW by 1% to 28% in 2030 and 2% to 30% in 2050. Transitioning to renewables addresses climate mitigation and promotes cleaner energy systems, vital for sustainable MSW management in ASEAN countries.

ASEAN countries need comprehensive reforms, including the implementation of stringent landfill regulations and the promotion of incentivised recycling practices, to reduce reliance on open dumping and potentially achieve over a 60% reduction in environmental costs. Transitioning from open dumping to controlled and sanitary landfills is essential to reduce health and environmental risks. Landfill mining offers a sustainable alternative, prolonging landfill lifespan, recovering valuable materials, and reducing greenhouse gas emissions. Although food waste constitutes a major component of MSW in the ASEAN region, its composting and anaerobic digestion are underutilised due to poor source separation and contamination with hazardous waste. Introducing source separation, public awareness campaigns, and market-based incentives, alongside adequate funding, are essential for improving organic waste management and advancing sustainable MSW management practices in the region. The findings of this study offer valuable insights for stakeholders, governments, and policymakers by providing detailed information on the environmental impacts and associated costs of MSW management systems in the ASEAN region, which facilitates the development of evidence-based policies.

Acknowledgments

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Logistics Efficiency Improvement and Waste Reduction using the Appropriate Forecasting Techniques Analysis for Hospital Pharmaceutical Demand Forecasting Error Reduction

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Abstract

Effective waste management is guided by the 7R framework (Refuse, Reduce, Reuse, Repair, Repurpose, Recycle, and Recover). This study emphasizes the first two most important principles (Refuse and Reduce) by improving pharmaceutical demand forecasting to reduce waste and enhance logistics efficiency. The objective of this research was to analyze the appropriate forecasting techniques for the case study hospital important pharmaceutical demand forecasting error reduction. Using ABC analysis, 219 products were classified, with Group A items (70.95% of total inventory value) selected for analysis. These were further categorized into cyclical/seasonal demand (31 SKUs) and demand without seasonality (188 SKUs). Randomized Complete Block Design (RCBD) was applied in the Design of Experiments (DOE) using the Analysis of Variance (ANOVA) and multiple comparisons test for the appropriate forecasting techniques analysis in order to reduce the important pharmaceutical demand forecasting error. The forecasting technique was the main factor and Mean Absolute Deviation (MAD) served as the response variable. According to the class A cyclical/seasonal demand pharmaceutical products, the most appropriate forecasting technique was the 12-month seasonal length Winters' method. The average of MAD obtained by the yearly seasonal length Winters' method decreased by 7.04 units per month comparing to the 3-month moving average which was the current forecasting method because of the seasonality of pharmaceutical demand. For the class A drugs without seasonality, the most appropriate forecasting technique was single exponential smoothing. The MAD of single exponential smoothing decreased by 38.47 units per month comparing to the 3-month moving average which was the as-is forecasting method of the case study hospital. It can be concluded that Winters' method with 12-month seasonal length was suitable for cyclical/seasonal demand drugs, reducing MAD by 11% compared to the traditional 3-month moving average. For pharmaceutical demand without seasonality, single exponential smoothing was the most appropriate forecasting method, reducing MAD by 17.5%. The findings demonstrated that selecting appropriate forecasting methods could significantly improve logistics efficiency, reduce pharmaceutical waste, and enhance hospital supply chain performance.

Keywords : Logistics Efficiency; Demand Forecasting; Pharmaceuticals; Forecasting Techniques

Introduction

Effective waste management involves the practice of 7R (Refuse-Reduce-Reuse-Repair-Repurpose-Recycle-Recover). Amongst these 7Rs, the first two important principles (Refuse and Reduce), relate to the non-creation of waste by refusing unsustainable products, avoiding excess of production over consumption, and reduce nonconforming products and production wastes in the manufacturing process [1]. The next two (Reuse and Repair) refer to increasing the usage of the existing product. There are numerous products commonly perceived as single use, can be reused multiple times. Repairing nonconforming products and fixing broken items can reduce waste generation. Repurpose and Recycle involve maximum usage of the materials used in the product, and Recover involves the recovery of embedded energy in the waste material [2]. Refuse and Reduce are the most critical because they directly address overproduction and unnecessary resource consumption, which are key drivers of inefficiency in logistics and supply chain operations. Efficient logistics management plays a vital role in reducing costs, eliminating waste, improving service quality, and ensuring the sustainable use of resources.

In the healthcare sector, pharmaceutical logistics presents a particular challenge. Hospitals must balance the need for reliable pharmaceutical availability with the risk of overstocking and wastes. Excessive pharmaceutical demand forecasting leads to surplus inventory, higher inventory carrying cost, and drug expiration, whereas underestimation results in shortages and treatment delays. These inefficiencies not only increase costs but also have significant effects on patient safety and healthcare quality [3].

Accurate pharmaceutical demand forecasting is therefore essential for hospital logistics efficiency improvement [4]. However, the as-is forecasting method of the case study hospital, which is the 3-month moving average, often fails to account for the cyclical and seasonal patterns in pharmaceutical demand. Recent studies highlight the importance of applying more advanced forecasting techniques to minimize forecasting errors and improve inventory management in healthcare supply chain [5, 6]. Despite these insights, limited research has examined the comparative effectiveness of different forecasting methods in reducing pharmaceutical demand forecasting errors for the important hospital drugs in Thailand.

To address this gap, this research investigated forecasting techniques for high-value hospital pharmaceutical products classified as Group A using the ABC analysis. Specifically, the objectives of the research were: (1) to analyze the effects of forecasting techniques on pharmaceutical demand forecasting errors, and (2) to identify the most appropriate forecasting method for reducing demand forecasting errors in essential (Group A) drugs. By focusing on error reduction, this study aimed to improve logistics efficiency, minimize pharmaceutical wastes, and strengthen hospital supply chain performance.

Methodology

The design of experiments was applied in this research for planning and conducting experiments, as well as for analyzing and interpreting the resulting data [7]. DOE is used in scientific research to study systems, processes, or products by analyzing independent variables (Xs) and their effects on measurable response variables (Y) [8]. DOE is a powerful statistical tool widely used across various industries [9], not only in engineering and product/ process development [10] but also in fields as follows: management, marketing, healthcare, tourism, food [11], pharmaceuticals, energy [12], and architecture [13].

This study applied the Design of Experiments (DOE) framework to plan, conduct, and analyze the research. A Randomized Complete Block Design (RCBD) was employed to minimize variability among pharmaceutical products, while Analysis of Variance (ANOVA) was used to evaluate the effects of forecasting techniques on demand forecasting error, measured by Mean Absolute Deviation (MAD). Then the main effects plot and multiple comparisons test were conducted to determine the most appropriate forecasting method for the MAD reduction.

1. Population and Sample

The ABC analysis was performed to classify pharmaceutical products into three inventory categories:

Group A: Top 70% of inventory value
Group B: Next 20%
Group C: Remaining 10%

Stock keeping units or SKUs for short are item codes of pharmaceutical products. This study focused on Group A pharmaceutical products, comprising 219 SKUs (12% of all hospital drug SKUs), which represented 70.95% of the total inventory value (THB4,433,258,336).

These were further divided into two subgroups based on demand patterns:

(1) Cyclical or seasonal demand (31 SKUs): for example, Molnupiravir and Favipiravir used in COVID-19 treatment, Oseltamivir (Tamiflu) for influenza, and Clotrimazole for fungal infections, which show seasonal variations, especially during the rainy season.

(2) Demand without seasonality (188 SKUs): for example, Atorvastatin (Xarator), a cholesterol lowering drug with consistently high demand throughout the year.

The classification of Group A pharmaceutical products by demand characteristics is illustrated in **Figure 1**.

The time series analysis forecasting techniques were evaluated as the independent variable [14]:

(1) 3-month moving average
(2) single exponential smoothing
(3) double exponential smoothing
(4) 9-month seasonal length Winters' Method
(5) yearly seasonal length Winters' Method

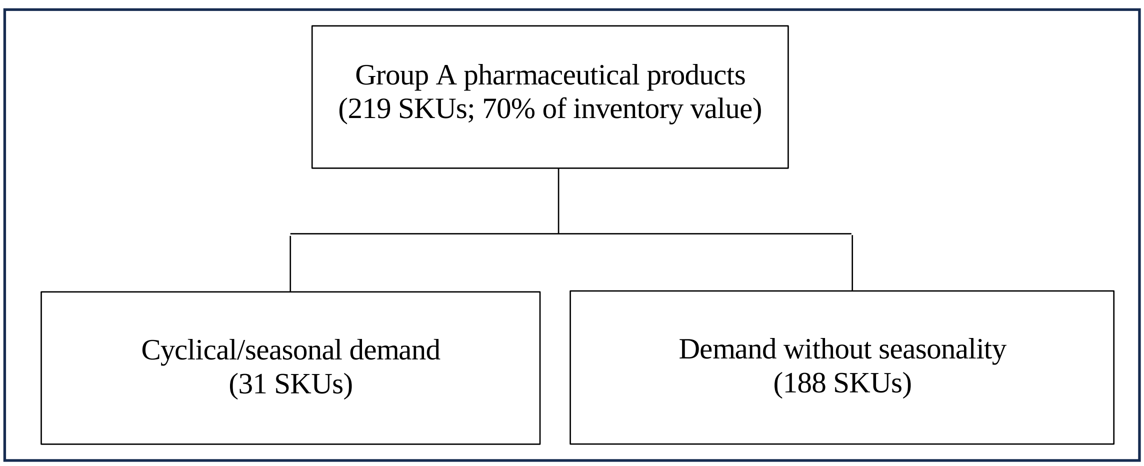

Figure 1 Classification of Group A pharmaceutical products by demand characteristics

In the additive Winters' method, the seasonal variations are assumed to be constant in magnitude, regardless of the level of the series. That is, the effect of seasonality is added to the base level and trend. The seasonal variations are assumed to be proportional to the level of the series in the multiplicative Winters' method. The seasonal effect is multiplied by the base level and trend [14]. Since (1) the pharmaceutical seasonal pattern was proportional to series level (not constant magnitude), (2) pharmaceutical demand seasonality grew or shrank with trend, and (3) the pharmaceutical demand variance was not constant and increased with level, the multiplicative Winters' method was applied in the pharmaceutical demand forecasting of the case study hospital.

The 9-month seasonal length Winters' Method was selected based on the observed demand pattern pharmaceutical products such as drugs used in the treatment of RSV infection. Respiratory Syncytial Virus (RSV) season typically lasts around 6-9 months. The yearly seasonal length Winters' Method was also selected based on the observed demand pattern pharmaceutical products. For example, the seasonality of drugs used in the treatment of seasonal influenza (Oseltamivir) was 12 months, generally with a peak during the rainy season. The response variable was the Mean Absolute Deviation (MAD), chosen for its reliability and interpretability in measuring pharmaceutical demand forecasting error.

2. Experimental Design

Time Series Analysis demand forecasting techniques was used in the experiment to determine the appropriate forecasting techniques [15]. The Analysis of Variance (ANOVA) was applied to experiment the five forecasting techniques (5 levels) effects and the blocking factor, which was the pharmaceutical products as follows: (1) pharmaceutical products with cyclical or seasonal demand (31 SKUs) and (2) drugs without cyclical or seasonal demand (188 SKUs). To control drug SKUs heterogeneity, a Randomized Complete Block Design (RCBD) was implemented, with the blocking factor defined as pharmaceutical product SKUs.

Analysis of Variance was applied to test for significant differences among forecasting methods, and the multiple comparisons test was conducted to identify the forecasting method that minimized the Mean Absolute Deviation (MAD), which served as the response variable. The smaller the MAD, the more desirable the forecasting method. Therefore, the pharmaceutical logistics efficiency was increased.

3. Data Collection

Monthly demand for Group A drugs were collected from hospital records covering a 60-month period (January 2020 – December 2024). The data were separated into the two demand categories identified earlier (seasonal demand vs. demand without seasonality).

4. Data Analysis

ANOVA was applied to test the effects of forecasting methods on demand forecasting error (MAD). Multiple comparisons tests were then conducted to determine which forecasting method produced significantly lower error. For benchmarking purposes, the hospital's existing forecasting method, the 3-month moving average, was included as a reference.

5. Validity and Reliability

Model adequacy checking was performed to confirm the appropriateness of applying ANOVA [16]. The assessment focused on three key assumptions: normality, equality of variance, and independence of residuals.

- Normality assumption: The distribution of the residuals was examined to ensure it followed a normal distribution, which was assessed using a normal probability plot.
- Equality of variance: Homogeneity of variances across groups was tested to confirm that error variances were consistent.
- Independence assumption: Residuals were examined to verify that residuals were independent.

Results and Discussion

1. Seasonal or cyclical demand drugs (31 SKUs)

From the analysis of variance (ANOVA) with Mean Absolute Deviation (MAD) as a response variable in **Table 1**, it was found that forecasting techniques had a significant effect on the MAD since the P-Value was less than the significance level of 0.05.

Table 1 ANOVA table for seasonal or cyclical demand drugs (31 SKUs)

General Linear Model: MAD versus Forecasting Method, Pharmacy

Analysis of Variance for MAD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Forecasting Method	4	1803	1803	451	17.03	0.000
Pharmacy	30	371954	371954	12398	468.69	0.000
Error	120	3174	3174	26		
Total	154	376931				

S = 5.14329 R-Sq = 99.16% R-Sq(adj) = 98.92%

According to the Randomized Complete Block Design (RCBD), the pharmaceutical products SKUs variable was a blocking factor [17]. It was not a factor to be analyzed in this research.

Multiple comparisons test was conducted as displayed in **Figure 2**. As shown in Figures 3, the main effects plot [18] for MAD was used to analyze and determine the most appropriate forecasting technique for pharmaceutical demand forecasting error reduction. According to the multiple comparison test, the adjusted P-Value of pairwise comparisons was less than 0.05, which was the significance level, as shown in the red rectangles in **Figure 2**. Therefore, it was concluded that the average of MAD obtained by the yearly seasonal length Winters' method was significantly smaller than the average of MAD obtained by (1) the 3-month moving average, (2) double exponential smoothing and (3) the 9-month seasonal length Winters' method.

Bonferroni Simultaneous Tests
Response Variable MAD
All Pairwise Comparisons among Levels of Forecasting Method
Forecasting Method = Double Exponential Smoothing subtracted from:

Forecasting Method	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Moving Average (MAL= 3)	−2.164	1.306	−1.657	1.0000
Single Exponential Smoothing	−7.461	1.306	−5.711	0.0000
Winters' Method (SL = 12)	−9.211	1.306	−7.051	0.0000
Winters' Method (SL = 9)	−3.274	1.306	−2.506	0.1354

Forecasting Method = Moving Average (MAL= 3) subtracted from:

Forecasting Method	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Single Exponential Smoothing	−5.297	1.306	−4.055	0.0009
Winters' Method (SL = 12)	−7.047	1.306	−5.394	0.0000
Winters' Method (SL = 9)	−1.110	1.306	−0.850	1.0000

Forecasting Method = Single Exponential Smoothing subtracted from:

Forecasting Method	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Winters' Method (SL = 12)	−1.750	1.306	−1.340	1.0000
Winters' Method (SL = 9)	4.187	1.306	3.205	0.0173

Forecasting Method = Winters' Method (SL = 12) subtracted from:

Forecasting Method	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Winters' Method (SL = 9)	5.937	1.306	4.545	0.0001

Figure 2 Multiple comparison test for seasonal/cyclical demand pharmaceutical products (31 SKUs)

From the main effects plot to analyze the most suitable forecasting method in **Figure 3**, it was found that the average of Mean Absolute Deviation (MAD) obtained by the 12-month seasonal length Winters' Method was the smallest value. The average of MAD using the yearly seasonal length Winters' method decreased by 7.04 units per month or 11% comparing to the 3-month moving average which was the current forecasting method because of the seasonality of pharmaceutical demand.

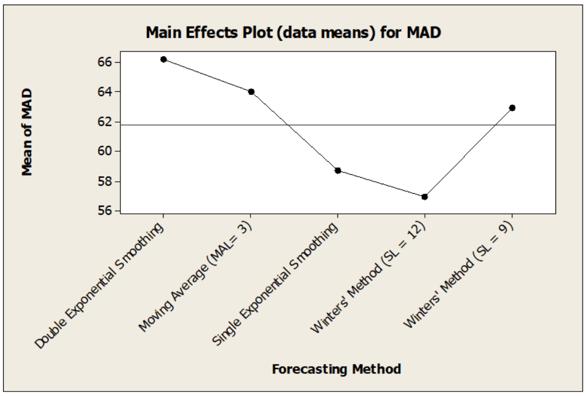

Figure 3 Main effects plot for seasonal demand

2. Non-cyclical or non-seasonal demand drugs (188 SKUs)

To control drug SKUs heterogeneity, a Randomized Complete Block Design (RCBD) was implemented. According to the Randomized Complete Block Design (RCBD), the pharmaceutical products SKUs variable was a blocking factor.

For the demand without seasonality of Class A pharmaceutical products, the ANOVA table in **Table 2** displayed that forecasting techniques had a significant effect on the MAD since the P-Value was less than the significance level of 0.05.

Table 2 ANOVA table for non-cyclical or non-seasonal demand drugs (188 SKUs)

General Linear Model: MAD versus Forecasting Method, Item Code

Analysis of Variance for MAD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Forecasting Method	4	324185	324185	81046	12.52	0.000
Item Code	187	392488453	392488453	2098869	324.31	0.000
Error	748	4840894	4840894	6472		
Total	939	397653532				

S = 80.4474 R-Sq = 98.78% R-Sq(adj) = 98.47%

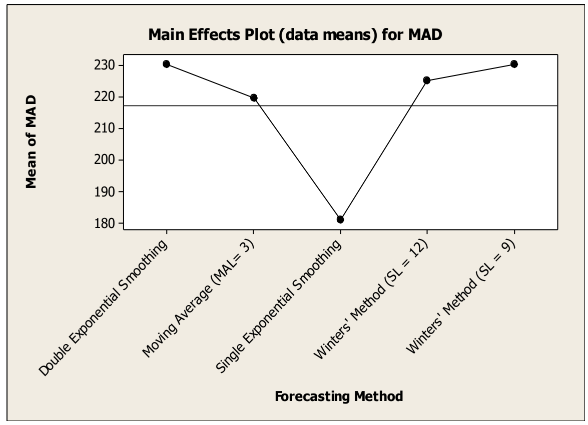

Figure 4 Main effects plot for non-seasonal demand

From **Figures 4**, the main effects plot for pharmaceutical demand without seasonality was used to analyze and determine the most suitable forecasting method for pharmaceutical demand forecasting error reduction. Multiple comparisons test was conducted as shown in **Figure 5**.

According to the main effects plot to analyze the most suitable forecasting method in **Figure 5**, it was found that the average of Mean Absolute Deviation (MAD) obtained by the single exponential smoothing was the smallest value. The average of MAD using the single exponential smoothing decreased by 38.47 units per month or 17.5% comparing to the 3-month moving average which was the as-is forecasting method. According to the multiple comparison test, the adjusted P-Value of pairwise comparisons was less than 0.05, which was the significance level, as shown in the red rectangles in **Figure 5**. Therefore, it could be concluded that the average of MAD obtained by the single exponential smoothing was significantly smaller than the average of MAD obtained by (1) the 3-month moving average, (2) double exponential smoothing, (3) the 9-month seasonal length Winters' method and (4) 12-month seasonal length Winters' method. Since most of non-cyclical or non-seasonal demand pharmaceutical products demand patterns were not increasing trend or decreasing trend, the double exponential smoothing was inappropriate to apply. Additionally, the Winters' method was also unsuitable because of the demand without seasonality.

