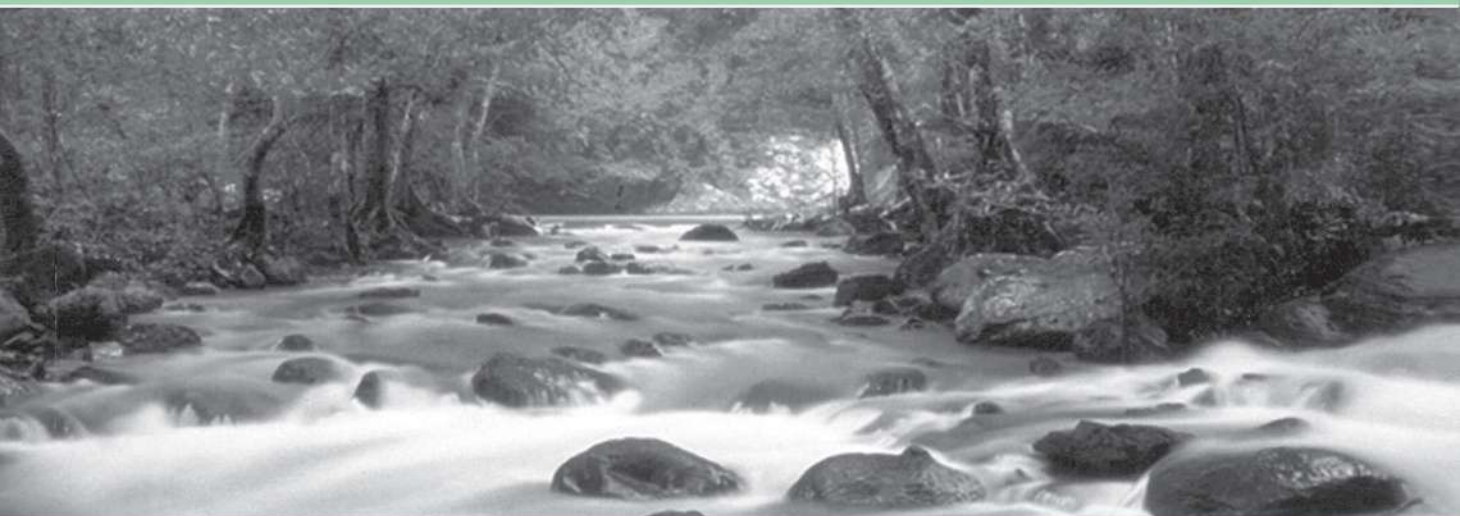


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Lithium Iron Phosphate, Nickel Manganese Cobalt, and Sodium-Ion Batteries: A Life Cycle Perspective on Battery Choices for Electric Vehicles

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Abstract

A comparative Life Cycle Assessment was conducted to analyze the environmental impact of three electric vehicle batteries, viz., Sodium-ion Battery (NIB), Nickel Manganese Cobalt (NMC), and Lithium Iron Phosphate (LFP). The functional unit of 1 kWh of battery capacity was defined, with a cradle-to-grave boundary including the production of the batteries in China, usage in Thailand, and the recycling of the batteries at the end of the lifecycle in China. The ReCiPe 2016 life cycle assessment method was used considering both the midpoint and endpoint environmental impacts. The findings indicated that the production stage added much to the total environmental burdens, especially on the NMC battery, on account of the intensive mining and refining of nickel, cobalt, and manganese. Conversely, the LFP battery had overall moderate impact in most of the categories, as it is made of simpler materials and does not contain any critical metals. The NIB battery had the lowest impact and had greater chances of future development, bearing in mind the large resources of sodium and less reliance on the scarce minerals. Nevertheless, the use stage in Thailand caused rather similar high emissions for LFP and NIB and lower emission for NMC battery as the electricity mix is dominated by fossil fuels. In general, the paper concludes that LFP is now the most environmentally appropriate choice, and NIB represents a promising alternative that should be optimized. To reduce the environmental impacts of future battery systems, a focus on clean energy, low-impact manufacturing, and effective recycling strategies is essential.