Bonferroni Simultaneous Tests
Response Variable MAD
All Pairwise Comparisons among Levels of Forecasting Method
Forecasting Method = Double Exponential Smoothing subtracted from:

Forecasting Method	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Moving Average (MAL= 3)	-10.79	8.298	-1.300	1.0000
Single Exponential Smoothing	-49.26	8.298	-5.936	0.0000
Winters' Method (SL = 12)	-5.00	8.298	-0.602	1.0000
Winters' Method (SL = 9)	0.11	8.298	0.013	1.0000

Forecasting Method = Moving Average (MAL= 3) subtracted from:

Forecasting Method	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Single Exponential Smoothing	-38.47	8.298	-4.636	0.0000
Winters' Method (SL = 12)	5.79	8.298	0.698	1.0000
Winters' Method (SL = 9)	10.90	8.298	1.313	1.0000

Forecasting Method = Single Exponential Smoothing subtracted from:

Forecasting Method	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Winters' Method (SL = 12)	44.26	8.298	5.334	0.0000
Winters' Method (SL = 9)	49.37	8.298	5.950	0.0000

Forecasting Method = Winters' Method (SL = 12) subtracted from:

Forecasting Method	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Winters' Method (SL = 9)	5.109	8.298	0.6157	1.000

Figure 5 Multiple comparison test for non-seasonal demand pharmaceutical products (188 SKUs)

Table 5 Appropriate forecasting method for pharmaceutical products with cyclical or seasonal demand

MAD of 3-month moving average	MAD of yearly seasonal length Winters' method	MAD Difference	% MAD Difference
64.01 unit per month	56.97 unit per month	7.04 unit per month	11%

Table 6 Suitable forecasting method for pharmaceutical demand without seasonality

MAD of 3-month moving average	MAD of single exponential smoothing	MAD Difference	% MAD Difference
219.52 unit per month	181.05 unit per month	38.47 unit per month	17.5%

- For cyclical or seasonal demand pharmaceutical products (31 SKUs), such as Molnupiravir (for adult COVID-19 patients), Favipiravir (for pediatric COVID-19 patients), Oseltamivir (Tamiflu, used for influenza A and B), and Clotrimazole (an antifungal agent frequently required during the rainy season), the most effective method was 12-month seasonal length Winters' method. The proposed forecasting method significantly outperformed the 3-month moving average, double exponential smoothing, and 9-month seasonal length Winters' method, achieving an 11% reduction in MAD (7.04 units per month) at the 0.05 significance level. The improvement reflects the ability of the forecasting model to capture cyclical and seasonal demand fluctuations.
- For pharmaceutical demand without seasonality (188 SKUs), such as Atorvastatin (Xarator), a cholesterol-lowering agent with consistent demand across all seasons, and other similar pharmaceutical products, the single exponential smoothing method was the most appropriate. It reduced MAD by 17.5% (38.47 units per month) compared to the current hospital forecasting method, which was the 3-month moving average, and also outperformed double exponential smoothing and Winters' methods with 9-month and 12-month seasonal lengths, with 0.05 significance level.

Limitation

- The scope of the data: a 60-month dataset from the case study hospital was used to analyze in this research.
- The study did not include external factors such as supply shocks that may influence pharmaceutical demand patterns.

Conclusions

This research employed the ANOVA to examine factors influencing the Mean Absolute Deviation (MAD) of the time series forecasting methods. Five forecasting techniques were evaluated: (1) 3-month moving average, (2) single exponential smoothing, (3) double exponential smoothing, (4) 9-month seasonal length Winters' Method and (5) 12-month seasonal length Winters' Method. The analysis focused on high inventory value Group A drugs, which were divided into two subgroups: cyclical/seasonal demand (31 SKUs) and non-cyclical or non-seasonal (188 SKUs). According to the class A cyclical/seasonal demand pharmaceutical products, the most appropriate forecasting technique was the 12-month seasonal length Winters' method. The average of MAD obtained by the yearly seasonal length Winters' method decreased by 7.04 units per month comparing to the 3-month moving average which was the current forecasting method because of the seasonality of pharmaceutical demand. For the class A drugs without seasonality, the most appropriate forecasting technique was single exponential smoothing. The MAD of single exponential smoothing decreased by 38.47 units per month comparing to the 3-month moving average which was the as-is forecasting method of the case study hospital. It can be concluded that

Winters' method with 12-month seasonal length was suitable for cyclical/seasonal demand drugs, reducing MAD by 11% compared to the traditional 3-month moving average. For pharmaceutical demand without seasonality, single exponential smoothing was the most appropriate forecasting method, reducing MAD by 17.5%.

These findings confirm that pharmaceutical demand forecasting methods should be tailored to demand seasonality and patterns rather than applied uniformly which are consistent with the research results of Merkuryeva et al. (2019) and Rathipriya et al. (2023). The present findings and previous studies are consistent as follows: the time series analysis methods are applied, and the multiplicative Winters' method is selected because of the pharmaceutical demand seasonality growth with trend. In practice, hospitals adopting suitable forecasting techniques can improve logistics efficiency, reduce inventory carrying cost, and minimize pharmaceutical wastes from overstocking and expiration. The results provide both theoretical evidence and practical guidance for hospital supply chain optimization.

The MAD reduction in pharmaceutical demand forecasting is a quantitative enabler of the 7R waste management. It prevents redundant pharmaceutical procurement through accurate forecasting, and reduces pharmaceutical inventory levels and expired stock to minimize resource use and waste generation. (Refuse and Reduce), enhances circular use of pharmaceutical products (Reuse, Repair, Repurpose and Recycle), and minimizes end-of-life losses (Recover). Reduction in MAD typically yields reduction in pharmaceutical waste, demand accuracy increase and improvement in hospital logistics efficiency, while strengthening environmental sustainability and patient care reliability.

Future research may extend this analysis to other measures of demand forecasting error as follows: Mean Absolute Percentage Error (MAPE) and Mean Squared Deviation (MSD). Future research may explore the combined impact of forecasting methods and inventory control policies to further strengthen hospital logistics performance.

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An Innovative Method for Upcycling Leaf Waste from Green Areas in Bangkok's Government Agencies

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Abstract

The rapid growth of urban green spaces in Bangkok's government agencies generates substantial amounts of organic leaf waste, which imposes significant financial burdens and environmental challenges when managed through conventional disposal methods. This study quantifies leaf waste generation in three government agencies and evaluates its potential valorization into composite panels as a sustainable alternative to plywood. Over a 30-day period, daily leaf waste generation ranged from 86.50 to 172.33 kg, highlighting a consistent biomass stream with high potential for reuse. Composite panels were fabricated by combining leaf waste with a urea-formaldehyde adhesive and a paraffin emulsion and then hot-pressed into 30 × 30 × 3 cm sheets. Mechanical testing revealed an average tensile strength of 0.063 MPa and a compressive strength of 5.45 MPa, values that are below the Thai Industrial Standard (TIS 966-2547) for Medium-Density Fiberboard (MDF) requirements for structural applications but are acceptable for lightweight, non-load bearing uses, such as interior decoration and furniture components. The findings underscore the dual benefits of this approach: reducing greenhouse gas emissions and landfill dependency while lowering waste management costs. By integrating circular economy principles, this research demonstrates the feasibility of upcycling leaf waste into innovative products, providing both environmental and socio-economic value.

Keywords : leaf waste; composite panel; organic waste management; material innovation

Introduction

Globally, the management of organic waste has become a pressing sustainability challenge. This issue is escalating due to rapid urbanization, population growth, and unsustainable consumption patterns. According to the United Nations Environment Programme (UNEP, 2021) [1], organic waste—including food scraps, yard trimmings, and agricultural residues—accounts for more than 40% of total municipal solid waste worldwide. When improperly managed, this waste contributes significantly to greenhouse gas emissions, leachate contamination, and land use burdens. These impacts undermine several United Nations Sustainable Development Goals (SDGs), especially SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [2]. Recent scholarship emphasizes that organic waste should no longer be viewed merely as a disposal problem. Instead, it is a valuable resource that can be transformed into energy, compost, or innovative biomaterials [3, 4]. This paradigm shift aligns with the principles of the circular economy, which seeks to extend material lifecycles, minimize environmental impact, and foster socio-economic benefits through waste valorization [5].

The global environmental situation is deteriorating with increasing severity, particularly the problem of solid waste, the volume of which is escalating due to consumption, especially in large urban areas. According to the Pollution Control Department (2023) [6], Thailand generated 28.71 million tons of municipal solid waste nationwide. Of this amount, 9.81 million tons (34.20%) were properly disposed of, 12.52 million tons (46.60%) were recycled or utilized, and a significant 6.38 million tons (22.20%) were improperly managed. In Bangkok alone, 4.95 million tons of waste were generated, with 1.10 million tons utilized and 3.85 million tons properly disposed of. Although no data on improper disposal in Bangkok was specified, a portion of the properly disposed waste could potentially be upcycled [7].

The operation to achieve the nation's solid waste management goals effectively according to international standards is mentioned in item 18 of the master plan under the National Strategy, 2018–2037 [8] emphasizes the need to achieve efficient waste management goals aligned with international standards. This requires focusing on waste reduction at the source. It calls for campaigns and awareness-building among the public and all relevant sectors, including households, educational institutions, businesses, and government offices. The plan also supports the use of environmentally friendly goods and services. It promotes the separation and recycling of waste and encourages the design of long-lasting, reusable products. This aligns with the principles of a circular economy, which seeks to resolve waste issues by adding value to discarded materials [9].

Government agencies are numerous and widespread throughout Bangkok. These agencies provide various public services and facilitate visitors, and nearly all maintain landscaped gardens and green spaces to create a pleasant and aesthetically pleasing environment [7]. However, managing these extensive green areas incurs significant annual expenses. These costs include landscape maintenance, monthly decorations, and the disposal of specific waste types, such as leaves, branches, and grass clippings. The daily accumulation of this waste presents a major disposal challenge, as municipal services often do not collect this type of waste, necessitating special private hauling services at a considerable budgetary expense.

This study specifically explores the management of leaf waste generated in the green areas of government agencies in Bangkok, addressing the practical challenges of collection, processing, and utilization. Three agencies with landscaped areas of at least 1 rai (1,600 m²) were selected as study sites. The research focuses on developing an innovative panel material by using leaf waste as a substitute for plywood and evaluating its properties in accordance with the Thai Industrial Standard for medium-density fiberboard (TIS 966-2547 for MDF) [10] for panels thicker than 15 mm. The study is guided by two primary objectives: (1) to quantify the amount of organic leaf waste generated in the green areas of these government agencies, and (2) to produce and assess the quality of composite panels derived from the collected leaf waste. By integrating waste quantification with material development and performance testing, this research aims to provide a sustainable approach for valorizing leaf waste while addressing practical challenges in urban waste management.

Methodology

Phase 1: Quantifying Leaf Waste

Population and Sample: For this phase, the population consisted of green areas at government agencies in Bangkok, each measuring at least 1 rai and maintained by staff or external contractors. Among 30 such agencies identified, a sample of three agencies volunteered to participate: (1) The Faculty of Science, Chulalongkorn University, (2) The Office of the Permanent Secretary, Ministry of Finance, and (3) The National Learning Museum.

Data Collection: At each of the three sites, leaves were collected and weighed daily for 30 consecutive days in May 2022 to measure the quantity of leaf waste. We collected leaf samples in May 2022 because this month represents the period with the lowest leaf-fall in the study area. By selecting a month with minimal leaf drop, we aimed to establish a baseline measurement of leaf waste, which allows for consistent comparison across sites. Collecting during months with higher leaf fall, such as in the autumn, could introduce variability that might obscure underlying patterns in leaf waste generation.

Phase 2: Production and Quality Testing of Composite Panels

Previous research has explored methods for producing plywood substitutes from natural waste materials, such as leaves, to add value and reduce waste volume. The general process involves collecting and cleaning the leaves, shredding them into small particles, and mixing them with a binder such as urea-formaldehyde adhesive before pressing. To avoid redundant experimentation, this study adopted a formula from a similar study.

This approach is further supported by the fact that, although leaf waste and cattail fiber originate from different plant sources, both materials are fundamentally lignocellulosic fibers, composed primarily of cellulose, hemicellulose, and lignin [11-13]. The presence of these polymers provides structural rigidity and binding potential, which are essential properties for fiberboard production. Despite differences in chemical composition ratios and particle morphology, the shared lignocellulosic nature of the two materials indicates that production methods and adhesive systems optimized for cattail fiber can be transferred, with minor adjustments, to leaf waste. Therefore, adopting the existing formula from the cattail fiber study is justified, providing a practical and scientifically supported starting point while maintaining material performance.

1. **Materials and Equipment**

Materials: Leaf waste from the sample sites, urea-formaldehyde adhesive, and paraffin emulsion.

Equipment: A material shredder, a Master Model 24N hot press, forming molds, a digital precision scale, a Universal Testing Machine (UTM) for tensile and compressive strength, and a moisture tester.

2. **Production Formula** The production ratio was based on the optimal formula identified by Phonieum (2016) [14] for producing composite panels from cattail plants. The optimal cattail particle board formulation was determined to be a ratio of 50 (Cattail): 75 (Urea formaldehyde): 10 (Paraffin emulsion) (10:15:2). This formulation yielded excellent physical properties, including a Modulus of Rupture (MOR) of 15 MPa, a Tensile Strength of 5.75 MPa, and a Moisture Content of 4.97%. Crucially, these measured properties were found to be in accordance with the requirements stipulated by the Thai Industrial Standard for Flat-Pressed Particle Boards. Consequently, the produced particle board is deemed highly suitable for various craft-making applications.

The ratio of materials is shown in **Table 1**.

3. **Production Process**

3.1 Selected leaf waste was sun-dried, ground in a semi-fine shredder, and then dried again before being formed (**Figure 1**). In a mixing container, 100 g of dried, ground leaf waste was combined with 150 g urea-formaldehyde adhesive and 20 g paraffin emulsion.

3.2 The mixture was poured into a 30 x 30 cm square mold at a thickness of 3 cm. The material was spread evenly, covered, and placed in a hot press at 120°C for 3 minutes. After pressing, the sheet was moved to a cooling rack for 3 minutes.

3.3 The finished composite panel was demolded and conditioned at room temperature for one week before testing.

Table 1 Material Ratio for Composite Panel Production

Component	Ratio	Experimental Quantity (g)
Leaf Waste	10	100
Urea-Formaldehyde Adhesive	15	150
Paraffin Emulsion	2	20

Figure 1 Preparation of leaf waste: leaves were sun-dried, ground using a semi-fine shredder, and dried again prior to forming

4. Physical Property Testing The physical properties of the composite panels were tested and compared against the TIS 966-2547 standard. Two key properties were evaluated:

a. Tensile Strength: This test measures the panel's ability to resist being pulled apart. Samples were cut to a standard size of 10 x 10 x 3 cm. Each sample was secured in the grips of a Universal Testing Machine (UTM). The samples were subjected to a standardized pulling force until failure. The maximum force before the sample broke was recorded. The tensile strength (σ) of a material represents its ability to resist deformation and failure under a pulling force. It is calculated using the following formula [15]:

$$\sigma = \frac{F_{\max}}{A}$$

Where:

σ = Tensile strength (MPa)
$F_{\max}$ = Maximum load applied to the specimen before failure (N)
A = Cross-sectional area of the specimen (mm²)

b. Compressive Strength: This test measures the panel's ability to withstand a crushing force. Samples were cut to a standard size of 5 cm × 5 cm × 5 cm. Each sample was placed in the UTM and subjected to an increasing compressive force until it deformed permanently or fractured. The maximum force the sample could withstand was recorded. The compressive strength (σ_c) of a material indicates its ability to withstand axial compressive forces without failure. It is calculated using the following formula [16]:

$$\sigma_c = \frac{F_{\max}}{A}$$

Where:

σ_c = Compressive strength (MPa)
$F_{\max}$ = Maximum load applied to the specimen before failure (N)
A = Cross-sectional area of the specimen (mm²)

Results and Discussion

Quantity of Organic Leaf Waste study

The study quantified leaf waste generation in the green areas of three selected government agencies in Bangkok. The results are summarized in **Table 2**.

Table 2 The amount of leaf waste in the sample areas

Agency	Area (rai)	Total Volume (kg/30 days)	Average (kg/day)	Transportation Cost (THB/month)
Faculty of Science, Chula.	9.18	2,750	88.71	3,000.00
The Office of the Permanent Secretary, Ministry of Finance	44.00	5,170	172.33	4,500.00
National Learning Museum	7.00	2,595	86.50	3,000.00

The results indicate that the three agencies—Faculty of Science, Chulalongkorn University; the Office of the Permanent Secretary, Ministry of Finance; and the National Learning Museum—generated differing amounts of leaf waste from their landscaped areas, averaging between 86.5 kg and 172.33 kg per day. This highlights a substantial and consistent source of organic waste with significant potential for valorization.

Transforming leaf waste into value-added products, such as composite panels, can address multiple challenges. First, it contributes to greenhouse gas mitigation by reducing methane emissions from landfill disposal, a major source of anthropogenic emissions [17]. Second, it offers cost-saving opportunities by lowering expenditures associated with waste collection and transportation, particularly in locations generating large volumes of leaf waste [3].

Moreover, the development of leaf-waste-based products aligns with circular economy principles, providing a sustainable pathway for resource recovery while adding economic value to organic residues. Advanced processing technologies, including biochemical or thermochemical conversion, can further enhance the quality and durability of these products, increasing their industrial applicability [18].

In conclusion, the significant volume of leaf waste from urban green areas presents a promising feedstock for sustainable product development. Utilizing this resource can simultaneously mitigate environmental impacts, reduce operational costs, and support circular economy strategies in urban waste management.

Composite panels from the leaf waste production

The production process successfully yielded 30 x 30 x 3 cm composite panels from the collected leaf waste (**Figure 2**).

Figure 2 Composite panels from the leaf waste

The Physical property tests of Composite panels from the leaf waste

Tensile Strength

Three samples of the composite panels (CP1, CP2, CP3) were tested. The results were 0.068 MPa, 0.080 MPa, and 0.038 MPa, respectively, yielding an average tensile strength of 0.063 MPa. When compared to the Thai Industrial Standard (TIS 966-2547) for Medium-Density Fiberboard (MDF) (thickness > 15 mm), which requires a minimum tensile strength of 0.5 MPa, the leaf-waste panels were significantly below the standard (**Figure 3** and **Table 3**).

The tensile strength of three composite panels (CP1, CP2, CP3) from leaf-waste was evaluated, and the results are summarized in Table 3. The measured tensile strengths were 0.070, 0.080, and 0.040 MPa, respectively, yielding an average tensile strength of 0.063 MPa. Compared to the Thai Industrial Standard (TIS 966-2547) for Medium-Density Fiberboard (MDF) with a thickness greater than 15 mm, which requires a minimum tensile strength of 0.5 MPa, the leaf-waste panels exhibited considerably lower mechanical performance. At the same ratio, when compared with the study of Phonieum (2016), which used *Typha angustifolia* (Cattail) as raw material, it was found that the fiberboard made from cattail had a tensile strength of 5.75 MPa. In contrast, the leaf-waste fiberboard showed an average tensile strength of only 0.063 MPa, which is considerably lower than that of the cattail board.

This significant deviation from the standard highlights the inherent limitation of using untreated leaf waste as a primary material for structural panels, likely due to the low fiber cohesion and insufficient binding strength. Previous studies have shown similar trends when using agricultural residues or natural fibers in composite panels, highlighting the need for chemical or physical modifications to enhance tensile performance [19, 20]. These modifications may include the use of stronger adhesives, fiber pre-treatment, or hybridization with higher-strength fibers to improve the load-bearing capacity of the panels.

Figure 3 Tensile strength measurements of composite panels from the leaf waste.

Table 3 Mean Tensile Strength Values of Leaf-Waste Composite Panels from Triplicate Tests

Three samples of leaf-waste panels	Tensile strength (MPa)
CP1	0.070
CP2	0.080
CP3	0.040
Average	0.063
Standard	0.500

Note: Units are in megapascals (MPa). FS refers to the standard value for medium-density fiberboard panels with a thickness greater than 15 mm, according to TIS 966-2547.

Implications: While leaf-waste panels may not meet structural standards for MDF, they still hold potential for non-structural applications, value-added products, or as eco-friendly alternatives in furniture and decorative panels, aligning with the principles of the circular economy and sustainable waste management [3, 17].

Compressive Strength:

Three samples (CP1, CP2, CP3) were tested (**Figure 4**).

The compressive strength of the composite panels fabricated from leaf waste was assessed through standard testing procedures. The results are as **Table 4**.

The compressive strength values obtained for the leaf waste composite panels, ranging from 4.96 MPa to 6.36 MPa with an average of 5.45 MPa, are lower than those of conventional construction materials; however, they still demonstrate potential for specific applications. For instance, the compressive strength of concrete typically ranges from 17 MPa to 70 Mpa [21], while fiber-reinforced composites often exhibit compressive strengths around 20 Mpa [22]. Although the values of leaf waste composites are comparatively lower, their performance suggests promising potential for lightweight, non-structural applications in sustainable construction. At the same ratio, when compared with the study of Phonieum (2016), which used *Typha angustifolia* (Cattail) as raw material, it was found that the fiberboard made from Cattail had a compressive strength of 15 MPa, while the leaf-waste fiberboard showed an average compressive strength of only 5.45 MPa, which is much lower than that of the cattail board.

Figure 4 Compressive Strength test of composite panels from the leaf waste

Table 4 Mean Compressive Strength Values of Leaf-Waste Composite Panels from Triplicate Tests

Sample	Compressive Strength (N)	Compressive Strength (MPa)
CP1	12,600.00	5.04
CP2	15,600.00	6.36
CP3	12,400.00	4.96
Average	**13,533.33**	**5.45**

Note: The compressive strength values are calculated by dividing the maximum load (in Newtons) by the cross-sectional area (in square millimeters) of each sample.

Besides mechanical performance, using leaf waste in composites offers environmental benefits by reducing waste and diverting organic matter from landfills, thereby reducing greenhouse gas emissions, such as methane [23]. Valorizing this biomass also supports the circular economy and sustainable waste management.

From an economic perspective, producing such composite panels can lower waste management costs and reduce dependence on virgin raw materials. By incorporating locally available leaf waste, transportation and procurement expenses are minimized, resulting in more cost-effective and environmentally sustainable production of building materials [24]. Although the leaf-waste panels did not satisfy industrial requirements for structural (load-bearing) applications, their current composition, manufacturing form, and measured mechanical behaviour indicate clear suitability for non-load-bearing uses, such as interior decoration, wall cladding (coverings fixed to walls), partitioning (dividing interior spaces), and certain furniture components. Evidence from recent literature shows that biomass-derived panels and natural-fiber composites (materials made from plant fibers and resins) have been successfully applied in lightweight interior panels and decorative elements when mechanical demands are moderate and surface treatment or lamination (applying a protective or decorative layer) is applied [25, 26]. Such applications capitalize on the low density (light weight), thermal, and acoustic (Sound-insulating) benefits, as well as the lower embodied carbon (total greenhouse gases emitted during production), of biomass panels compared with many conventional materials [27].

To improve applicability and marketability for interior, non-structural roles, several development pathways are recommended. First, mechanical reinforcement and hybridization, blending leaf fiber with higher-strength fibers or wood particles, or incorporating particulate reinforcements, have been shown to increase stiffness and compressive/tensile performance without excessively increasing density [28, 29]. Hybrid panel formulations and optimized particle size distributions can substantially reduce thickness swelling and improve modulus of rupture. Second, adhesive chemistry and pre-treatments (e.g., fiber surface modification, alkaline treatments, or coupling agents) can significantly enhance fiber matrix bonding and long-term durability, thereby raising tensile and bending strengths and improving moisture resistance [28]. Third, process and finishing improvements, including hot-press parameter optimization, the addition of suitable binders or thermoset/thermoplastic matrices, and the application of surface laminates or coatings, enhance surface aesthetics, abrasion resistance, and dimensional stability, rendering panels suitable for visible interior applications [25, 27].

Beyond technical performance, valorizing leaf waste into panels delivers notable environmental and economic co-benefits. Life-cycle and environmental assessments of upcycled panel products indicate reductions in landfill demand and associated methane emissions, lower embodied carbon relative to many conventional materials, and potential operational cost savings from reduced waste hauling and lower raw-material procurement needs, outcomes that strengthen the circular-economy case for on-site or municipal valorization programs [27]. For example, one life-cycle assessment (LCA) study of wood waste panels showed cradle-to-grave GHG emissions of approximately 321 kg CO_2 - eq per tonne of panel, compared to ~1,610 321 kg CO_2 - eq for conventional disposal routes (Al-Saadi et al., 2022). Another bio-based multilayer panel study reported a ~12% reduction in climate-change impacts compared to a fossil-based benchmark [29].

In summary, while further R&D is needed to enhance mechanical properties for structural use, current evidence supports a practical approach: utilizing leaf-waste panels initially in non-structural interior applications (such as decorative panels, partitions, and furniture), while pursuing improvements in reinforcement, finishing, and processes to broaden their use and acceptance. This staged strategy balances short-term environmental and economic benefits with ongoing performance advances [25, 28].

Conclusions and Recommendations

This study demonstrates that the substantial amount of leaf waste from government green areas in Bangkok represents an underutilized resource of great value. The tests showed that panels made from leaf waste are not yet strong enough for building structures, but they are firm and suitable for indoor uses, such as room dividers, wall coverings, and decorative furniture. Besides being useful, making these panels helps lower greenhouse gas emissions, reduces city waste costs, and aligns with Thailand's goals for improved waste management and the United Nations' Sustainable Development Goals. Future research should aim to enhance the material's strength and appearance by combining fibers, treating the leaves with chemicals, and refining the surface, as recent studies suggest these steps are highly beneficial. Turning leaf waste into panels presents a practical and creative approach to supporting the circular economy in cities, yielding positive outcomes for the environment, economy, and society.

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Conditional Optimization for Treatment of Wastewater from Ethanol Production Process Using Ozonation

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Abstract

This study aimed to determine the optimal conditions for removing COD and color from ethanol production effluent using the ozonation process. The investigation employed Response Surface Methodology (RSM) with a Central Composite Design (CCD) model, focusing on two key variables: ozone dosage rate (900, 1,200, and 1,500 mg/hr) and contact time (60, 90, and 120 minutes). The results showed that the highest COD and color removal efficiencies—63.32±1.28% and 75.65±1.42%, respectively—were achieved at an ozone dosage of 1,500 mg/hr and a contact time of 120 minutes. Based on the ANOVA statistical analysis of the treatment results, the Quadratic Model and the Linear Model were found to be suitable for describing the relationship between the variables (ozone dosage rate and contact time) and the COD and color removal efficiencies of effluent from a UASB tank, which is the wastewater after preliminary treatment, using the ozonation process. According to the model, the optimal conditions for maximum treatment efficiency were an ozone dosage rate of 1,500 mg/hr and a contact time of 116.881 minutes, which predicted COD and color removal efficiencies of 63.99% and 75.79%, respectively. To validate these findings, a series of experiments was conducted under the recommended optimal conditions. The average COD removal efficiency observed was 62.99±0.68%, which closely aligns with the model prediction, with a deviation of only 1.60%. Similarly, the average color removal efficiency was 73.22±0.62%, showing a minor deviation of 3.51% from the predicted value. These results confirm the reliability and suitability of the CCD model in optimizing the ozonation process for treating effluent from ethanol production.

Keywords : ozonation process; ethanol production wastewater; Response Surface Methodology; Central Composite Design

Introduction

The ethanol industry is a sector that requires a large amount of water in its production process, starting from the preparation of raw materials, which involves washing and cleaning before being processed into a starch solution. The process then moves on to boiling, fermentation, and distillation, respectively. The wastewater generated from production contains high levels of COD, BOD, and color, while having a low pH (high acidity), making it difficult to treat [1]. This leads to negative impacts on surrounding communities, such as the discharge of wastewater into rivers or ethanol wastewater overflowing into residential areas. The overflowing wastewater is characterized by a brown color, an unpleasant odor, and chemical contamination. These issues not only affect local communities but also pose significant environmental concerns [2].

Currently, the ethanol industry often adopts anaerobic wastewater treatment systems. These systems help reduce costs by eliminating the need for aeration and generating less sludge, thereby lowering sludge disposal expenses. Additionally, anaerobic treatment can produce biogas, mainly composed of methane gas, which can be used as fuel or an alternative energy source within the factory, leading to further energy cost savings [3]. Nevertheless, although anaerobic systems are widely utilized in ethanol wastewater treatment, the treated water often has a brown color and high COD levels that do not meet discharge standards. There are also issues related to unpleasant odors. To address these problems, various treatment methods have been explored, including membrane filtration, activated carbon adsorption, ozonation, and the Fenton process. Each method has its limitations depending on the treatment process. Previous studies have shown that ozonation is effective in removing color and organic substances from ethanol production wastewater [4]. However, prior research lacks an in-depth study on determining the optimal conditions of ozone dosage and contact time using Response Surface Methodology (RSM) specifically for treating wastewater from the ethanol production process. Therefore, this research was conducted to study the optimal conditions for treating wastewater from the ethanol production process using the ozonation method, by comparing the water quality before and after treatment.

Ozonation is currently used in wastewater treatment, as it does not produce toxic byproducts in the treated water. This process involves removing pollutants in the form of biologically non-degradable organic compounds through a chemical reaction using ozone. Ozone is a powerful oxidizing agent capable of breaking down complex organic molecules. Additionally, ozone is an unstable gas that can decompose into oxygen, releasing various radicals such as hydroxyl radicals ($OH\bullet$) and superoxide anion ($O_2^{\bullet}$). These radicals are highly reactive and act as strong oxidizing agents, readily reacting with various substances. The use of ozone in degrading organic matter in water reduces the toxicity of these compounds and enhances their biodegradability [5, 6]. Furthermore, COD and many colored and complex organics are broken into smaller, less colored or colorless compounds. Ozone is also a powerful disinfectant, making it highly effective in eliminating pathogens [7]. The key reactions in the ozonation process for wastewater treatment occur through both direct and indirect oxidation mechanisms. In direct oxidation, ozone reacts directly with certain organic and inorganic compounds via electrophilic attack, particularly targeting functional groups such as double bonds, activated aromatic rings, or amines, as illustrated in Equation 1. In indirect oxidation, ozone decomposes in water, especially under alkaline conditions, to generate hydroxyl radicals ($OH\bullet$), which are highly reactive and non-selective oxidants (Equations 2–6). Once formed, these hydroxyl radicals can rapidly oxidize a wide range of organic pollutants, often more efficiently than ozone itself, as shown in Equation 7 [8].

$$\mathrm{O_3} + \text{pollutant} \rightarrow \text{oxidized products} + \text{byproducts} \quad (1)$$

$$\mathrm{O_3} + \mathrm{OH^-} \rightarrow \mathrm{HO_2^-} + \mathrm{O_2} \quad (2)$$

$$\mathrm{HO_2^-} \leftrightarrow \mathrm{O_2^-} + \mathrm{H^+} \quad (3)$$

$$O_3 + O_2^- \rightarrow O_3^- + O_2 \quad (4)$$

$$O_3^- + H^+ \leftrightarrow HO_3 \quad (5)$$

$$HO_3 \rightarrow OH \bullet + O_2 \quad (6)$$

$$OH \bullet + \text{pollutant} \rightarrow \text{oxidized products} + H_2O \quad (7)$$

This study focused on two primary variables influencing pollutant removal efficiency: ozone dosage rate and contact time. To evaluate their effects and interactions, the Central Composite Design (CCD) approach was utilized through the Design Expert software. This statistical method enabled a structured assessment of how these factors impact treatment performance. Moreover, the integration of advanced analytical tools and computational techniques has significantly improved the ability to determine the most effective treatment parameters. Design Expert's Response Optimizer feature further aids in forecasting and confirming the optimal conditions for achieving maximum removal efficiency.

Methodology

This research emphasizes determining the optimal conditions for treating wastewater from the ethanol production process using the ozonation method. The study commenced with the collection of wastewater samples from the effluent discharge point after the UASB (Upflow Anaerobic Sludge Blanket) reactor of an ethanol production plant in Ubon Ratchathani province. Wastewater samples were collected every two weeks from November to December 2023. The collection, preservation, and handling of wastewater samples were performed in compliance with Standard Methods for the Examination of Water and Wastewater [9]. An experimental design was then developed based on the principles of RSM. Treated water samples were analyzed to evaluate treatment efficiency and validate the accuracy of the mathematical model generated by the software. The CCD experimental design was executed as a batch experiment, with each experimental run performed in duplicate to determine the mean and standard deviation. The characteristics of the wastewater sample were analyzed according to standard methods, as displayed in **Table 1** [10]. Based on primary research, two key process variables, ozone dosage rate and contact time, were adjusted to values of 900, 1,200, and 1,500 mg/hr, and 60, 90, and 120 minutes, respectively [4, 11]. The ozone dosage rate generated by the ozone generator was analyzed following the standard method [10].

The optimization process using RSM involves designing a structured set of experiments where key variables are systematically adjusted. The experimental data are then used to develop a mathematical model that illustrates the relationship between the independent variables (factors) and the dependent variable (response). This model enables the prediction of the response outcome based on different combinations of factor levels. Additionally, it plays a crucial role in determining the optimal conditions for enhancing contaminant removal, reducing chemical oxygen demand (COD), and improving the color and odor quality of the treated wastewater [12-14]. The RSM model is typically represented by the following equation [15].

Table 1 Parameters and methods for analyzing characteristics of wastewater from ethanol production

Parameter	Analysis method
pH	pH Meter
COD (mg/L)	Closed Reflux Colorimetric Method
Color	ADMI Method

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum \sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \quad (8)$$

Where y is the model response, β_0 is the intercept, β_i are the linear coefficients for each independent variable, β_{ii} are the quadratic coefficients for the squared terms of each independent variable, β_{ij} are the interaction coefficients between the variables X_i and X_j, X_i and X_j are the independent variables, k is the number of independent variables, and ε is the error term. This equation is essential for understanding the impact of changes in process variables on the response and plays a crucial role in process optimization.

Results and Discussion

The preliminary analysis of the wastewater samples revealed that the effluent from the ethanol production process contains relatively high levels of pollution, particularly in terms of COD and color, as shown in **Table 2**. This indicates a significant load of organic and inorganic substances in the wastewater [11]. The effluent appears as dark brown water with black sludge, as illustrated in **Figure 1**.

Treatment of wastewater sample from ethanol production using ozonation

The study on the efficiency of COD and color removal from ethanol production wastewater using the ozonation process showed that color could be reduced to 173±15.6 ADMI, and COD to 1,772±82.5 mg/L. The resulting color value meets the industrial effluent standards set by the Ministry of Industry, while the COD value exceeds the permissible limit. Additionally, experimental results revealed an increase in the pH of the treated water, as shown in Table 2. The rise in pH is attributed to the formation of hydroxide ions (OH^-) during the reaction, leading to a condition where the concentration of hydroxide ions [OH^-] is greater than that of hydronium ions [H_3O^+], resulting in a more basic solution and, consequently, a higher pH after treatment [17]. **Figure 2** illustrates the physical characteristics of the wastewater sample and treated water. As seen from the figure, the color of the water sample changed from dark brown to lightly cloudy white.

A comparison between the experimental results and the predicted values for COD and color removal efficiencies obtained from the Design-Expert software is demonstrated in **Table 3**. It should be noted that the "Prediction" values in the table are calculated using the derived Quadratic and Linear equations (Equations 9 and 10), respectively. The results indicate that the predicted COD removal efficiencies closely match the experimental data. Similarly, the color removal efficiencies obtained from both the experimental results and the Design-Expert predictions are also comparable, as shown in **Table 3**, further confirming the model's accuracy. The highest COD and color removal efficiencies were observed at an ozone dosage rate of 1,500 mg/hr and a contact time of 120 minutes, achieving 62.93% and 75.92% removal efficiencies, respectively. In contrast, the lowest removal efficiencies were found at an ozone dosage rate of 900 mg/hr and a contact time of 60 minutes, with COD and color removal rates of 11.86% and 62.54%, respectively.

Table 2 Wastewater characteristics from ethanol production

Parameters	Average value before treatment	Average value after treatment	Standard values of effluent discharge [16]
pH	7.59±0.2	8.68±0.3	5.5 – 9.0
COD	4,830±247.5 mg/L	1,772±82.5 mg/L	≤ 120 mg/L
Color	708±7.1 ADMI	173±15.6 ADMI	≤ 300 ADMI

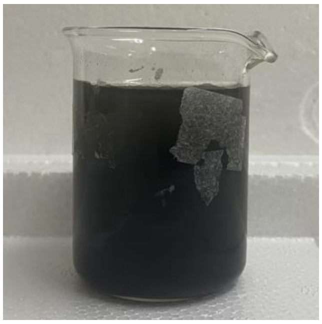

Figure 1 Wastewater sample from ethanol production

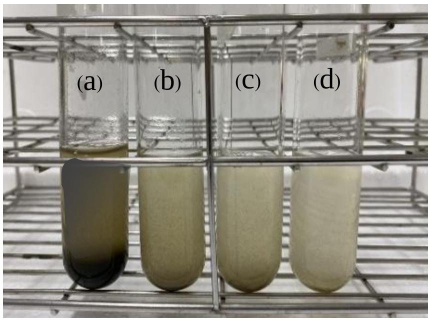

Figure 2 Physical characteristics of the wastewater sample and treated water at different contact times (a) 0 min, (b) 60 min (c) 90 min (d) 120 min

Table 3 Comparison between experimental and predicted values of removal efficiency

No.	Ozone dosage rate (mg/hr)	Contact time (min)	Removal efficiency (%)			
			COD		Color	
			Experiment	Prediction	Experiment	Prediction
1	900	60	14.14±3.07	11.86	62.37±1.90	62.54
2	900	90	40.63±4.29	42.21	70.52±0.14	70.20
3	900	120	51.59±1.26	53.10	72.96±1.41	73.11
4	1200	60	22.74±1.78	29.19	63.74±0.22	63.29
5	1200	90	56.52±0.73	53.34	72.96±0.69	73.11
6	1200	90	54.39±5.32	53.34	72.91±3.44	71.17
7	1200	90	55.06±6.89	53.34	71.15±3.59	71.17
8	1200	90	55.48±2.07	53.34	69.75±0.17	71.17
9	1200	90	52.20±6.73	53.34	68.22±1.99	71.17
10	1200	120	59.14±3.31	58.02	74.73±0.19	74.31
11	1500	60	50.70±5.02	46.53	64.18±4.39	64.46
12	1500	90	59.09±1.01	64.46	73.12±1.88	72.57
13	1500	120	63.32±1.28	62.93	75.65±1.42	75.92

Statistical analysis

Based on the experimental results using the RSM, the data from Table 3 were used to identify the most appropriate mathematical model for predicting COD and color removal efficiencies in ethanol production wastewater treated by the ozonation process. The model summary statistics indicated that the quadratic model, with an adjusted R^2 value of 0.9209, was selected to describe the relationship between the process variables (ozone dosage rate and contact time) and COD removal efficiency. The linear model was suggested for the prediction of color removal efficiency. Statistical analysis revealed that the equation for the percentage of COD removal had an F-value of 41.02 and a P-value of < 0.0001. Since the P-value is less than 0.05, this indicates that the model is statistically significant and suitable for explaining the relationship between COD removal efficiency and the studied variables in the ozonation process. Furthermore, the coefficient of determination (R^2) was found to be 0.9535, as presented in Table 4, indicating that 95.35% of the experimental data can be explained by the predicted values from the mathematical model [18]. A high R^2 value signifies high accuracy in the model's predictive capability. Similarly, the adjusted R^2 (Adj R^2) was 0.9303, which is higher than the minimum acceptable value of 0.64 [10, 18-19], suggesting that the model is well-suited for predicting COD removal. The predicted R^2 (Pred R^2) was 0.7701, with a difference of only 0.1602 from the Adj R^2. Since this difference is less than 0.2, it implies that the model has no significant problems regarding prediction adequacy [19-20]. Furthermore, the coefficient of variation (C.V.) was 8.40%, which is below the 10% threshold [10, 18], indicating that the predictive model has good repeatability and precision. Additionally, the adequacy precision was 21.9545, as shown in **Table 4**. Since this value is greater than 4 [10, 18], it demonstrates that the model is reliable [10].

For color treatment, the statistical analysis revealed that the equation for the percentage of color removal had an F-value of 41.56 and a P-value of < 0.0001, which is less than 0.05. This indicates that the model is statistically significant and suitable for explaining the relationship between the color removal efficiency and the investigated factors in the ozonation process. When examining the coefficient of determination (R^2), a value of 0.9205 was obtained, as shown in **Table 5**, indicating that 92.05% of the experimental data can be explained by the mathematical model's predictions [17]. A high R^2 value suggests high accuracy in the model's ability to predict outcomes, which is essential in mathematical modeling for experimental design. In general, R^2 values range from 0 to 1, and a good model should have an R^2 value close to 1. Likewise, the adjusted R^2 (Adj R^2) was found to be 0.8637, which exceeds the minimum acceptable value of 0.64 [10, 18-19], confirming the model's suitability. The predicted R^2 (Pred. R^2) was 0.8560, differing from the Adj R^2 by only 0.0077. Typically, this difference should not exceed 0.2, indicating that the model has no significant issues regarding prediction reliability [19-20]. Moreover, the coefficient of variation (C.V.) was only 2.28%, which is well below the 10% threshold [10, 18]. A lower C.V. implies better reliability and precision in the model's reproducibility. The adequacy precision value was 12.3015, as shown in Table 5, which is greater than 4 [10, 18], further demonstrating the model's reliability [10]. Additionally, the statistical analysis indicated that both factors had a significant impact on the removal efficiency of COD and color.