Keywords : Electric vehicle batteries; sustainable transportation; life cycle assessment (LCA); nickel sodium-ion battery (NIB); nickel manganese cobalt (NMC); lithium iron phosphate (LFP)

Introduction

Electric vehicles (EVs) have received significant attention as a developmental step towards reducing greenhouse gas emissions and climate change [1]. Over the years, the market demand for electric vehicles has grown as concern over the environment has increased and the need to eliminate the use of fossil fuels has also increased. The shift is underscored by worldwide carbon-neutral plans, as major economies, including Thailand, the United States, European Union, and Japan, aim to achieve carbon neutrality by 2050, while China has set a target of 2060. Governments and organizations eager to reduce carbon emissions by reducing dependence on Internal Combustion Engine (ICE) vehicles have implemented interventional policies, and now EVs have become a growing topic of interest as a viable form of transportation [2]. This has given a boost to the industry, as the world sold nearly 6.7 million EVs in 2021 [3]. Since battery is the primary energy source of an electric car, it affects the car's effective mileage, power consumption, and output [4]. At present, lithium nickel cobalt manganese oxide (NMC) and lithium iron phosphate (LFP) batteries are the most prevalent in the EV industry. However, the manufacturing of EV batteries poses significant ecological issues, such as the large quantities of different substances, including lithium, cobalt, and nickel, which are found only in a few places [5]. The increase in the EV industry at a high rate has added pressure on both resources and the environment in the battery industry. Some of the environmental issues associated with the mining of these materials include the depletion of natural resources and socio-economic issues that surround mining regions worldwide [6]. Additionally, a significant portion of the energy-intensive battery production makes batteries a key factor in production emissions, which can be offset by the environmental benefits of EVs during their lifetime [7]. Moreover, the world's lithium resources are scarce, thus posing a resource-based challenge and increasing prices.

Conversely, the resources of sodium are large, evenly distributed, and less expensive. The promising alternative to lithium-ion

batteries has therefore been gaining growing traction in the use of sodium-ion (NIB) batteries [8]. The first-generation NIB developed at Contemporary Amperex Technology Co., Limited (CATL) was as energy dense as LFP batteries and had excellent cost management and safety performance. Nonetheless, the current studies of NIB primarily concern the development of battery materials and the enhancement of their performance, and there are few studies available on the environmental impact assessment of NIB. One such methodology that is very crucial in analyzing these cumulative effects is the Life Cycle Assessment, which can be applied from the extraction of raw materials to disposal at the end of the life of an item [9, 10]. The use of LCA on EV batteries is thus important in supporting informed decision-making and in capturing the opportunities to reduce adverse environmental effects [11]. The seminal LCA studies have proven the outstanding environmental footprint of the production of lithium-ion batteries, driving the creation of greener chemistries [12, 13]. More recent studies have extended to examine other forms of battery technologies. Lithium iron phosphate, batteries are considered with greater attention due to safety considerations and reduced environmental influence [14]. At the same time, sodium-ion, batteries are now a promising option, and studies have shown that they are safer and more cost-effective as well, because sodium is abundant [15, 16]. In spite of these developments, an important gap exists in literature.

Although significant focus has been put on known battery chemistries, no complete life cycle analysis comparing NMC, LFP, and NIB, batteries have been conducted under consistent scenarios [17]. It is also necessary to evaluate the differences in resource and environmental effects of sodium-ion, batteries and lithium-ion, batteries to facilitate the green transformation of the global energy storage sector [12, 18]. Moreover, the inclusion of the principles of the circular economy, battery recycling, and resource recovery has not been fully investigated in comparative studies. Their regional impacts on the lifecycle, especially in regions with different energy grid compositions, are usually neglected,

but they also affect the total carbon footprint of EV battery production [19].

To fill this gap, this study has performed a comparative LCA of NIB, LFP, and NMC battery technologies. Their effects are compared in terms of the use of resources and emissions during the product life cycle. The results are expected to offer significant knowledge to manufacturers, consumers, and policymakers to encourage the creation of more sustainable practices and inform strategic imperatives creation of the electric vehicle sector.

The first objective of this study is to perform a detailed LCA of battery technologies of electric vehicles to promote sustainable mobility solutions. To achieve this goal, the research establishes some main objectives. To begin with, it aims to determine the environmental performance of EV batteries throughout their life cycle, including resource extraction and production, use, and disposal. Second, it intends to compare environmental performance of common and new battery chemistries, namely, NMC, LFP, and NIB batteries. A further objective is to identify the differences in environmental performance between established and new battery types, such as NIB, LFP AND NMC, focusing on resource efficiency, regional variance of the energy grids, and the implementation of recycling. Finally, the study seeks to provide, based on these findings, specific policy interventions and actionable recommendations for policymakers, producers, and scientists to make the EV battery supply chain more environmentally friendly.

Methodology

A comparative life cycle assessment was conducted following the methodology provided in ISO 14040 and ISO 14044 standards to evaluate the environmental impacts of three major electric vehicle battery chemistries: sodium-ion, lithium iron phosphate, and nickel

manganese cobalt, based on their production and recycling in China and assembly and use in Thailand [20].