A comparison of the experimental results with other related research confirms the robustness of the findings. The maximum COD removal efficiency of 63.32±1.28% and color removal of 75.65±1.42% in this study are higher than the 43.51±1.86% COD removal reported for ozonation treatment of rubber wastewater [11]. However, the observed color removal was lower than that reported in the dye wastewater study, where efficiencies reached 98% under optimal conditions [14]. The high R^2 values of the models (0.9535 for COD and 0.9205 for color) are also consistent with the statistical accuracy found in optimization research for landfill leachate and industrial wastewater decolorization processes [12-13]. These results reinforce the potential of the ozonation process as a highly effective technology for treating this type of wastewater.

Table 4 Fit statistical results for COD removal using the ozonation process

Std. Dev.	3.86	**R^2**	0.9535
Mean	48.91	**Adjusted R^2**	0.9303
C.V. %	8.40	**Predicted R^2**	0.7701
Adequacy precision			21.9545

Table 5 Fit statistical results for color removal using the ozonation process

Std. Dev.	1.60	**R^2**	0.9205
Mean	70.17	**Adjusted R^2**	0.8637
C.V. %	2.28	**Predicted R^2**	0.8560
Adequacy precision			12.3015

The experimental data can be used to construct a mathematical model (Actual Equation) as shown in Equations 9 and 10 for COD and color removal efficiencies, respectively. Note that the last two terms in Equation 10 can be omitted, thus making Equation 10 a linear equation.

$$\%R.E.COD = -196.48857 + 0.099158A + 3.25477B - 0.000690AB - 0.010815B^2 \quad (9)$$

$$\%R.E.\ Color = 34.54805 - 0.003865A + 0.629209B + 0.0000024AB + 2.33716*10^{-6}A^2 \quad (10)$$

Where A is the ozone dosage rate (mg/hr), and B is the contact time (min).

Conditional optimization for the COD and color removal using ozonation

From the conditional optimization for treating wastewater from the ethanol production process using ozonation and based on the CCD model, a total of seven conditions were identified. However, the model recommended the optimal condition for both COD and color removal to be at an ozone dosage rate of 1,500 mg/hr and a contact time of 116.88 minutes. Under these conditions, the COD removal efficiency was 63.99%, and the color removal efficiency was 75.79%, with an overall desirability score of 0.995, as shown in **Figure 3**. Since this value is close to 1.00, it indicates that the optimal condition for treating ethanol production wastewater using the ozonation process, derived from the mathematical model, is highly reliable [21].

A set of experiments was conducted to validate the optimal treatment conditions obtained from the model. The experiment was performed in triplicate using the conditions recommended by the model, an ozone dosage rate of 1,500 mg/hr and a contact time of 117 minutes. The average COD removal efficiency was found to be 62.99 ± 0.68%. This experimental result was very close to the model's predicted value, with only a 1.602% deviation. The average color removal efficiency was 73.22 ± 0.62%, also closely matching the model's prediction, with a 3.51% deviation. These results confirm that the CCD model is both reliable and suitable for determining the optimal conditions for treating wastewater from the ethanol production process using ozonation, as the deviation between the experimental results and the mathematical model was less than 10% [10]. It is important to emphasize that the resulting model is constructed only from data within the specified experimental range (900-1,500 mg/hr and 60-120 minutes) and should not be used for prediction outside this range, as treatment efficiency may not always follow the predicted trend. Furthermore, while the absolute optimal condition found is highly accurate for the batch tested, the characteristics of wastewater from ethanol production can vary across different production batches. Therefore, the application of the developed CCD model serves as an effective tool for rapidly and accurately adjusting the optimal conditions to accommodate this wastewater variability.

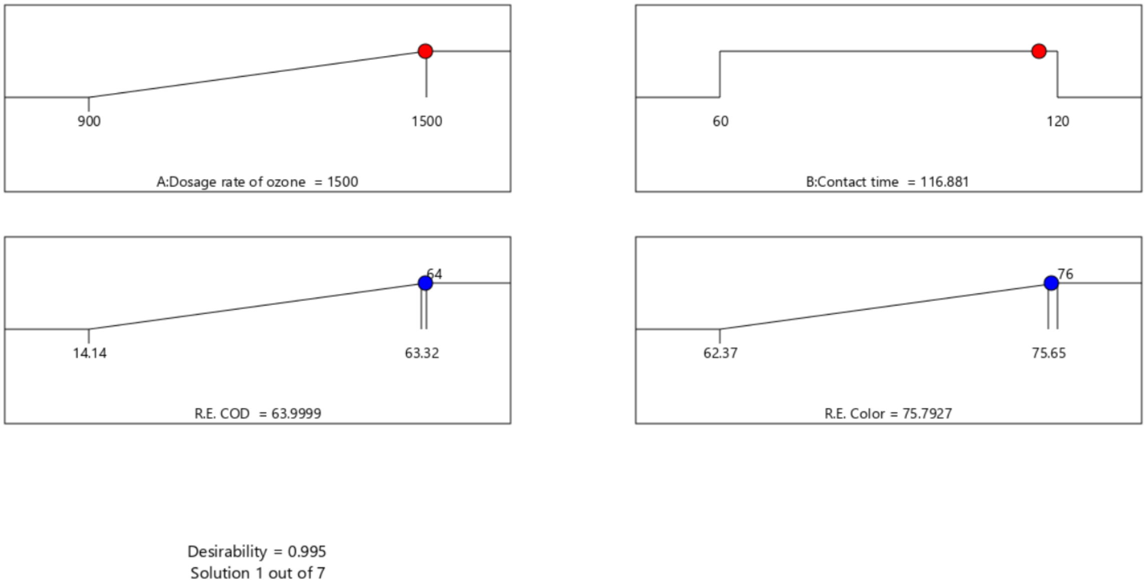

Figure 3 Desirability ramps for COD and color removal using ozonation at the optimal conditions

Conclusions

This research focuses on the treatment of wastewater from ethanol production using the ozonation process. Two key factors affecting the treatment efficiency were considered: the ozone dosage rate and contact time. It was found that an ozone dosage rate of 1,500 mg/hr and a contact time of 120 minutes resulted in the highest removal efficiencies of COD and color, which were 63.32 ± 1.28% and 75.65 ± 1.42%, respectively.

Statistical analysis revealed that both factors significantly influenced COD and color removal efficiencies. A quadratic model was found to be suitable for predicting COD removal efficiency, while a linear model was appropriate for predicting color removal efficiency. Based on conditional optimization, the model recommended the optimal conditions for COD and color removal at an ozone dosage rate of 1,500 mg/hr and a contact time of 116.88 minutes, yielding a COD removal efficiency of 63.99% and a color removal efficiency of 75.79%, with a desirability of 0.995, indicating a high level of suitability. The findings from this research can be applied to wastewater treatment in ethanol production plants or other processes with similar wastewater characteristics.

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People's Perception and Water Consumption Behavior in High Fluoride Risk Area

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Abstract

Fluoride contamination in groundwater remains a persistent environmental and public health challenge in northern Thailand, where natural geological formations contribute to elevated fluoride concentrations. This study aimed to assess residents' awareness of fluoride-related risks, drinking water practices, and acceptance of defluoridation technologies in high-fluoride areas of San Kamphaeng District, Chiang Mai Province. A total of 205 residents were interviewed using a structured questionnaire. The results showed that bottled water was the most commonly used for household water consumption, accounting for 66.9% for drinking and 42.3% for cooking. However, some households in high-fluoride villages still relied on untreated groundwater, with drinking and cooking accounting for up to 4.2% and 14.3% of total daily water use, respectively. Although 92.7% indicated strong support for a community defluoridation system, most respondents demonstrated limited knowledge of fluoride contamination and its health implications. No significant effects of gender or age were observed regarding knowledge, perceived risk, perception of groundwater use, or the desire for defluoridation system. These findings underscore the need for strengthened public education and community-based communication strategies to promote safer water consumption and support long-term access to safe drinking water.

Keywords: People perception; Water consumption behavior; Fluoride contamination; Groundwater; and Tap water

Introduction

In many parts of the world, groundwater is used to produce drinking water because it is of higher quality and has less microbial contamination than surface water. Additionally, some regions have few sources of surface water or contaminated surface water. Therefore, groundwater is a better source of raw water for drinking water. However, due to geochemical properties, groundwater can occasionally become naturally contaminated. The two main examples of naturally occurring contaminants in groundwater are fluoride and arsenic. The presence of fluoride in drinking water can reduce the incidence of dental caries when its concentration lies in the optimal range of 0.5-0.7 mg/L [1]. On the other hand, excessive levels of fluorosis can result in a variety of issues, from mild dental fluorosis to disabling skeletal fluorosis as the level and duration of fluoride exposure increase [2]. The effects of fluoride overdose can be acute and chronic. Acute fluoride poisoning may cause symptoms such as nausea, vomiting, abdominal pain, and diarrhea, and in severe cases, it can be fatal. Chronic exposure, which is more common in communities relying on naturally contaminated groundwater, often results in dental fluorosis, characterized by white or brown discoloration on the tooth surface. In more severe cases, prolonged exposure can lead to skeletal fluorosis, causing bone deformities, joint pain, and even spinal abnormalities. In addition to dental and skeletal effects, fluoride toxicity has also been associated with damage to soft tissues. Further investigated the effects of high fluoride exposure on kidney and liver function, with findings providing strong evidence of significant renal and hepatic impairment at elevated fluoride doses [3].

In several regions of Thailand, including rural communities in Chiang Mai, groundwater is severely contaminated with fluoride, often exceeding the World Health Organization (WHO) guideline of 1.5 mg/L, leading to dental and skeletal fluorosis among affected populations. In Thailand, the national standard for fluoride in drinking water is set at a maximum of 0.7 mg/L, with a permissible limit of 1.0 mg/L (**Table 1**).

Table 1 Fluoride concentration standards in drinking water established by various regulatory bodies

Organization	Guideline value (mg/L)	Reference
WHO	≤ 1.5	[4]
Provincial Waterworks Authority	≤ 1.0	[5]
Ministry of Natural Resources and Environment	≤ 0.7 (max 1.0 mg/L permissible)	[6]
Department of Health	≤ 0.7	[7]
Ministry of Public Health	≤ 0.7	[8]

Fluoride removal from water can be achieved through coagulation, ion exchange, reverse osmosis, and adsorption. Coagulation removes fluoride via chemical precipitation and is cost-effective, but it offers only moderate removal efficiency. Ion exchange achieves high fluoride removal by replacing fluoride ions with other anions, though it requires regular regeneration and operational control. Reverse osmosis removes fluoride via membrane separation and achieves very high removal efficiency; however, it entails high costs, energy consumption, and wastewater generation. Adsorption removes fluoride via surface binding to materials such as activated alumina or bone char and is widely used due to its simplicity, low cost, and effective removal performance. However, the adoption of these techniques remains low.

Behavioral factors influencing people's safer water consumption in areas contaminated with fluoride are crucial determinants. Despite widespread documentation of fluoride contamination in groundwater, limited evidence exists on the relationship between residents' awareness of fluoride-free water and their actual water-consumption behaviors in high-fluoride-risk areas. This study, therefore, aimed to examine people's awareness of fluoride contamination and their water-consumption behaviors in high-risk areas for fluoride exposure, and also to educate risk perception and promote informed decision-making regarding daily water use.

Methodology

The study area was Buak Khang Municipality, San Kamphaeng District, Chiang Mai, Thailand **(Figure 1)**. As of 2025, the population of Ban Buak Khang Subdistrict was 8,772. The area had a high fluoride risk, with groundwater contamination ranging from 0.7 to 10 mg/L [9]. Data collection was conducted from May 2024 to December 2024. It involved engagement with community leaders who were invited to facilitate voluntary participation of residents in the survey. The study employed a convenience sampling method, and participants were required to meet the following inclusion criteria: be Thai, be at least 20 years old, live in high-fluoride-risk areas for at least 3 months, and be willing to participate in the survey. A final sample of 205 participants was included in this study. This number is consistent with prior behavioral and community-based survey research, such as a cross-sectional survey of 220 participants across five communities, in which the authors acknowledged that although the sample was smaller than ideal, it was adequate for the analyses performed and for interpreting the overall intervention package [10].

A structured questionnaire was used to collect information on respondents' demographic characteristics, awareness of fluoride and its associated health risks, water consumption behaviors, and acceptance of defluoridation technologies in communities exposed to high groundwater fluoride levels. The questionnaire items were adapted from previously validated instruments used in behavioral studies on safe water practices and fluoride-related health risks [11, 12]. The items were modified to fit the local context and research objectives, ensuring relevance to communities at risk of fluoride exposure. The questions were constructed based on knowledge of fluoride, living in a fluoride-risk area, perceptions of groundwater, and desire for a defluoridation system. The questionnaire was reviewed and approved by the Chiang Mai University Research Ethics Committee (CMUREC No. 67/172).

All data were analyzed using Microsoft Excel (version 2404, Build 16.0.17531.20120) and IBM SPSS Statistics (version 30.0.0.0 (172)) for descriptive analysis, chi-square tests, and independent t-tests.

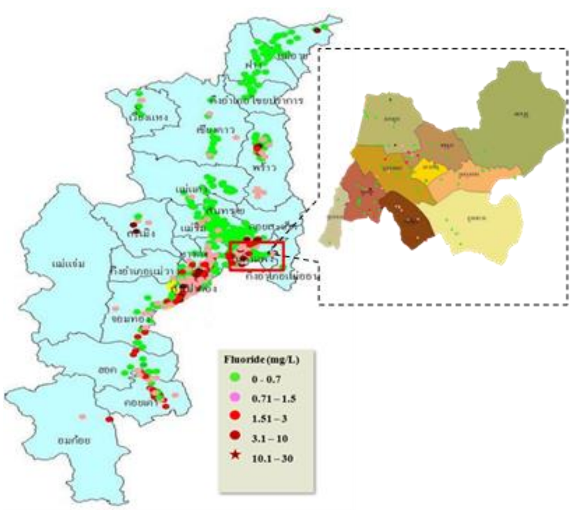

Figure 1 Fluoride contamination in groundwater in San Kamphaeng District [9]

Results and Discussion

The socio-demographic characteristics of 205 survey participants are presented in **Table 2.** Most participants were female (60.5%), with an average age of 56 years and an average of 46 years in fluoride-risk areas. Most of their careers included employees (56.1%), personal business (20.0%), farmers (13.2%), housekeepers (3.4%), and unemployed (1.0%).

Table 2 Socio-demographic characteristics of the respondents (N=205)

Characteristics	Value
Gender (%)	
Male	38.0
Female	60.5
Unspecified	1.5
Age (year)	
Mean ± S.D.	56.7±11.7
Living period (year)	
Mean ± S.D.	46.9±18.5
Career (%)	
Personal Business	20.0
Employee	56.1
Housekeeper	3.4
Farmer	13.2
Unemployed	1.0
Unspecified	6.3

Table 3 presents 10 questions administered to respondents regarding their understanding of fluoride contamination in water, perceived risk of high fluoride levels, perceptions of groundwater, and desire for a defluoridation system. Cronbach's alphas, which measure internal consistency, for questions on knowledge of fluoride and risk were 0.778 and 0.817, respectively. These numbers indicate acceptable (>0.7) to good (>0.8) levels [13].

The respondents had limited general knowledge of fluoride contamination; 21.0-32.2% demonstrated a correct understanding. The lowest score (21%) was for understanding that the safe level of fluoride in drinking water should be ≤0.7 mg/L. This demonstrates a lack of detailed knowledge about fluoride, which may be due to limited public communication and health education on fluoride risks, despite the broad promotion of public health interventions such as water safety [14, 15]. Few respondents recognized that they lived in regions at risk of fluoride exposure (18.0%) and that they could be exposed through drinking water and food preparation (34.1%). In addition, 32.7% of respondents reported that groundwater is safe for drinking, whereas the remaining 67.3% perceived it as unsafe. This reflects a substantial lack of confidence in groundwater quality. The survey also revealed that most respondents (92.7%) expressed a desire for a defluoridation system to treat their water.

The results show apparent inconsistency between low levels of knowledge and perceived risk and high demand for defluoridation systems. It may be due to respondents perceiving general signs of poor water quality or having observed health problems in their community, such as dental discoloration. As pointed out by Chamnanprai et al. [9], who reported dental fluorosis in 15.6% of children in Chiang Mai, based on a survey of 167 participants in high-fluoride areas, but did not fully elucidate the specific role of fluoride or its long-term health effects. Their demand for defluoridation may, therefore, be driven more by indirect risk perception or past experiences with unsafe water. Consequently, this underscores a significant discrepancy between perceived water safety and the actual fluoride-related risks, emphasizing the necessity for public education alongside the deployment of effective fluoride-removal technologies. This initiative should include the development of informational materials on the long-term toxicity associated with consuming fluoride-contaminated water. Furthermore, community meetings and public forums are vital for reinforcing the roles of local authorities and public health agencies in advocating for the use of fluoride-free water and for disseminating information on fluoride-related health risks through local communication channels, such as village audio announcements.

The analysis examined associations between demographic characteristics, including gender and age group, and the four constructs: knowledge of fluoride, living in a fluoride-risk area, perception of groundwater, and desire for a defluoridation system. No significant relationships were found between gender and fluoride knowledge (male = 1.18; female = 1.40; t = -0.99, p = 0.322), living in a fluoride-risky area (male = 0.71; female = 0.88; t = -1.061, p = 0.290), groundwater perception (male = 0.71; female = 0.65; t = 0.860, p = 0.391), or desire for a defluoridation system (male = 0.94; female = 0.92; t = 0.428, p = 0.669). Younger respondents, 20-40 years old, had a higher average score of knowledge items (1.59) than those in their 41-60 (1.27) and 61-85 (1.28), but no significant difference (F = 0.461, p = 0.631). When asked about perceived risk of living in a fluoride-exposed area, younger respondents reported the lowest average score (0.78) compared with those in the 41-60 (0.83) and 61-85 (0.81) age groups, but the differences were not statistically significant (F = 0.025, p = 0.976). Young respondents also had the lowest groundwater perception score (0.52), whereas 41-60 (0.68) and 61-85 (0.72) did not differ significantly (F = 1.840, p = 0.162). For the desire for a defluoridation system, young respondents showed the lowest score (0.89), while 41-60 (0.93) and 61-85 (0.94) did not differ significantly (F = 0.337, p = 0.714). In sum, they did not differ across demographic groups, indicating that these concerns are shared broadly within the community

Most respondents purchased water for daily drinking: bottled water (66.9%) and vending machines (13.5%). A small proportion (2.3%) of respondents drank water from filtered systems. Some respondents used groundwater (2.3%). **Figure 2** maps respondents' drinking water sources and the levels of fluoride contamination in water by villages. The respondents in villages with high fluoride levels (0.71-10 mg/L): Buak Khang Moo 1, Roi Phrom, Rong Kong Khoa, Buak Khang Moo 2, Ban Du, and Ko Sa Laemg reported their groundwater use for drinking, with the highest use at Roi Phrom 4.2%. This indicates that the respondents in villages with high fluoride levels are experiencing distressing fluorosis-related health problems. The health impacts of fluoride are chronic, not acute, meaning that prolonged exposure to high fluoride levels is required to adversely affect humans. The occurrence of dental fluorosis is directly dependent on groundwater fluoride content and the dietary intake of fluoride-containing drinking water [16]. Recent studies reported that high levels of fluoride intake would cause detrimental health effects such as dental fluorosis, skeletal fluorosis, and hypertension [17]. However, the severity of fluoride toxicity may vary with groundwater fluoride concentration, ingestion rate, duration of exposure, and local climate factors, such as air temperature, a key driver of daily water intake. For instance, exposure to groundwater fluoride levels above the safe limit led to the development of dental fluorosis (1.5-3 mg/L), skeletal fluorosis (3-6 mg/L), and bone crippling (>6 mg/L) in human individuals [18].

Regarding the water source for cooking, most respondents used bottled water (42.3%) and tap water (37.5%). The respondents also use groundwater for cooking, which accounted for a higher proportion (4.4%) than for drinking water. In Roi Phrom village, where high groundwater fluoride levels were detected, 14.3% of respondents reported using groundwater for cooking (**Figure 3**). Using groundwater or tap water containing fluoride at concentrations as high as 10 mg/L can be harmful to human health in the long term. When fluoride-containing water is used to soak rice or boil vegetables, fluoride accumulates in the rice or vegetables, causing indirect fluoride intake from food and potentially becoming a significant source of daily fluoride exposure. Thus, the fluoride intake from food cooked in boiling water is comparable to, or even greater than, that from drinking water [19]. These survey results suggest that even households that do not directly consume groundwater for drinking water may still face substantial fluoride exposure through food preparation. Prolonged consumption of such food may contribute to dental and skeletal fluorosis, particularly among children and the elderly. Therefore, raising public awareness of the risks of fluoride in cooking practices in addition to drinking is also essential.

The household water expenditure survey for domestic use. The findings indicate that the average monthly expenditure on drinking water was 191 ± 247.2 THB (1 THB ≅ 0.03 USD) per household, while the average expenditure on cooking water 184.5 ± 207.8 THB per household. Data from the Provincial Waterworks Authority indicated that community-level household water expenditures vary considerably depending on several factors, including the source of purchased water, the availability of local water resources, and the overall volume of household consumption. In general, such expenditures have been observed to range between 100 and 500 THB per household per month. In the present study, the combined average monthly expenditure for both drinking and cooking water among sampled households was 375.6 ± 352.1 THB.

When respondents were asked about their willingness to pay for drinking and cooking water, they reported substantially lower amounts, at 143.9 ± 164.9 THB per household per month. This discrepancy indicates that actual household expenditure was 1.61 times the preferred amount, thereby implying a considerable economic burden associated with accessing clean water for domestic consumption. Such findings may further reflect structural limitations, including inadequate local water sources and infrastructure deficiencies that constrain equitable access to safe water. Consequently, strategies to mitigate the financial burden of household water expenditure should prioritize the promotion of safe, affordable alternative sources. Examples include using certified piped water or adopting household-level treatment technologies, such as filtration and disinfection systems. In parallel, public participation in efficient and safe water management should be strengthened to align with community needs.

Table 4 shows the respondents' satisfaction with the current water's color, odor, and taste. Median satisfaction scores were 5 out of 6 for all parameters. The independent t-test analysis revealed no statistically significant differences between genders concerning satisfaction with water color or odor ($p > 0.05$). However, for cooking water, a significant difference in taste satisfaction was observed between males and females ($t = -1.981$, $df = 200$, $p = 0.049$), with females reporting lower satisfaction than males. This suggests that women may be more sensitive to, or have higher expectations for, the taste of water used for cooking, which could influence household water-use preferences and practices. As reported from previous studies, females generally perform better in taste function tests compared to males [20], and women are more likely to perceive tap water taste negatively than men [21].

Table 3 Residents' understanding of fluoride contamination in water and risk (N=205)

Construct	Cronbach's alpha	Item	Percentage of correct understanding/ acceptance (%)
Knowledge on Fluoride	0.778	Safe level of fluoride in drinking water ≤0.7 mg/L	21.0
		High fluoride water cannot be detected by the naked eye or smell	32.2
		High fluoride water cannot be safely treated by boiling or filtering with a household filter	30.2
		Fluoride in water should be treated by reverse osmosis or adsorption system	20.5
		Fluoride is added in water, milk, or salt to prevent dental caries in some countries	27.8
Living in a fluoride risky area	0.817	I live in area at high fluoride risk	18.0
		I may expose to high fluoride levels through drinking water or cooking	34.1
		My community may expose to high fluoride levels through drinking water or cooking	29.3
Groundwater Perception	-	I think groundwater is drinkable	32.7
Desire for defluoridation	-	My household want defluoridation system for water consumption	92.7

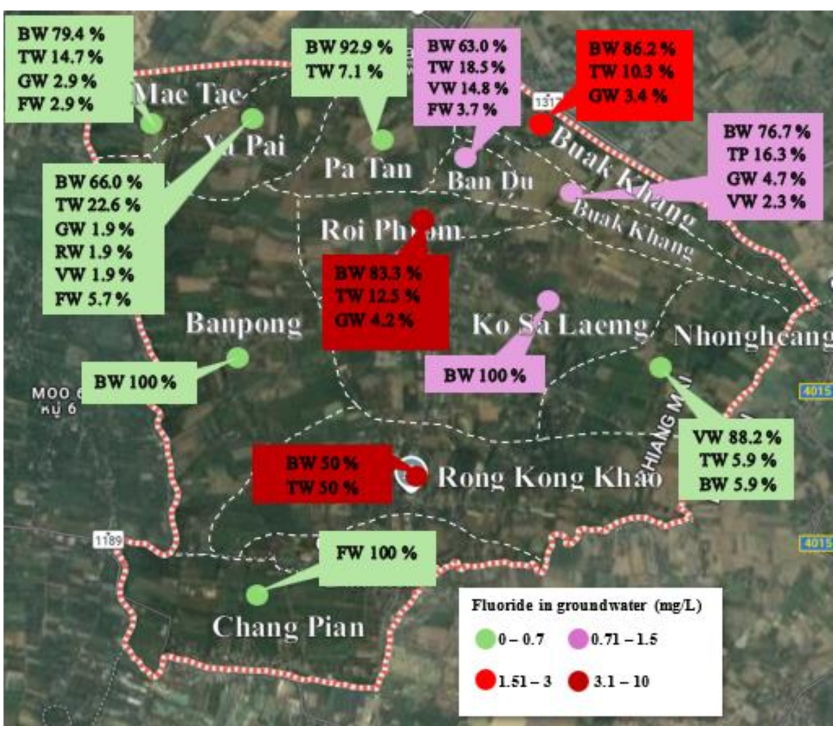

Figure 2 Water sources used for drinking in the study area.

Description: RW=Rainwater, GW=Ground water, TW=Tap water, BW=Bottled water, VW=Vending machine water, FW=Filtered water home use. Proportion equals 100% for each village.

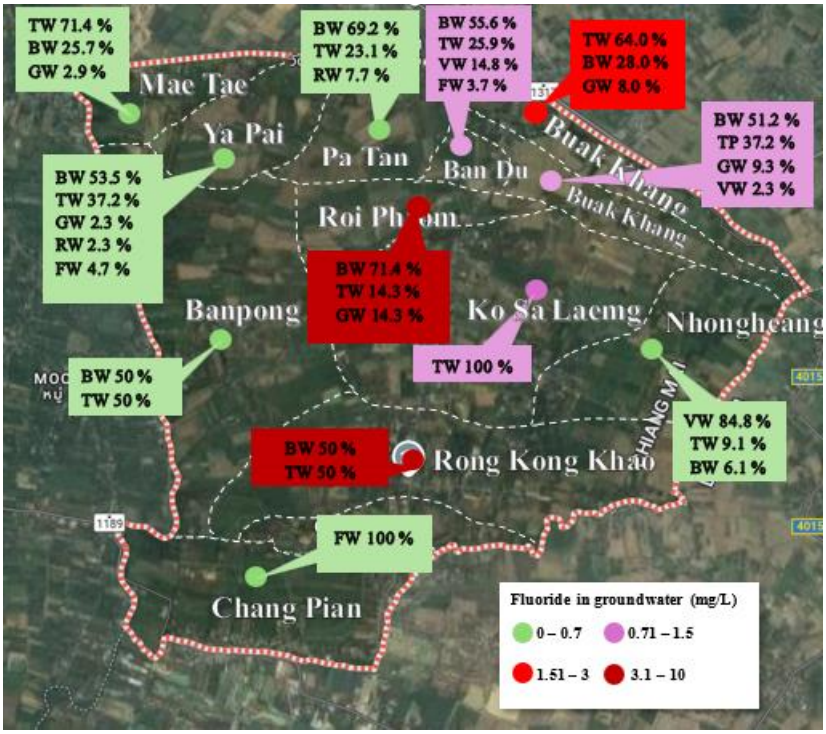

Figure 3 Water sources used for cooking in the study area.
Description: RW=Rainwater, GW=Ground water, TW=Tap water, BW=Bottled water, VW=Vending machine water, FW=Filtered water home use. Proportion equals 100% for each village.

Table 4 Households' satisfaction with water consumption

Purpose	**Mean ± S.D.**		**Median***
Drinking	Male (N=79)	Female N=126)	All (N=205)
Color	4.4 ± 1.8	4.7 ± 1.4	5
Odor	4.2 ± 1.9	4.6 ± 1.6	5
Taste	4.8 ± 1.2	4.7 ± 1.4	5
Cooking	Male (N=79)	Female (N=126)	All (N=205)
Color	4.2 ± 2.0	4.1 ± 2.1	5
Odor	3.9 ± 2.1	3.8 ± 2.2	5
Taste	4.5 ± 1.7	3.8 ± 2.1	5

*Response level provided from 6 = strongly satisfied to 1 = strongly dissatisfied.

Conclusions

The present study provides insight into local water consumption behaviors and levels of understanding of fluoride risk among residents living in a high-fluoride-contaminated area, Buak Khang municipality, San Kamphaeng district, Chiang Mai, Thailand. The study found that participants living in high-fluoride areas demonstrated limited knowledge of fluoride contamination and low awareness of its health risks. Neither gender nor age was significantly associated with knowledge, perceived risk, perception of groundwater use, or desire for the defluoridation system. Although bottled water was commonly used for drinking and cooking purposes, reliance on groundwater and tap water in some locations indicates ongoing exposure risks. Furthermore, the results revealed that groundwater used for cooking accounted for a higher proportion than groundwater used for drinking. Despite limited awareness of the risks of fluoride, respondents strongly desire a defluorination system for their water. This reveals a gap between perceived safety and actual risks, highlighting the need for public education and effective fluoride removal. Policy-focused recommendations include routinely monitoring household and community water quality, promoting the use of household defluoridation technologies, and encouraging the use of fluoride-safe water for drinking and cooking. These recommendations ensure that residents have access to clean water in their daily lives, in line with Sustainable Development Goal 6 on Clean Water and Sanitation.

The questionnaire and interview methods employed in this study were instrumental in enhancing respondents' knowledge and awareness regarding fluoride-related issues following participation. Moreover, these methods provided valuable insights into the knowledge, perceptions, and behaviors of individuals residing in areas at risk of fluorosis. However, the results were based on a limited sample of 205 participants; future research could expand the sample to more representative groups. The method used also relied on self-reported data, which may introduce recall or perception biases inherent to questionnaire-based surveys. Additionally, the study employed a cross-sectional design, providing a snapshot of awareness, behaviors, and water conditions at a specific point in time but not capturing potential seasonal or temporal variations. Future research may incorporate longitudinal assessment.

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Application of Submerged Nanofiltration Membrane for Treating Natural Organic Matter from Reservoir Water

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Abstract

Surface water quality continues to be compromised by expanding residential and industrial activities. Chlorine is widely used in conventional treatment systems due to its low cost and availability; however, its reaction with natural organic matter (NOM) generates disinfection by-products (DBPs), particularly trihalomethanes, which are known as human carcinogens. Despite the increasing interest in nanofiltration (NF) membranes, studies on the application of submerged NF systems for treating real surface water without pretreatment remain limited, especially regarding trihalomethane precursor removal, ion rejection, and permeate stability. Comparative data with conventional treatment systems is also insufficient. This study investigates the performance of a submerged NF membrane relative to a conventional treatment system in a previous study for NOM removal. Water samples were collected every three days from Ang Kaew Reservoir, and the NF system was operated at a constant flux of 11 $L/m^2 \cdot h$. All samples were analyzed at the Environmental Engineering Laboratory, Chiang Mai University. The NF membrane achieved significant reductions in turbidity (93-98%), electrical conductivity and total dissolved solids (36-65%), UV254 (74-89%), dissolved organic carbon (68-80%), and trihalomethane formation potential (66.54%). In contrast, the conventional system exhibited limited ion removal and, in some cases, increased ion concentrations. These results indicate that submerged NF membranes offer superior ion rejection and effective control of DBP precursors, demonstrating their potential for producing high-quality drinking water from surface water under stable operating conditions.

Keywords : disinfection by-products; nanofiltration; natural organic matter; submerged membrane; trihalomethanes

Introduction

The demand for tap water is continuously increasing. Additionally, water contamination problems are exacerbated by the ongoing expansion and development of urban housing, industrial activities, and surface runoff. Therefore, effective water management is essential to maintaining water quality. In conventional treatment systems, chlorine is commonly used as a disinfectant. However, DBPs are formed when chlorine reacts with NOM present in the water. These DBPs are considered carcinogenic and may pose significant risks to human health. Among the most concerning DBPs are trihalomethanes (THMs) [1]. Potential health risks associated with DBPs include congenital abnormalities, early pregnancy loss, and an increased incidence of bladder cancer. DBPs have been identified in association with the use of the four primary disinfectants—chlorine, chloramines, ozone, and chlorine dioxide—as well as with newer disinfection technologies such as ultraviolet treatment followed by post-chlorination [2, 3]. Sriboonnak et al. [4] reported that the maximum concentration of THMs detected was 189.52 µg/L at the point following sodium hypochlorite disinfection in a conventional water treatment system. The World Health Organization (WHO) sets guideline values for each trihalomethane compound to lower the long-term health risks of drinking water. According to WHO guidelines, the recommended values are 300 µg/L for chloroform (CF), 100 µg/L for bromoform (BF), 100 µg/L for dibromochloromethane (DBCM), and 60 µg/L for bromodichloromethane (BDCM). WHO emphasizes that these values should not be combined into a single "total THMs" limit because each compound has different toxicological characteristics. Instead, WHO recommends assessing cumulative risk by calculating the ratio of the measured concentration of each compound to its respective guideline value and summing these ratios. The total must not exceed 1 for the water to be considered safe for consumption [1].

Previous studies have highlighted that the removal of DBP precursors, such as NOM, is a critical step in minimizing the formation of THMs and haloacetic acids (HAAs). Techniques including enhanced coagulation, granular activated carbon adsorption, and membrane filtration have been widely investigated for their effectiveness in precursor removal [5, 6]. Alternative disinfection strategies, such as ozone, chloramines, or ultraviolet treatment followed by post-chlorination, can reduce the formation of certain DBPs, yet they may also generate new by-products with potential toxic effects [2]. Although membrane technologies, particularly NF membranes, have demonstrated strong performance in reducing DBP precursors, most studies have been conducted under controlled laboratory conditions or using pressurized NF systems, with limited evidence from submerged NF systems treating real surface water sources [7, 8]. In addition, long-term operational data regarding permeate stability, fouling behavior, cleaning frequency, and ion rejection under variable raw water conditions are scarce. These limitations indicate a clear knowledge gap: there is a need for comprehensive field-based studies to evaluate the effectiveness, reliability, and operational feasibility of submerged NF membranes in minimizing DBP formation in actual surface water treatment scenarios, particularly in regions with variable water quality and limited treatment infrastructure.

NF membranes have a wide range of applications, with wastewater treatment and drinking water production being among their primary uses. NF membranes are versatile and can be employed to treat various water sources, including groundwater, surface water, and wastewater. Additionally, they are often utilized as a pre-treatment step in seawater desalination processes, enhancing overall system efficiency and membrane lifespan [9]. The widespread application of membrane technologies has contributed significantly to the reduction of particulate matter and NOM concentrations in drinking water. The effectiveness of these membrane-based treatments depends on several factors, including membrane type, physicochemical properties, module configuration, operating conditions, and overall system efficiency [10]. Particulate and dissolved pollutants, such as synthetic organics, salts, hardness, pathogenic bacteria, and DBP precursors, are effectively eliminated by NF membranes. Additionally, in terms of regulating dissolved organic matter (DOM), membrane separation competes with other cutting-edge treatments like granular activated carbon when used in conjunction with the current water treatments. Additionally, membrane separation is competitive in the economy of the future because of the ensuing technological advancements [11]. Sentana *et al.* [12] reported that the amounts of DBPs in natural waters decreased when NF membranes were used. Three commercial NF membranes—models NF270, NF90 (Dow Chemical Inc.), and Desal-HL-51 (GE Water)—have been used to investigate the manufacturing potential of trihalomethane and haloacetic acid (THMFP and HAAFP). The NF90 membrane reduced more than 90% of the possibility of generating DBCM and BDCM. The NF270 and Desal-HL-51 membranes decreased less THMFP. A submerged membrane system is used to separate suspended particles, microbes, and other contaminants. The operation of a submerged membrane system involves submerging the membrane module directly into water. The submerged membrane technology takes far less space than the conventional treatment system. Additionally, this system has outstanding fouling resistance [13]. This study aimed to evaluate the efficiency of a submerged NF membrane, operated without any pretreatment, in reducing THMFP to produce clean water with minimized health risks.

Materials and Methods

Experimental protocols

Water samples were collected from Angkaew Reservoir every three days over a two-week experiment period. The samples were subsequently analyzed for physical and chemical characteristics at the Department of Environmental Engineering, Chiang Mai University. The laboratory-scale was operated at a constant permeate flux of approximately 11 $L/m^2.h$ and maintained at a feed temperature of 20 °C. Daily, 200 mL of permeate was collected and immediately analyzed for water quality parameters. Dissolved organic carbon (DOC) analysis was performed on a weekly basis, with samples stored under refrigeration until analysis. The THMFP was analyzed once during the experiment. Membrane cleaning was carried out every six days by gently scrubbing the membrane surface with a sponge prior to initiating a new experimental cycle. The specific ultraviolet absorbance (SUVA) was determined to assess the aromaticity of DOM in water samples. SUVA was calculated using the following equations:

$$SUVA = \frac{UV254\ (1/cm)}{DOC(mg/L)} x100 \qquad \textbf{Equation 1}$$

Analysis

The electrical conductivity (EC) and total dissolved solids (TDS) were measured using a portable conductivity analyzer (Starter 300C, OHAUS Corporation, USA). Every sample underwent turbidity analysis (Merck, Turbiquant 1100 IR, Sigma-Aldrich Canada Co., or Millipore (Canada) Ltd., Canada). A 0.45-micron nylon membrane filter was used to pre-filter each sample. A TOC analyzer was used to measure the DOC (Multi N/C 3100, Analytikjena, Germany, Standard Method 5310). A UV/VIS spectrophotometer (Lambda365, Perkin Elmer, Perkin Elmer Inc., Boston, MA, USA, Standard Method 5910B) was also used to measure the sample's ultraviolet absorbance at 254 nm (UV254). Chlorination of the raw water and permeate was performed in amber glass bottles at target doses of 10.28 mg/L and 2.85 mg/L, respectively. The chlorinated samples were then stored in the dark for 24 hours. The concentration of free chlorine was determined in accordance with standard methods [14] and maintained in the range of 1-2 mg/L during the experiment to ensure that sufficient residual chlorine remains in the system to completely react with the organic matter. The amount of THMs was determined by adding 5.0 g of sodium sulfate anhydrous to 25 mL of the sample solution in 40 mL amber vials. After that, the mixture was vigorously agitated to create a uniform mix. A 2.5 mL solution of tert-butyl methyl ether (MTBE) was added, and the mixture will be extracted for three minutes. The top layer of MTBE was used for concentration analysis via gas chromatography spectrometry (GC) with an electron capture detector (ECD) system (Agilent 4890D (EPA

551.1)). The GC column uses a VF-X fused silica capillary column (30 m × 0.32 mm × 0.1 micron), and helium was used as a carrier gas. Samples were injected into split mode (5:1) at 200 °C. The oven was programmed from 45 °C to 130 °C at 5 °C/min. The ECD was maintained at 250 °C with nitrogen makeup gas at 45 mL/min. Standard THM solutions in methanol were used for calibration.

Nanofiltration membrane and module

This study employed the NF270 membrane (DuPont/FilmTec, Midland, MI, USA), with a total effective filtration area of 56 cm^2. The membrane was operated in a submerged configuration using an outside-in filtration mode. Initially, the pure water flux was determined by filtering deionized water through the submerged NF270 membrane. Subsequently, the collected water samples were analyzed and subjected to the filtration process. The membrane system is installed as shown in **Figure 1**.

Results and Discussion

Membrane Properties

The NF270 membrane (DuPont/Filmtec, USA) is a thin-film polyamide NF membrane that removes solutes via size exclusion and electrostatic interactions [15]. Its active layer contains carboxylic and amine groups and exhibits characteristic polyamide absorption peaks [16, 17]. NF270 is hydrophilic (contact angle ~27–30°), which enhances water permeability and reduces organic fouling [18, 19]. It remains negatively charged across pH 2-10, lacking an isoelectric point in this range [20].