1. Goal and Scope Definition

The functional unit was defined as 1 kWh of usable electrical energy delivered by the battery system, providing a consistent basis for comparison among battery chemistries. Each battery system was first modeled over its full operational lifetime, corresponding to a total driving distance of 200,000 km, from which the total lifetime energy delivered was obtained. All life-cycle inputs and outputs were then internally normalized into 1 kWh of delivered energy. Accordingly, the reference flow corresponds to the fraction of the complete battery system required to deliver 1 kWh of usable electricity [3, 13, 20]. The system boundary is set as cradle-to-grave, covering all major life cycle stages, including raw material extraction, cell production, battery pack assembly, use phase, and end-of-life treatment (Figure 1). The material production and recycling activities were modeled in China, while battery assembly and the use phase were modeled in Thailand. The value of 1 kWh is used only as the functional unit for environmental comparison among the three battery types. The end-of-life stage considered both hydrometallurgical and pyrometallurgical recycling routes. These methods allow recovery of valuable materials such as metals, which can reduce the overall environmental impacts of the battery life cycle. While the difference between the two routes was not the focus of this study, including both ensures that potential material recovery is accounted for in the LCA results. The inventory data mentioned below represents the inventories for major components. Inventory data for the inputs of these major components are attached as annexes. The comprehensive inventory data are provided in Tables A1–A43.

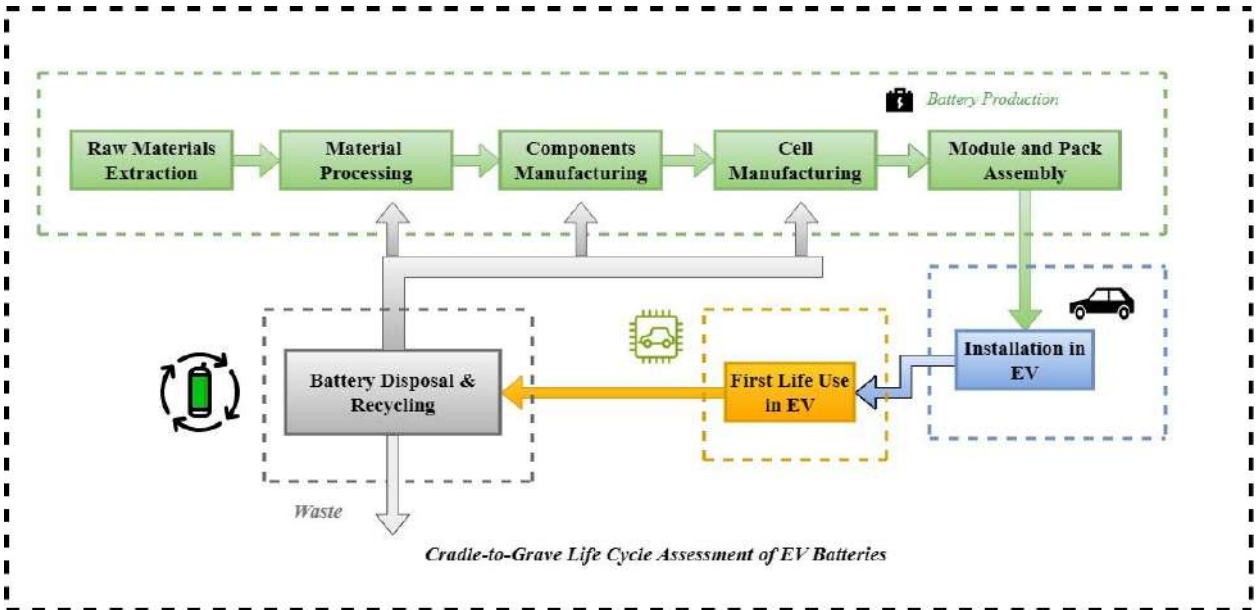


Figure 1 System boundary of the study

2. Data Collection and Life Cycle Inventory Analysis

The inventory data used in this study were collected from multiple authentic sources, such as peer-reviewed research articles and industry reports, to ensure completeness. All data are modeled in SimaPro (version 10.1.0.6), developed by PRé Sustainability, which serves as one of the mainstream platforms for life cycle modelling and impact assessment. The ecoinvent 3.10 database (compiled March 2024) is used to connect background processes such as material production, electricity generation, and transportation. Material and energy inputs for each battery chemistry, including anode, cathode, electrolyte, separator, and assembly processes, are modeled according to the cradle-to-grave approach. Each stage, from production to use and end-of-life, is analyzed to identify its contribution to the overall environmental performance. The collected inventory data is then used for the calculation of environmental impacts across all life cycle stages.

3. Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) is based on the ReCiPe 2016 method and provides a holistic assessment of the environmental pressures at both midpoint and endpoint levels. This analysis concentrates on the

most important impact indicators: global warming, fossil depletion, human toxicity, and terrestrial ecotoxicity. The Hierarchist (H) perspective, version 1.10, with the World 2010 baseline, was used for both midpoint and endpoint evaluations. In the midpoint impact category all 18 impact categories considered and for the endpoint level, results are aggregated into three areas: damage to human health, ecosystem quality, and resource depletion.