Quality of water in reservoir

The pH values of the water samples fell within the neutral range, between 7.5 and 8.5. The raw water quality parameters are summarized in **Table 1**. While the EC and TDS of the raw water were within acceptable limits, its turbidity exceeded the standard threshold. The concentration of DOC was measured at 3.55 mg/L, and the UV254 was 0.0947 cm^{-1}. The SUVA index was calculated by dividing the UV254 absorbance value by the DOC concentration and multiplying the result by 100 [21]. The SUVA value below 2 L/(mg·m) typically indicated that the organic matter is predominantly composed of aliphatic hydrocarbons or non-humic substances with low hydrophobicity. In contrast, a SUVA value above 2 L/(mg·m) suggests the presence of hydrophobic and hydrophilic NOM, aromatic hydrocarbons, or aquatic humic substances [22]. The calculated SUVA value for this water source was 2.66 L/(mg·m), indicating that the organic matter present was primarily humic in nature, with a significant proportion of aromatic hydrocarbon structures.

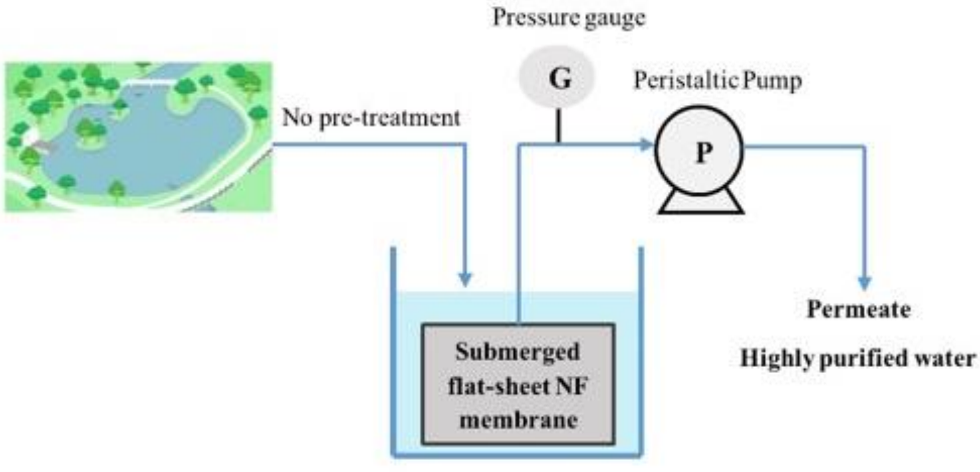

Figure 1 Experimental setup

Table 1 Characteristics of a water source

Parameters	Unit	Value	Standard*
pH	s.u.	8.48 ± 0.48	6.5-8.5
EC	µS/cm	141.0 ± 5.30	<500**
TDS	mg/L	70.3 ± 2.54	<600
Turbidity	NTU	11.36 ± 1.62	<4
UV254	cm^{-1}	0.0947 ± 0.01	-
DOC	mg/L	3.55 ± 0.22	-

*Water supply quality standard in Thailand
**Guidelines of Drinking Water Quality, 4^{th} ed.; World Health Organization (WHO)

Operational stability

Minimal fouling occurred during the experiment when surface water was directly treated using NF at a low permeate flux, resulting in a slight increase in transmembrane pressure (TMP) from 90 to 92 kPa **(Figure 2)**. Following membrane cleaning, the TMP exhibited a modest decrease, indicating that the system operated in a relatively stable manner throughout the experiment. The cleaned membrane was subsequently reused for further experiments, confirming that the cleaning procedure effectively restored membrane performance without compromising rejection efficiency. In the previous study, Fujioka *et al.* [13] indicated that the TMP increased from 35 to 37 kPa. Given that many of Thailand's water sources are characterized by high concentrations of organic matter and turbidity, the relatively high TMP observed in this study is not unexpected. Nonetheless, the TMP increase of approximately 2 kPa observed in both studies suggests that the low and stable permeate flux operation was a key factor contributing to this moderate fouling. Despite variations in the quality of the water sources, the system demonstrated consistent performance throughout the experiment.

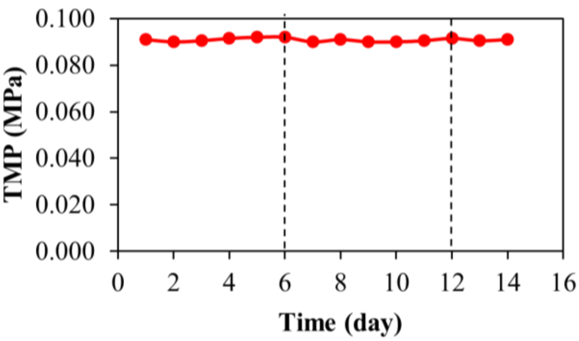

Figure 2 TMP changes when the reservoir is treated with NF at low permeate flux

The UV254 and DOC results are presented in **Figure 3b**. The submerged NF membrane system demonstrated a high efficacy in rejecting organic compounds, with removal efficiencies ranging from 74% to 89%. This rejection corresponded to organic molecules, such as aromatic hydrocarbons and compounds containing double bonds, as inferred from the characteristics of the raw water. Throughout the operation, the NF membrane was effective in rejecting organic materials with a molecular weight cut-off (MWCO) between 200 and 1000 Da [24]. Consequently, the accumulation of organic matter in the feed tank increased over time. Furthermore, the permeate quality remained highly consistent, exhibiting a very low UV254 value. This suggests that the NF270 membrane is effective in rejecting small particles, particularly aromatic and double-bonded molecules. The NF270 membrane demonstrated a substantial DOC removal efficiency ranging from 68% to 80%, indicating its ability to reject certain organic matter dissolved in the water. The DOC value of the resulting permeate was significantly lower, further supporting the conclusion that DOM are effectively rejected by the NF270 membrane. Additionally, the SUVA index decreased from 2.66 to 1.87 L/(mg·m), reflecting a reduction in the concentration of humic substances. Given that humic compounds share characteristics with polyaromatic hydrocarbons in aqueous environments, these results suggest that the NF270 membrane can effectively reject such compounds as well.

The turbidity of the feed water ranged from 9.17 to 13.54 NTU. Throughout the duration of the experiment, the turbidity of the permeate remained consistently low, ranging from 0.20 to 0.76 NTU. The results indicated that the NF270 membrane was highly effective in removing turbidity from surface water, achieving removal efficiencies between 93% and 98% when employed directly, without any pre-treatment **(Figure 3c)**. These findings demonstrate that the NF270 membrane is particularly efficient in removing larger particles responsible for turbidity in water sources.

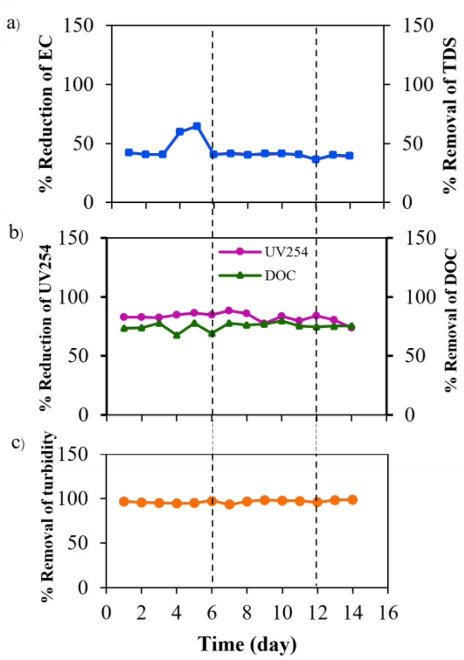

Figure 3 Membrane efficiency in removing (a) EC and TDS, (b) UV254 and DOC, and (c) turbidity over a period of 14 days

These removal rates are broadly consistent with previous literature, though some differences are evident. For instance, in a nanofiltration study using surface water, the NF270 membrane demonstrated nearly 100% UV254 rejection. Meanwhile, in a study on low-SUVA drinking water [25], Dubowski et al. [26] reported DOC rejection of 86-89% and UV254 reduction of 94-96% for NF270 at various pressures. The higher UV254 and DOC removal in those studies compared to ours may reflect differences in feed composition (e.g., aromaticity, molecular weight distribution of natural organic matter) or operating conditions (such as pressure and recovery). Additionally, while our turbidity removal is very high (93-98%), turbidity is not always reported in the NF270 literature, making direct comparison difficult. Overall, despite some variance, our results confirm that NF270 provides strong removal of organics and particulates and performs reliably in real-water applications, similarly to prior bench- and pilot-scale research.

THMFP concentrations

THMs comprise four principal compounds: CF, BDCM, DBCM, and BF. The concentrations of total trihalomethanes (TTHMs) detected in this water source are summarized in **Table 2**. Among the DBPs identified, only two THM species—BDCM and CF—were present. The presence of bromide, a key precursor for brominated THMs, is most plausibly attributed to naturally occurring bromine in groundwater. This bromide can migrate upward and mix with surface water, particularly in regions characterized by bromide-rich geological formations or soil strata. [27]. With respect to THMFP, the presence of natural organic matter in water sources plays a critical role in the formation of THMs, as these compounds are produced when organic constituents react with chlorine during the disinfection process. Evaluating THMFP also provides insights into the characteristics of DOM present in the water. Analytical results revealed a TTHMs concentration of 789.73 ppb in the untreated water source. Following treatment with a submerged NF270 membrane, TTHM levels were reduced by 66.54%. Specifically, the concentrations of CF and BDCM decreased by 51.66% and 84.4%, respectively. Notably, the MWCO of the NF270 membrane exceeds the molecular weights of common THM species (CF = 119.4 g/mol, BDCM = 163.8 g/mol, DBCM = 208.3 g/mol, and BF = 252.7 g/mol), indicating that mechanisms other than size exclusion—such as adsorption or diffusion—may contribute to the observed reductions [28]. Consequently, NF270 removes THMs through the mechanisms of surface adsorption, initial membrane fouling, and gaps between polymer chains [29]. In Thailand, there is currently no explicit national standard for TTHMs in drinking water. Although the Department of Health provides general drinking water quality standards covering various chemical parameters, THMs are not specifically regulated. Some utilities, such as the Metropolitan Waterworks Authority (MWA), refer to the WHO guideline values, using the "sum of ratio" approach to assess compliance and minimize health risks. The overall TTHM ratio for this water source was calculated to be 7.5, which exceeds the recommended safety thresholds. This finding highlights the critical importance of removing NOM from the source water before the chlorination process. By doing so, the formation of THMs during disinfection can be minimized, as NOM plays a key role in the generation of these harmful compounds when chlorine reacts with organic materials in the water.

In the treatment process, the NF270 membrane was used to filter the water, resulting in a permeate with a guideline value (G.V.) of 1.7. While the NF270 membrane effectively reduced the concentration of TTHMs, the G.V. of the treated water remained above the acceptable limit of 1.0. This indicates that, although the treatment significantly lowered the TTHM levels, the water still does not meet the safety standards for direct human consumption. Consequently, further treatment or post-processing would be required to ensure the water is safe for drinking.

Comparison between the conventional treatment system and submerged NF system

Sriboonnak *et al*. [4] indicated that the conventional water treatment systems had an efficiency of removing UV254 and DOC at 74.63% and 58.02%, respectively. The result shows that the efficiency of previous studies is in the same range of removal efficiency as NF, which indicated that NF had higher removal efficiency depending on the water quality. Moreover, Sriboonnak's study showed that the EC in water after conventional treatment increased from 170.0 to 194.7 µS/cm. The result indicated that the ions in water cannot be eliminated by the conventional treatment system, as shown in **Table 3**. In contrast, the NF system can reject only a small number of ions in the water, even though permeate has a relatively high EC (< 88.2 µS/cm). Furthermore, Sriboonnak's research revealed that the disinfection procedure in the conventional system considerably raised the amount of THMs in the water. NOM and THMFP of water treatment processes were studied by Wong *et al*. (2007) [30]. The results indicated that after water treatment, the MSR plant had a removal efficiency of 44%. On the other hand, the NF system had better efficiency and was successful in lowering THMs by 66.54%. Overall, the findings show that NF is a more successful method than the conventional treatment for removing DOM and ions. Conventional coagulation–sedimentation–filtration (CSF) systems can remove turbidity by 84–95% depending on water quality and operating conditions [31]. However, DOC and UV254 removal are generally lower and more variable. Compared to CSF, NF270 provides more consistent and higher removal of DOC and UV254, and achieves nearly complete turbidity removal, demonstrating its superior ability to improve water quality and control disinfection by-product precursors.

The findings of this submerged NF membrane study consistently demonstrate superior performance in NOM removal and DBP precursor control compared to typical conventional water treatment practices. While conventional systems, typically comprising coagulation-flocculation, sedimentation, and rapid sand filtration, are highly effective in removing suspended solids and turbidity [32, 33], their efficacy in eliminating DOM remains a persistent challenge, particularly for hydrophilic and low molecular weight (LMW)

NOM components [33, 34]. Comparative data from various studies highlights this limitation. Internationally, conventional treatment processes have been reported to achieve total organic carbon (TOC) removal efficiencies averaging around 62.8% [26]. In Thailand, a conventional Water Treatment Plant (WTP) in the southern region showed DOC reductions ranging from 56-56.0% [35]. Even when enhanced coagulation is employed, conventional systems may achieve higher UV254 reductions (up to 89.4% in a South African WTP study [35]) because UV254 primarily measures aromatic/humic substances, which are more readily removed by coagulation than the total DOC [35]. In contrast, the submerged NF270 system used in this research achieved high DOC and UV254 removals ranging from 68-80% and 74-89%, respectively, without the need for chemical pretreatment. The most critical advantage of the NF system is its control over DBP precursors. The limited DOM removal by conventional processes means that the subsequent chlorination step frequently generates high levels of THMs. Studies on chlorinated distribution networks in various Thai municipalities, such as Chiang Mai and Khon Kaen, have reported total THM concentrations up to 189.52 μg/L [33] and $CHCl_3$ concentrations as high as 112 μg/L [36]. This finding confirms the significant risk of THM formation in water treated using conventional methods followed by standard chlorination. Conventional treatment processes, which typically rely on coagulation and chlorination, often leave behind organic materials that can react with chlorine during disinfection, leading to the formation of DBPs such as THMs. The results demonstrate that without adequate removal of these precursors, water treated by conventional methods can pose considerable health risk due to elevated DBP levels. In contrast, the NF270 membrane system achieved a substantial 66.54% reduction in THMFP, offering a strong barrier against the creation of DBPs. This level of performance is comparable to other NF applications, which commonly report THMFP rejections in the range of 70-85% [4]. This confirms the inherent superiority of NF technology over conventional coagulation-based methods for effective DBP precursor control [37].

Table 2 THMFP in raw water and permeate water

Samples	**Species of THMs (ppb)**				**TTHMs (ppb)**
	CF	**BDCM**	**DBCM**	**BF**	
Raw	430.71	359.02	ND [b]	ND [b]	789.73
Permeate	208.19	56.02	ND [b]	ND [b]	264.21
Guideline [a]	300	60	100	100	

[a] Guidelines for Drinking Water Quality, 4th ed.; World Health Organization (WHO)
[b] ND = Not detected, if the concentration was lower than 10 ppb (< 10 μg/L)

Table 3 Analysis of the differences between conventional treatment systems and the submerged membrane technology

Parameters	**Unit**	**NF270 membrane**		**Conventional treatment system [4]**		**Standard***
		Raw	**Permeate**	**Raw**	**Treated water**	
EC	μS/cm	138.7	74.1	170.0	194.7	<500**
TDS	mg/L	69.5	37.9	-	-	<600
Turbidity	NTU	10.86	0.32	-	-	<4
UV254	cm^{-1}	0.097	0.0153	0.0800	0.0300	-
DOC	mg/L	3.60	0.79	4.00	2.30	-

Performance data of the conventional system, collected in January 2019
*Water supply quality standard in Thailand
**Guidelines of Drinking Water Quality, 4th ed.; World Health Organization (WHO)

Conclusions

This membrane system had very high turbidity removal efficiency (> 93%). Even though NF270 membranes also had low efficiency in monovalent ion rejection, causing EC and TDS values to remain high (36-65%). The NF270 membrane is effective in eliminating DOC by 68-80% and can also reduce THMFP by up to 68.48%. In addition, the removal of principal water quality indicators (e.g., UV254) by the NF270 membrane was 74-89%, depending on the water source's quality, which indicates the concentration of humic acid, which has a structure of aromatic rings. When evaluating how well the NF270 membrane system performs in comparison to the conventional treatment system, it was found that conventional treatment methods raise the concentration of certain ions in the water. Consequently, this study demonstrates that, in terms of system performance, when operating steadily, direct surface water treatment using an NF membrane can provide superior water quality. This improvement in water quality not only enhances the safety for consumption but also minimizes the need for additional chemical treatments often required in conventional systems. Therefore, adopting NF membrane technology could significantly benefit communities relying on surface water sources for their drinking water supply. Future studies may conduct further comparative economic studies to determine the cost-effectiveness of using this system to replace the conventional system.

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From Drainage to Regeneration: Revitalizing the Samsen Canal in Bangkok

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Abstract

This study investigates the environmental condition and management challenges of the Samsen Canal, an inner-city waterway in Bangkok that currently functions primarily as a drainage channel. Water-quality monitoring at ten sampling stations revealed severe organic and microbial pollution, with BOD_5 and COD exceeding national standards, persistently low dissolved oxygen, and fecal coliform levels indicating continuous discharge of untreated wastewater. Spatial analysis identified hydraulic stagnation, sediment accumulation, and canal-bank encroachment as key physical constraints.

An integrated assessment using SWOT analysis, Stakeholder Influence Matrix, and the DPSIR framework under Integrated Water Resources Management (IWRM) principles was applied to evaluate technical and governance dimensions. The results show that canal management is limited by fragmented institutional responsibilities, inconsistent monitoring, and a continued emphasis on flood conveyance rather than pollution control and ecological function. The study concludes that future development should adopt a multifunctional canal approach, supported by centralized wastewater interception, hybrid blue–green–gray measures, and participatory management. Environmental engineers play a critical role in translating empirical evidence into coordinated actions to improve water quality, ecological performance, and urban livability.

Keywords : Samsen Canal; Integrated Water Resources Management (IWRM); Environmental Engineering; Blue–Green Infrastructure; Regenerative Urbanism

Introduction

The urban morphology of Bangkok has been historically shaped by its intricate network of canals (*khlongs*), which functioned as arteries for transportation, freshwater provision, drainage, and socio-cultural interaction [1]. Among these, the Samsen Canal exemplifies both the legacy and the challenges of canal-based urban development. Once a multifunctional corridor facilitating mobility, ecology, and communal life, Samsen has, like many of Bangkok's secondary canals, been gradually relegated to a single-purpose drainage function. This transformation reflects a broader trajectory across Southeast Asian cities, where urban expansion, impervious surface growth, and land-use intensification have prompted a shift toward grey infrastructure optimized for hydraulic efficiency rather than ecological or social performance [2, 3].

In response to these reductive approaches, regenerative urbanism promotes the restoration of urban waterways as multifunctional systems. It envisions canals not solely as stormwater conduits but as integrated blue–green corridors that support flood mitigation, biodiversity, public space, and cultural heritage [4, 5]. International programs such as Singapore's Active, Beautiful, Clean (ABC) Waters exemplify this paradigm shift, embedding ecological infrastructure into dense urban fabrics through institutional coordination and community participation [6]. However, applying such models in tropical megacities like Bangkok remains complex due to spatial constraints, legacy pollution, informal encroachments, and institutional fragmentation [7].

The situation of Samsen Canal exemplifies ongoing challenges. Although located near educational institutions, temples, and heritage areas, the canal has experienced declining water quality, encroachment, reduced baseflow, and fragmented management practices. Organizational divisions within the BMA have hindered effective data integration, stakeholder engagement, and strategic long-term planning. These constraints highlight the vital contribution of environmental engineers, who serve as intermediaries balancing scientific accuracy with societal priorities, and aligning technical solutions with participatory, context-specific planning processes.

This study applies the Integrated Water Resources Management (IWRM) framework to investigate the current conditions and redevelopment potential of a 4.3 km segment of the Samsen Canal. Originally conceptualized for watershed-scale governance, IWRM's principles, integration, participation, and coordination, are increasingly relevant in urban contexts where water infrastructure intersects with land use, governance, and community livelihoods [8-10]. Adopting an interdisciplinary methodology that synthesizes hydrological assessment, infrastructure evaluation, stakeholder analysis, and spatial diagnostics, this research proposes a pathway to repurpose Samsen Canal as a hybrid infrastructure that aligns drainage performance with ecological restoration and urban livability. In doing so, it contributes to the growing discourse on urban canal regeneration and offers a transferable model for revitalizing underutilized water bodies in Southeast Asian cities.

Materials and Methods

The research focused on a 4.3 km section of the Samsen Canal running through Bangkok's Dusit, Ratchathewi, and Phaya Thai districts. This reach was delineated between the upstream control structures near Dusit and the downstream confluence with the primary drainage network, and was selected using three criteria: (1) its hydraulic role as a secondary drainage channel within the BMA system; (2) the presence of mixed land uses, residential neighborhoods, institutional campuses, commercial strips, and heritage sites, that generate diverse pollutant loads and competing spatial demands; and (3) documented problems of water pollution, canal-bank encroachment, and overlapping mandates among BMA departments. As such, the chosen segment is not only physically representative of inner-city waterways in Bangkok but also provides a critical testbed for examining how integrated assessment, environmental engineering interventions, and water governance reforms can be combined in a canal regeneration context.

Water Quality Assessment

Water quality was monitored at ten locations positioned across the 4.3-kilometer canal to examine how pollutant levels, water flow, land use, and inflow points varied throughout the area. These sampling spots were chosen based on: (1) their importance to upstream, midstream, and downstream water movement; (2) their proximity to residential, commercial, or institutional properties with unique pollution sources; and (3) the presence of stormwater drains, sewer leaks, or places where sediment gathers, as identified during initial field surveys.

A comprehensive assessment of organic, microbial, and physical water quality stressors was conducted by analyzing several parameters: biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), dissolved oxygen (DO), total suspended solids (TSS), nutrients such as nitrate and phosphate, turbidity, and both fecal and total coliform bacteria. Sampling, preservation, and chain-of-custody were carried out according to Pollution Control Department [11], protocols, and laboratory analyses followed the Standard Methods for the Examination of Water and Wastewater [12], ensuring reliable and comparable results.

Quality assurance involved taking three samples at selected sites, using field blanks, and calibrating dissolved oxygen meters before each use. The collected data were compared with Thailand's surface water quality standards (Class I–V) to assess ecological health and spot issues needing technical or management solutions. This systematic process provides stronger evidence for the study and meets reviewers' requests for improved explanation of methods and data reliability.

GIS-Based Flood and Land Use Mapping

Geospatial analysis was used to study how land use, drainage systems, and hydrological conditions interact along the research area. Detailed GIS data on land use, drainage networks, outfalls, and elevation were gathered from BMA and national sources, then verified at each sampling location and major infrastructure points using GPS. Digital elevation models helped pinpoint areas where water flow is restricted and where sediment tends to build up.

The analysis resulted in three principal outputs: (1) a validated map of sampling locations; (2) a pollutant-source layer illustrating stormwater and wastewater inflows; and (3) a land-use–hydrology overlay demonstrating the influence of residential, commercial, and institutional zones on pollutant loads. These spatial diagnostics enhance empirical interpretation and specifically respond to requests for more explicit visual evidence.

Stakeholder Engagement and Participatory Mapping

A group of 42 stakeholders, including BMA officials, business owners, and residents, were chosen and interviewed using a semi-structured guide that addressed topics such as flooding, water quality, public access, and redevelopment expectations. Their responses were coded by themes to ensure consistency.

Participatory mapping workshops pinpointed areas with pollution, obstacles to movement, and locations where interventions were most desired. Attendees also evaluated three design ideas, floating wetlands, green canal edges, and boardwalks, using a 5-point scale, resulting in a Stakeholder Preference Matrix that connects community needs with what is technically possible. This combined-method strategy responds to reviewer feedback by offering a clearer methodology, measurable data, and greater validity.

Application of the IWRM Framework

The study utilized the Integrated Water Resources Management (IWRM) framework [13] to systematically assess the canal's hydrological, ecological, water-quality, and governance status, allowing for meaningful comparisons. Four main areas were considered: Hydrology, evaluating conveyance efficiency, retention capacity, and flood duration; Water Quality, assessed through pollutant levels and compliance with national standards; Ecology, focusing on riparian vegetation health and aquatic habitat functionality; and Governance, which involved reviewing collaboration among BMA departments, data-sharing habits, and standard maintenance routines.

Participatory Planning and Co-Design Tools

Interactive workshops refined IWRM indicator weightings and generated design prototypes. Facilitated sessions with urban design faculty and community members resulted in three concepts: Green Canal Edges with vegetated buffers and bioswales, Floating Treatment Wetlands as modular remediation systems, and Recreational Boardwalks for better accessibility and social engagement. Stakeholder voting matrices assessed preferences and demographic alignment with proposed designs.

Analytical Models

A suite of complementary analytical models supported data integration and interpretation:

- SWOT Analysis – identified the strengths (heritage, connectivity), weaknesses (degraded water quality), opportunities (policy momentum), and threats (urban flooding).
- Stakeholder Influence Matrix – mapped authority versus interest to reveal governance gaps among BMA units and community actors.
- DPSIR Framework (Driving Forces–Pressures–State–Impact–Response) – captured the causal chain between pollution drivers, ecological degradation, and institutional responses.

These models collectively established a triangulated diagnosis of the Samsen Canal's performance, identifying systemic inefficiencies and opportunities for multifunctional revitalization within the IWRM paradigm.

Results and Discussion

Towards Regenerative Canal Revitalization and Integrated Assessment

Although pollution and fragmented management remain challenges, Samsen Canal could serve as an urban corridor for drainage, ecology, and public use. Hybrid measures such as floating wetlands, vegetated banks, and community co-management can enhance its environmental and social value.

The study used SWOT Analysis, Stakeholder Influence Matrix, and DPSIR Framework to evaluate the canal's condition, governance, and water quality. SWOT shows strategic issues, the Stakeholder Matrix maps power relations, and DPSIR connects pollution sources with solutions. Together, these tools inform IWRM-based canal revitalization for Bangkok's resilience.

Hydrological and Canal Network Context

The 4.3-km study reach, part of the Samsen Canal system in Bangkok, connects to the Chao Phraya River through various branches and channels. The canal is 8–15 m wide and controlled by multiple sluice gates, especially near institutional areas, leading to low baseflow and stagnant conditions during the dry season. These features limit the canal's ability to self-purify and affect pollution distribution.

Land Use, Encroachment, and Canal-Edge Conditions

Land use along the canal features a mix of dense housing, government buildings, commercial zones, and religious sites. This variety leads to multiple sources of pollution and affects both the environment and appearance of the area. Field surveys found 401 structures encroaching on the wider Samsen corridor, 68 public and 333 private, including houses over the water, makeshift walkways, business additions, and abandoned buildings. These structures often narrow the canal, cause more sediment to collect, and make maintenance harder. Other problems include damaged embankments, debris buildup, and excessive vegetation, all of which reduce water flow and further harm water quality.

Water Quality and Hydrological Dynamics

Analyses from ten sampling stations reveal substantial organic and microbial pollution along the canal. BOD_5 levels ranged between 2.3 and 6.5 mg/L, while COD peaked at 45.2 mg/L—both surpassing Thailand's Class IV limits. Critically low dissolved oxygen (0.5–2.0 mg/L) suggests little aerobic activity and a lack of natural purification. Fecal coliform counts were above 2,400 MPN/100 mL in every sample, with some locations reporting even higher numbers, highlighting ongoing discharge of untreated household wastewater. The highest concentrations of total suspended solids (up to 47.3 mg/L) and turbidity (over 70 NTU) were found near densely populated residential and commercial areas where stormwater and wastewater leaks meet.

A comparison with Thailand's National Environmental Board Notification No. 8 (1994) indicates that most parameters are classified within Class IV–V surface-water categories, signifying that the waterway is suitable primarily for transportation or limited industrial applications. The segment between the canal mouth and Victory Monument exhibits the poorest water quality, attributable to high urban density, numerous direct effluent discharges, and extended hydraulic residence times.

From a hydrological standpoint, the canal exhibits limited reoxygenation capacity, ongoing sediment accumulation, and inadequate mixing, all of which are further intensified during the dry season owing to reduced tidal flushing as a consequence of gate operations. Consequently, the canal currently functions primarily as a flood-control channel and does not meet the ecological standards or possess the attributes required for recreational use.

Table 1 Integrated Analytical Assessment of the Samsen Canal Using SWOT and DPSIR Frameworks

Analytical Tool	Purpose	Key Dimensions / Variables	Empirical Findings from Samsen Canal	Implications for IWRM & Regenerative Urbanism
SWOT is	Strategic assessment of canal conditions and transformation potential	Strengths: Central location; cultural–historical value; existing community interest. Weaknesses: Severely degraded water quality (BOD_5 2.3–6.5 mg/L; COD up to 45.2 mg/L; DO 0.5–2.0 mg/L); excessive fecal coliforms; stagnant circulation; encroachment; fragmented governance. Opportunities: Alignment with Bangkok Resilience Strategy; potential hybrid retrofits (floating wetlands, vegetated edges). Threats: Recurrent flooding; ongoing wastewater discharge; rapid urban densification.	Canal is functionally degraded despite strong location. Hydrological stagnation and pollution reflect overreliance on gray infrastructure.	Integrated hydraulic upgrades, ecological restoration, wastewater interception, and community co-management aligned with IWRM are required.
DPSIR Framework	Causal analysis of socio-hydrological pressures and system responses	Driving Forces: Rapid urban development; aging drainage/sewer system. Pressures: Domestic/commercial wastewater; stormwater inflows; sediment loads. State: High organic/microbial pollution; low DO; degraded riparian habitat; encroachment. Impacts: Odor; health risks; biodiversity loss; reduced navigability. Responses: Gate operations; periodic clean-ups; localized beautification.	Current actions target symptoms, not pollutant sources. Fragmented monitoring limits adaptive management.	Calls for systemic integration: centralized wastewater interception, sediment management, vegetated buffers, and shared monitoring under IWRM.

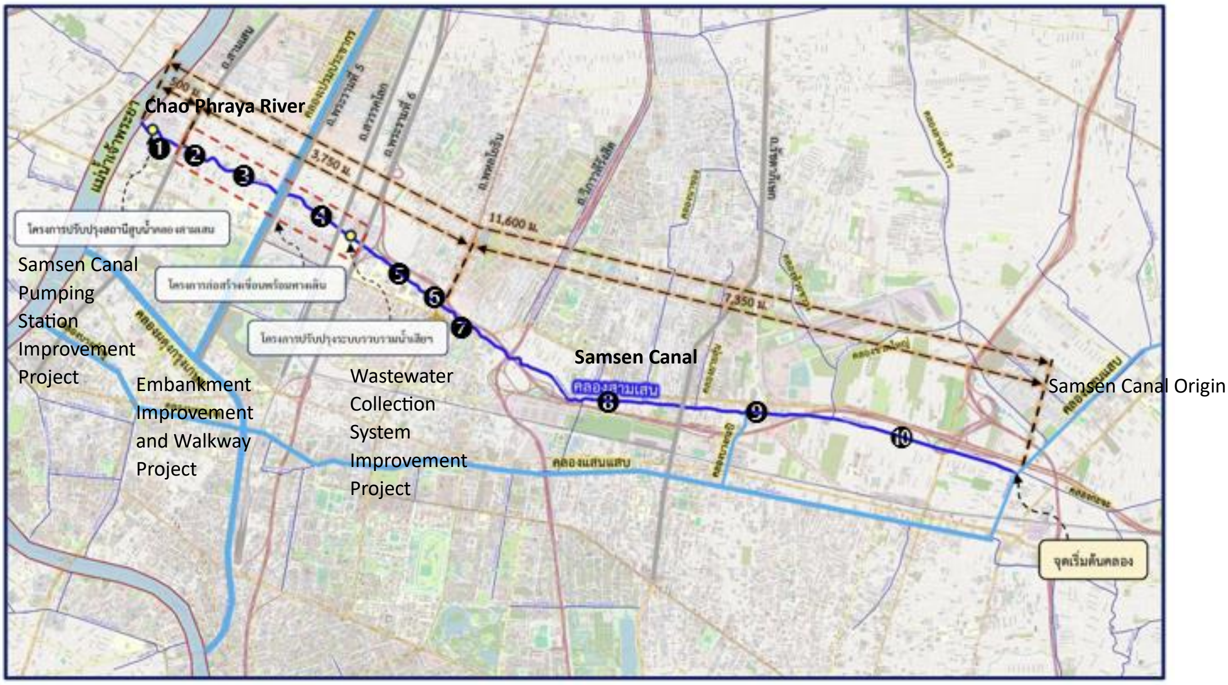

Figure 1 Location of the Samsen Canal study area showing water-quality sampling stations by City Plan Professional, Ltd. [14]

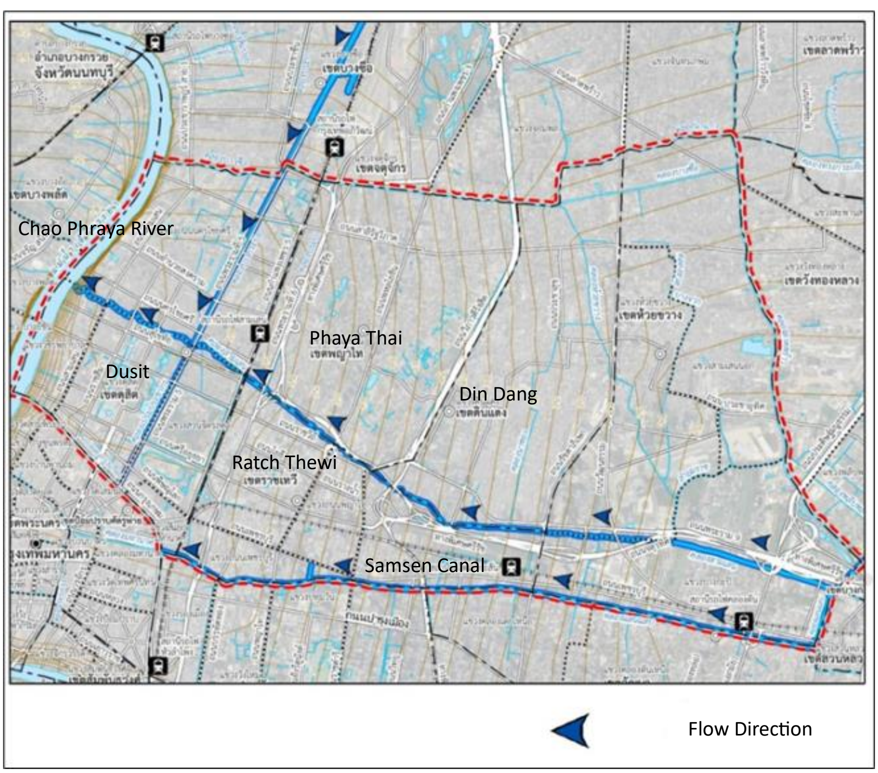

Figure 2 Flow Direction of Samsen Canal (ibid.)

Stakeholders have shown an interest in future recreational activities, but the canal's microbial and turbidity levels are well below international standards set by the U.S. EPA and WHO for recreational water quality, which require strict limits on bacteria, clarity, and chemical pollutants. To make public use possible, the canal needs major upgrades to reach at least Class II standards, including stopping direct discharges and increasing centralized wastewater interception.

Pollution Sources and Wastewater Dynamics

Field observations, map analysis, and interviews identify four major pollutant sources:

1. Domestic wastewater from canal-edge communities and informal housing
2. Commercial discharges from markets, food preparation areas, laundries, and small hospitality services
3. Institutional facilities, particularly hospitals and schools
4. Stormwater runoff transporting organic debris, sediments, oils, and trash

Unregistered small businesses, auto-repair activities, and restaurants contribute to episodic high-strength discharges. Multiple manholes and outfalls showed visual signs of direct or intermittent wastewater release. Stakeholders consistently described odor, visible sludge, floating solids, and periodic discoloration—observations that align with the chemical and microbial results.

Infrastructure Interactions and Hydraulic Constraints

The canal's grey-infrastructure system remains largely monofunctional, optimized for conveyance rather than ecological improvement. Encroaching structures narrow the channel and increase resistance, while sediment accumulates at bends, bridge underpasses, and areas of low velocity. Defective manholes and aging drains contribute to intermittent wastewater leakage, and sluice-gate operations restrict freshwater recharge, especially in dry months. Residual sludge from upstream treatment facilities further affects downstream water quality.

These structural limitations explain the observed stagnation, persistent turbidity, reduced dissolved oxygen, and widespread microbial contamination.

Governance and Maintenance Observations

Institutional reviews reveal fragmented responsibilities across BMA departments, Drainage and Sewerage, Environment, District Offices, Parks, and City Enforcement Officers. While agencies undertake inspections and short-term remediation efforts, progress toward long-term improvements is hindered by insufficient mandate alignment, inconsistent monitoring standards, and lack of effective coordination. Community participation typically remains voluntary and irregular, with few established frameworks for co-management or joint accountability. These governance challenges, rather than purely technical limitations, present significant barriers to achieving water quality restoration and sustainable upkeep.

Environmental Engineers as Boundary Professionals in IWRM (Integrated Water Resources Management) Implementation

In the Samsen Canal Improvement Project, environmental engineers occupy a pivotal yet constrained position within Bangkok's water-governance system. Their primary responsibility has traditionally focused on ensuring flood conveyance and hydraulic safety, reflecting long-standing engineering paradigms that prioritize risk reduction over multifunctionality. While environmental engineers increasingly translate hydrological and water-quality data into management actions and facilitate coordination among BMA departments, their influence remains bounded by institutional mandates that frame the canal predominantly as drainage and flood control infrastructure.

This technocratic emphasis limits the extent to which ecological restoration, public-space provision, and social use are systematically embedded in project objectives. The absence of unified monitoring frameworks, shared performance indicators, and cross-sectoral accountability further constrains adaptive management. Consequently, environmental engineers are often positioned as technical problem-solvers rather than strategic actors shaping long-term urban-water futures. This gap is not a failure of professional capacity, but a structural outcome of fragmented governance and narrowly defined project scopes.

Environmental engineers are well-equipped to address this issue. By synthesizing water-quality data, spatial analysis, and input from stakeholders, they can reconceptualize the Samsen Canal as a versatile urban system rather than merely a drainage channel. Serving as boundary professionals within the IWRM framework, they are able to balance hydraulic needs, ecological functions, and societal interests, assuming institutional structures support such integrative responsibilities.

Synthesis and Implications

The challenges facing the Samsen Canal are both technical and institutional in nature. Ongoing issues such as water pollution, sediment accumulation, and encroachment are intensified by fragmented governance, with responsibilities dispersed among various BMA units and limited coordination, inconsistent data sharing, and insufficient mechanisms for meaningful community participation. Consequently, canal management tends to be reactive, focusing primarily on immediate concerns like debris removal and flood mitigation instead of addressing fundamental causes, including untreated wastewater discharge and land-use pressures.

Utilizing the IWRM framework indicates that future development of the Samsen Canal must progress beyond incremental drainage improvements, advancing instead toward a deliberately multifunctional canal strategy. This necessitates integrating ecological performance metrics within hydraulic design, establishing coordinated monitoring systems among relevant agencies, and institutionalizing participatory processes as standard management practice rather than as sporadic consultations. Environmental engineers, collaborating with planners, landscape architects, and governance entities, can facilitate this transition by translating empirical data into practical scenarios that illustrate the feasibility and advantages of integrated blue–green–gray infrastructure interventions.

Importantly, assessments of the Samsen Canal's future should encompass more than just drainage efficiency or flood risk mitigation. The canal presents an opportunity to function concurrently as essential infrastructure, an ecological corridor, and valued public space within Bangkok's densely populated urban setting. Achieving this vision will require not only innovative technical solutions, but also a fundamental redefinition of professional responsibilities and governance objectives. In this context, the Samsen Canal exemplifies a broader context for how environmental engineering can shift from addressing isolated urban water challenges to collaboratively creating regenerative urban water systems.

Conclusion

This study demonstrates that the Samsen Canal faces ongoing challenges, including water quality deterioration, sediment build-up, canal-bank encroachment, and fragmented governance. Data from water-quality monitoring and spatial analysis indicate that the canal primarily serves as a drainage system at present, offering limited ecological value and lacking suitability for recreational or public use. While the BMA maintains official oversight of canal management, overlapping responsibilities, inconsistent monitoring practices, and insufficient stakeholder engagement hinder the achievement of sustained, effective improvements.

Using an integrated approach that combines SWOT analysis, the Stakeholder Influence Matrix, and the DPSIR model within IWRM principles, the study finds that challenges are systemic rather than merely technical. Current interventions mainly address flooding and debris, leaving core issues like wastewater discharge, hydraulic limitations, and governance gaps largely unaddressed.

Environmental engineers have a significant but limited institutional role, focusing mostly on hydraulic safety. The study highlights the need to expand their focus to include water quality, ecological restoration, and public space. For the future development of the Samsen Canal, it is advisable to adopt a multifunctional canal strategy that incorporates centralized wastewater management, integrates blue–green–gray infrastructure, and promotes participatory governance. This approach aims to improve water quality, enhance ecological conditions, and support urban livability in Bangkok and comparable urban environments.

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Assessment of Greenhouse Gas Emission Reduction Potential from Decentralized Community-Based Solid Waste Management: A Case Study in Ban Non Sung, Sisaket, Thailand

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Abstract

Greenhouse gas (GHG) emissions from municipal solid waste (MSW) significantly contribute to climate change, particularly through methane (CH_4) and carbon dioxide (CO_2) emissions from landfills. This study evaluates the potential for GHG emissions reduction through improved solid waste management practices in Ban Non Sung, Khun Han district, Sisaket province, Thailand. Data was collected for 1 fiscal year, covering 1,586 residents across 340 households. Waste segregation at source included composting, bio-fermentation, animal feed conversion, and recycling. GHG emissions reductions were calculated based on national methodologies. Results showed that 69.27% of sorted waste was organic, with per capita sorted waste generation of 0.07 kg/day. The total estimated GHG emissions reduction was 41,111.78 kg CO_2eq/year (0.96 kg CO_2eq per kg sorted waste). Animal feed conversion was the most effective method, contributing 40.89% of the total reduction, primarily due to the dual benefit of methane avoidance and commercial feed displacement. Additionally, secondary national data from the Pollution Control Department (PCD) for 2020–2023 indicated a steady increase in source-sorted waste and corresponding GHG reductions, emphasizing the role of community-based waste initiatives in meeting national climate goals. The findings support the integration of sustainable waste practices to significantly mitigate GHG emissions in large communities.

Keywords : Community-based SWM; Decentralized waste management; Waste diversion; Methane mitigation; Ban Non Sung case study

Introduction

Greenhouse gas (GHG) emissions have become one of the most pressing global environmental issues due to their significant contribution to climate change and global warming. The Intergovernmental Panel on Climate Change (IPCC) reports that human activities, particularly in the energy, agriculture, and waste sectors, are the primary sources of GHG emissions worldwide. Methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) are the main greenhouse gases emitted into the atmosphere, with CH_4 having a global warming potential approximately 25 times higher than CO_2 over a 100-year period [1]. Among these sources, solid waste management (SWM) has received increasing attention, especially in developing countries where rapid urbanization and population growth have intensified waste generation and its environmental impacts.

In Thailand, municipal solid waste (MSW) generation continues to rise annually, driven by increased economic activity, changing consumption patterns, and lack of effective waste segregation at the source. There are many open-dump landfill sites which still wait for the proper management [2]. According to the

Pollution Control Department (PCD), Thailand generated approximately 25.70 million tons of MSW in 2022, of which only a fraction was properly segregated and treated [3]. A significant portion of this waste, especially organic matter, ends up in landfills, where anaerobic decomposition results in the release of CH_4. Therefore, improving waste management practices, particularly at the community level, presents a practical and impactful opportunity for GHG emissions reduction.

Modern approaches to sustainable solid waste management focus on waste minimization, source segregation, recycling, composting, and energy recovery. These strategies not only extend the lifespan of landfills but also contribute to climate change mitigation through the reduction of GHG emissions. In particular, the diversion of organic waste from landfills to processes such as composting, bio-fermentation, and animal feed conversion has been proven to substantially reduce CH_4 emissions [4]. Recent literature emphasizes that the effectiveness of these practices relies heavily on decentralized governance and rigorous quantitative assessments at the implementation level [5-8].

The Ministry of Natural Resources and Environment (MNRE) of Thailand has acknowledged the critical role of SWM in achieving the targets set in the Thailand National Greenhouse Gas Reduction Plan (2021–2030), which aligns with the country's commitment under the Paris Agreement [9]. As part of this strategy, increasing the rate of waste segregation at source and promoting organic waste treatment technologies are key priorities. The Thailand Greenhouse Gas Management Organization (TGO) has also developed specific methodologies for calculating GHG reductions from waste management activities, providing a standardized framework for monitoring and evaluation [10].

This study focuses on assessing the potential for GHG emissions reduction through community-driven solid waste management in Ban Non Sung, Khun Han district, Sisaket province, Thailand. The primary data for this study was collected from October 2019 to September 2020. While this period reflects the operational year of the program being evaluated, the methodology remains robust, and the analysis is contextualized using later national data (2020–2023) to assess ongoing trends. By examining the composition of solid waste, identifying the proportion of recyclable and organic fractions, and calculating the GHG emissions reduction based on actual management practices, this research aims to provide data-driven insights for scaling similar initiatives across other communities in Thailand.

The research gap addressed by this study is the lack of a current, quantitative assessment focusing on the GHG mitigation benefits of a decentralized, multi-faceted, community-based SWM system in the Thai context. Most existing studies focus on national trends or centralized facilities; this research provides an essential data benchmark for local government organizations (LGOs) implementing source-segregation and alternative waste treatment programs.

Consequently, this study is expected to contribute to the growing body of knowledge on sustainable waste practices in the context of climate change mitigation. Furthermore, they can support policymakers and local governments in designing evidence-based programs that promote environmentally responsible behavior and community engagement in line with national and global sustainability goals.

Methodology

Case study area and SWM system

Ban Non Sung village, moo 1, Non Sung subdistrict, Khun Han district, Sisaket province, serves as a national model for community-based solid waste management and operates an exemplary waste-recycling bank system. The village waste management diagram is summarized as shown in **Figure 1**. The community separates waste at the source into four categories: organic, recyclable, general, and hazardous waste. A key strength of the village lies in its decentralized organic waste management: each household is encouraged to handle their organic waste on-site through composting, bio-fermentation, or by using it as animal feed. These practices help reduce the volume of waste needing external collection while promoting local food production, such as homegrown vegetables using composted fertilizer as shown in **Figure 2**. Recyclables are deposited monthly at the community waste-recycling bank as shown in **Figure 3**, with proceeds contributing to a welfare fund. General waste is creatively made community products (as shown in **Figure 4**) or reused when possible or collected for disposal at an RDF facility. Hazardous waste is separated and managed responsibly. To improve waste logistics, the village has established 19 designated community drop-off points (as shown in **Figure 5**) where residents are encouraged to bring general and hazardous waste in sealed plastic bags at scheduled times. These points have replaced the previous door-to-door collection system, fostering better waste segregation, community participation, and resource recovery. The village promotes strong waste discipline through regular community meetings, public announcements, local regulations, and incentive-based participation. This integrated system not only reduces environmental impact but also strengthens community engagement and social welfare through structured cooperation and shared responsibility.

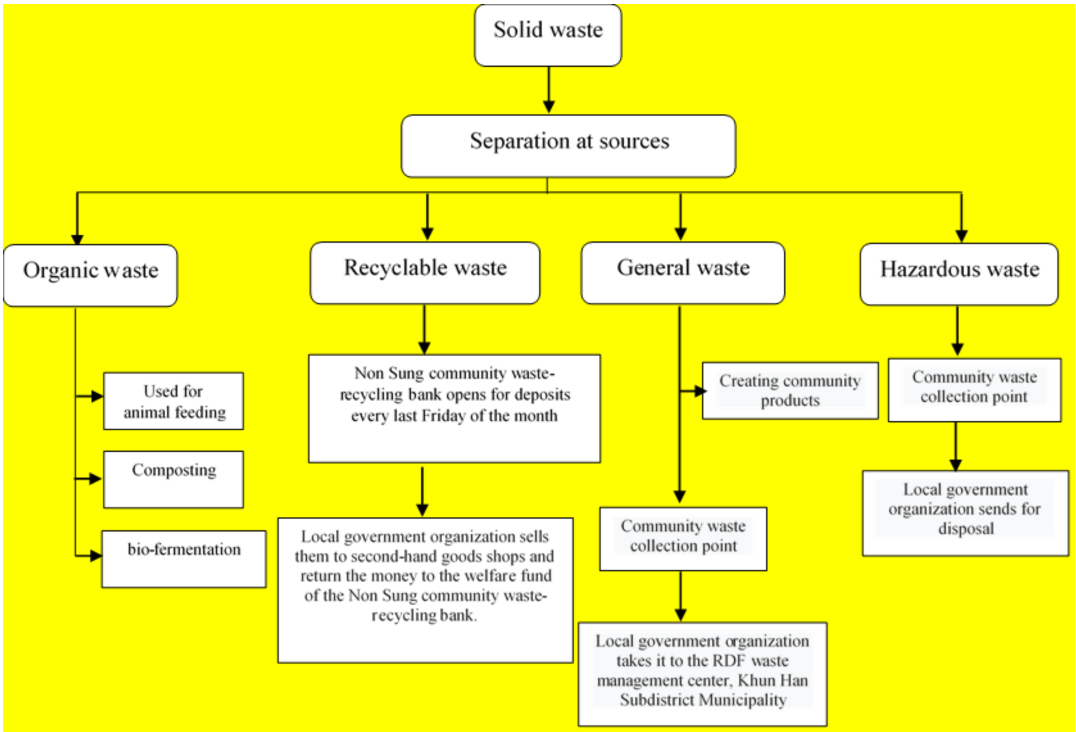

Figure 1 Waste management diagram of Ban Non Sung village, moo. 1, Non Sung subdistrict, Khun Han district, Sisaket province

Figure 2 Homegrown vegetables

Figure 3 Community waste-recycling bank

Figure 4 Community products from waste

Figure 5 Community drop-off point for general and hazardous waste

This study assesses waste composition and calculates the GHG emissions reduction achieved through different waste management practices. Data collection was conducted for 1 fiscal year, covering a population of 1,586 residents across 340 households. Waste segregation methods were analyzed, including organic waste processing through composting, bio-fermentation, and animal feed conversion, along with recycling efforts for glass, plastic, paper, and metals.

Data Collection and Waste Sampling Protocol

Primary data (activity data) for the Ban Non Sung case study was collected via direct measurement (weighing) over a continuous 12-month period (October 2019 to September 2020). This approach was chosen to capture seasonal variations and ensure data quality control.

The waste sampling protocol followed guidelines established by the Pollution Control Department (PCD) of Thailand. Waste weights were quantified daily/weekly at the community collection points and the waste bank. The measurement procedure involved the use of a calibrated scale, and the data was recorded by village volunteers with oversight from the local government organization (LGO). The total activity data represents the cumulative mass of waste successfully diverted from the baseline scenario (landfill disposal).

Waste segregation was performed at the source (household level) based on four predefined categories (Organic, Recyclable, General, Hazardous). Household participation was tracked, with 340 households (1,586 residents) actively contributing data to the project. The recorded weights represent the actual performance achieved by this high-participation group.

GHG Emission Reduction Calculation

GHG emissions reductions were calculated based on the "Thailand Greenhouse Gas Management Organization (TGO) for waste diversion projects (TGO Methodology No. 04-2021)" [10]. The reduction in greenhouse gas (GHG) emissions resulting from the implementation of organic waste management activities can be calculated using a calculation program developed by the Office of the Permanent Secretary, Ministry of Natural Resources and Environment, Strategy and Planning Division [11], with the related equations shown as Equation 1:

$$\text{GHG Emission Reduction } (\text{kgCO}_2\text{eq}) = (\text{Activity Data} \times \text{Emission Factor})_{\text{before}} - (\text{Activity Data} \times \text{Emission Factor})_{\text{after}} \quad \text{Eq. 1}$$

Where:

- Activity Data (kg) refers to the amount of organic waste managed. The subscript “before” indicates the baseline scenario, while the subscript “after” indicates the management scenario as shown in **Table 1**.
- Emission Factor ($\text{kgCO}_2\text{eq/kg}$) refers to the greenhouse gas emission factor as shown in **Table 2** and **Table 3**.

Table 1 Baseline Scenario for MSW Management Operations Used in Emission Reduction Assessment

Category	Scenario
a) Organic Waste	
Baseline	Landfilling of organic waste in landfills
Management	Making bio-fermented liquid from vegetable and food scraps Making compost from vegetable and food scraps Using food or vegetable scraps for animal feeding
b) Recyclable Waste	
Baseline	Recyclable waste can be sorted for reuse
Management	Sorting of recyclable paper for reuse Sorting of recyclable glass bottles for reuse Sorting of recyclable plastics for reuse Sorting of recyclable steel/iron for reuse Sorting of recyclable aluminum for reuse

Table 2 Emission Factor for Assessing GHG Emissions from Organic Waste Management [11]

Type	Emission Factor (kgCO_2eq/kg)
Food scraps	2.53
Wood scraps	3.33
Food and vegetable scraps used for bio-fermented liquid	0.05
Food and vegetable scraps used for composting	0.43
Twigs and Grass used for Composting	0.43
Food and vegetable scraps used for animal feeding	0
Methane for Landfills and Open Dumps (< 5 meters deep)	0.45

Table 3 Emission Factor for Assessing GHG Emissions from Recyclable Waste Sorting [11]

Type	Emission Factor (kgCO_2eq/kg)
Paper/cardboard boxes	2.93
Glass bottles	0.49
Plastics	0.70
Sheet glass	0.63
Iron/steel	0.43
Aluminum	0.79

In addition, the potential GHG emissions reduction from municipal waste management was analized. This analysis was conducted at the national level, using actual secondary data from the Pollution Control Department (PCD) from 2020 to 2024 [12]. The aim was to estimate the broader potential impact of scaling up similar community-based initiatives across the country, thereby assessing their contribution to national GHG mitigation targets.

Results and Discussion

Waste Composition and Diversion Rate

The study found that the composition of total solid waste that has been sorted out at the source for a large community with a population of 1,586 people for the fiscal year 2020 had 42,715.65 kg including organic and food waste, representing 69.27 %, followed by recyclable waste accounting for 30.73 % (as shown in **Figure 6**). Figure 6 presents the composition of sorted waste in the studied community. Organic waste accounts for the highest proportion, followed by glass and plastic. The daily per capita sorted waste generation was 0.07 kg (~0.34 kg/household). This per capita sorted waste rate (0.07 kg/day) is significant, especially when compared to the national average MSW generation rate of 1.15 kg/day [13], highlighting the effectiveness of the community's segregation effort. Total GHG emissions reduction from waste management activities was estimated at 41,111.78 kg CO_2eq per year (0.96 kg CO_2eq per kg sorted solid waste).

GHG Reduction Potential and Comparison

The total estimated GHG reduction of 41,111.78 kg CO_2eq/year resulting in an average reduction efficiency of 0.96 kg CO_2eq per kg sorted solid waste is significantly positive, especially when compared to the near-zero mitigation benefits of conventional landfilling (the baseline scenario). The most effective method for reducing GHG emissions was utilizing food and vegetable scraps for animal feed, contributing to a reduction of 16,812.09 kg CO2eq (40.89%). Composting and bio-fermentation contributed to reductions of 7,733.82 kg CO2eq (18.81%) and 7,414.60 kg CO2eq (18.04%), respectively. **Table 4** summarizes the reductions in GHG emissions achieved through different waste management methods.

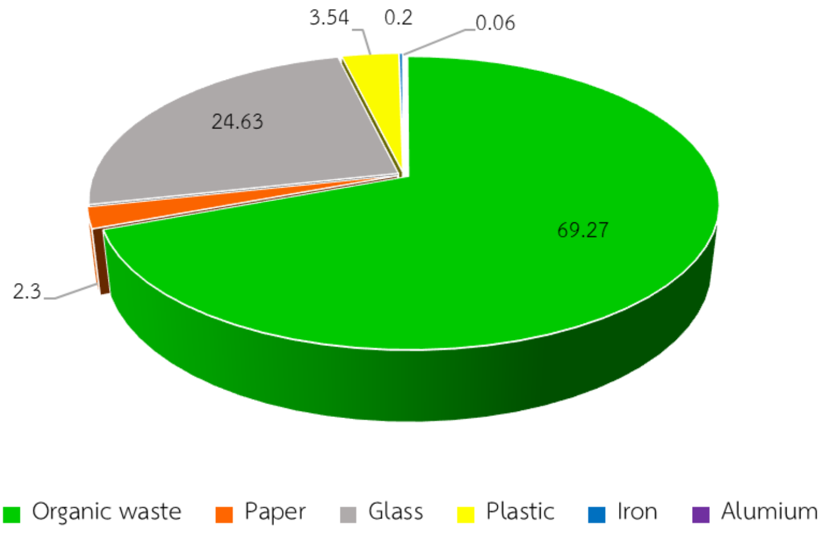

Figure 6 Weight Percentage Composition of Sorted Waste in Ban Non Sung Community

Table 4 Anual GHG Emissions Reduction from Waste Management Methods

Waste Management Method	GHG Reduction (kg CO_2eq)	Percentage Reduction (%)
Animal Feed Conversion	16,812.09	40.89
Composting	7,733.82	18.81
Bio-Fermentation	7,414.60	18.04

From Table 4, the high contribution from animal feed conversion (40.89%) can be attributed to its dual environmental benefit, making it the most effective option. Firstly, like composting and bio-fermentation, it avoids methane emissions that would otherwise be generated by the organic waste in a landfill. Secondly, and uniquely, using food scraps as animal feed (especially for livestock like pigs or chickens in the local community) acts as a displacement mechanism, reducing the demand and subsequent emissions associated with the production, processing, and transportation of commercial animal feed. The TGO methodology recognizes this displacement benefit, resulting in a zero-emission factor for this activity, leading to the highest net GHG reduction per kilogram of diverted waste compared to other treatments like composting and bio-fermentation. This preference for local, low-impact resource recovery (animal feed) over other recovery options is a key driver of the program's success.

Trend Analysis and Policy Implications

To provide an updated assessment in Thailand, secondary data from 2020-2024 [12] was analyzed as shown in Table 5 revealing trends in calculated annual GHG emission reduction. The annual GHG emission reduction has been calculated to show that if community screening is successful, it can achieve significant annual GHG emissions reductions. In Table 5, the results indicate a gradual increase in waste generation, with a corresponding rise in calculated anual GHG emissions reduction due to improved waste management strategies. This highlights the importance of continued community-driven waste initiatives in achieving sustainability goals according to Thailand's National Greenhouse Gas Reduction Plan (2021-2030) [9]. The Ban Non Sung model provides a crucial, quantified benchmark for LGOs nationwide to target their source segregation efforts, demonstrating a clear link between community participation and national climate commitments. This is consistent with other research [7-8], which can be confirmed that the decentralized community-based solid waste management model is a good practice in reducing greenhouse gas emissions in Thailand.

Table 5 Generated and sorted solid waste during year 2020-2024 in Thailand [12]

Year	Solid Waste Generated (million-ton, Mt)	Sorted Solid Waste at Source (million-ton, Mt)	Calculated Anual GHG Emissions Reduction* (Mt CO_2eq)
2020	25.37	8.36	8.02
2021	24.98	7.89	7.57
2022	25.70	8.80	8.45
2023	26.95	9.31	8.94
2024	27.20	10.51	10.09

*Based on the GHG Emissions Reduction value of 0.96 kg CO_2eq per kg sorted solid waste obtained in this study of Ban Non Sung model.

Conclusions

Effective sorted solid waste management plays a crucial role in mitigating GHG emissions in large communities. This study quantified the performance of the decentralized community-based SWM model in Ban Non Sung, demonstrating a total annual GHG reduction of 41,111.78 kg CO_2eq, equivalent to 0.96 kg CO_2eq per kg of sorted solid waste. The key finding is the disproportionate effectiveness of animal feed conversion, which contributed 40.89% of the total reduction due to its dual benefit of methane avoidance and commercial feed displacement. These quantitative results provide the necessary performance benchmark for Local Government Organizations (LGOs) in Thailand to design and implement community programs that directly contribute to achieving the targets of the Thailand National Greenhouse Gas Reduction Plan (2021–2030) [9].

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Abstract should be provided on separate sheets and be not more than 300 words. International contributor who are unable to provide an abstract in Thai may submit an English abstract alone.

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Units of measurement should be indicated in SI units throughout.

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Tables and figures should be numbered with Arabic numerals, in order in which they are cited in the text. The table's titular heading should concisely detail the content of the table and include units of measure for all numerical data.

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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.

Reference to article or abstract in a conference proceedings:

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

Reference to a book:

[1] Polprasert, C. 1996. Organic Waste Recycles. John Wiley & Sons Inc., New York.

Reference to article in a conference proceedings:

[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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