4. Sensitivity Analysis

To further assess the robustness of LCA results, a deterministic approach was adopted to perform a sensitivity analysis. All inventory flows associated with production-phase of battery life cycle were uniformly varied by -10% and $+10\%$ relative to the baseline, while keeping the functional unit, system boundaries and impact assessment method constant. Then, the endpoint impacts for human health, ecosystem quality, and resource scarcity for all the battery systems were considered and compared with baseline results. The $\pm 10\%$ variation was selected to represent typical variability in battery manufacturing inventory data as this approach enabled evaluation of the influence of production-phase assumptions on result stability and comparative ranking of the considered batteries.

Results and Discussion

1. Midpoint results

The impact assessment revealed that significant differences existed in how the three battery chemistries of LFP, NIB, and NMC performed in the environment in all the categories rated (Figure 2). The disparities in the emissions and resource use were mainly defined by the chemical composition of the cathode materials, the energy intensity of the manufacturing, and the power of electricity used in the use phase. In general, the use stage was found to be the most prevalent in the majority of categories, and the production stage produced major effects in the material- and energy-intensive operations, including metal mining and cathode manufacturing. The recycling stage added a relatively smaller contribution because of minimal energy consumption and the possible positive impact on the environment regarding material recovery.

1.1 Fossil resource scarcity

The fossil resource scarcity impact assessment showed that the NMC battery had the maximum impact, followed by LFP and NIB as shown in (Figure 2a). The production stage dominated the NMC battery, which was mainly associated with the high energy demand of battery material processing, electrode manufacturing, and cell assembly, and the use of critical metals. For the LFP battery, the production stage also contributed considerably, driven by the energy-intensive processing of iron-based cathode materials, and battery manufacturing processes, although its total impact remained lower than that of NMC. In contrast, the NIB battery showed substantially lower production-related fossil resource scarcity, reflecting its reduced reliance on fossil-intensive material production. The use phase contributed similarly across LFP and NIB battery chemistries based on electricity consumption; the NMC contributed relatively less to this phase. The end-of-life of the NIB battery was related to a high use of fossil resources. This was simply because pyrometallurgical recycling consumes a lot of energy. Processed through hydrometallurgy, both LFP and NMC batteries exhibited a significantly

less substantial impact because their recycling process is less energy consuming.

1.2 Mineral resource scarcity

The effects on mineral resource scarcity were noted to be the greatest for the NMC battery, then LFP and NIB as illustrated in (Figure 2b). The production stage prevailed in NMC, as the extraction and refining of valuable minerals, including nickel, cobalt, and manganese, involved heavy energy demand and contributed significantly to the resource depletion. On the other hand, LFP and NIB batteries had significantly smaller impacts because of their compositions of more prevalent elements like iron and sodium. Nonetheless, there was a significant contribution to the recycling stage of NIB, which is explained by the metal recovery process and secondary resources consumption. Comparatively, the effects of the use phase were relatively negligible for all battery chemistries. The same concerns have been expressed, and it was emphasized that cathode composition and critical metal content are the most significant issues that can define the scarcity of minerals in nickel-based battery systems [13, 21]. The net impact of the end-of-life stage on the scarcity of mineral resources was minor. Although hydrometallurgical recycling was in general more efficient for recovering valuable metals and hence providing minor credit, the pyrometallurgical methods were not effective. In general, recycling had a minor impact on this category as compared to the original manufacturing of the batteries.

1.3 Water consumption

The most critical contribution to water consumption came from NMC battery, with LFP and NIB following at noticeably lower levels (Figure 2c). For NMC, the production phase contributed most to this impact, which makes sense since water-intensive processes are required for mining, chemical processing, and cathode synthesis cooling [22]. It is noted that the most water-intensive part of battery production is the mining of cobalt and nickel, especially in regions where fresh water is not available. For LFP and NIB, production phase

also remained the main contributor, while the use phase showed only a minor contribution, reflecting electricity generation impacts, as power plants supplying electricity often rely on water-intensive thermal systems. The recycling phase showed comparatively low contributions across all batteries, with LFP slightly higher than NMC, and NIB the lowest, which can be associated with wet hydrometallurgical recovery processes. It was reported that hydrometallurgical processes are generally more water-efficient than pyrometallurgical recycling, which explains the limited contribution

observed [21, 23]. The implementation of closed-loop water systems and dry processing techniques in battery manufacturing has the potential to substantially reduce the overall water footprint across the battery life cycle. The notable water use at the end-of-life stage was more evident for NMC and LFP, which was attributed to the requirement of aqueous solutions during chemical leaching processes, whereas the simpler material chemistry of NIB batteries resulted in comparatively lower water consumption during recycling.

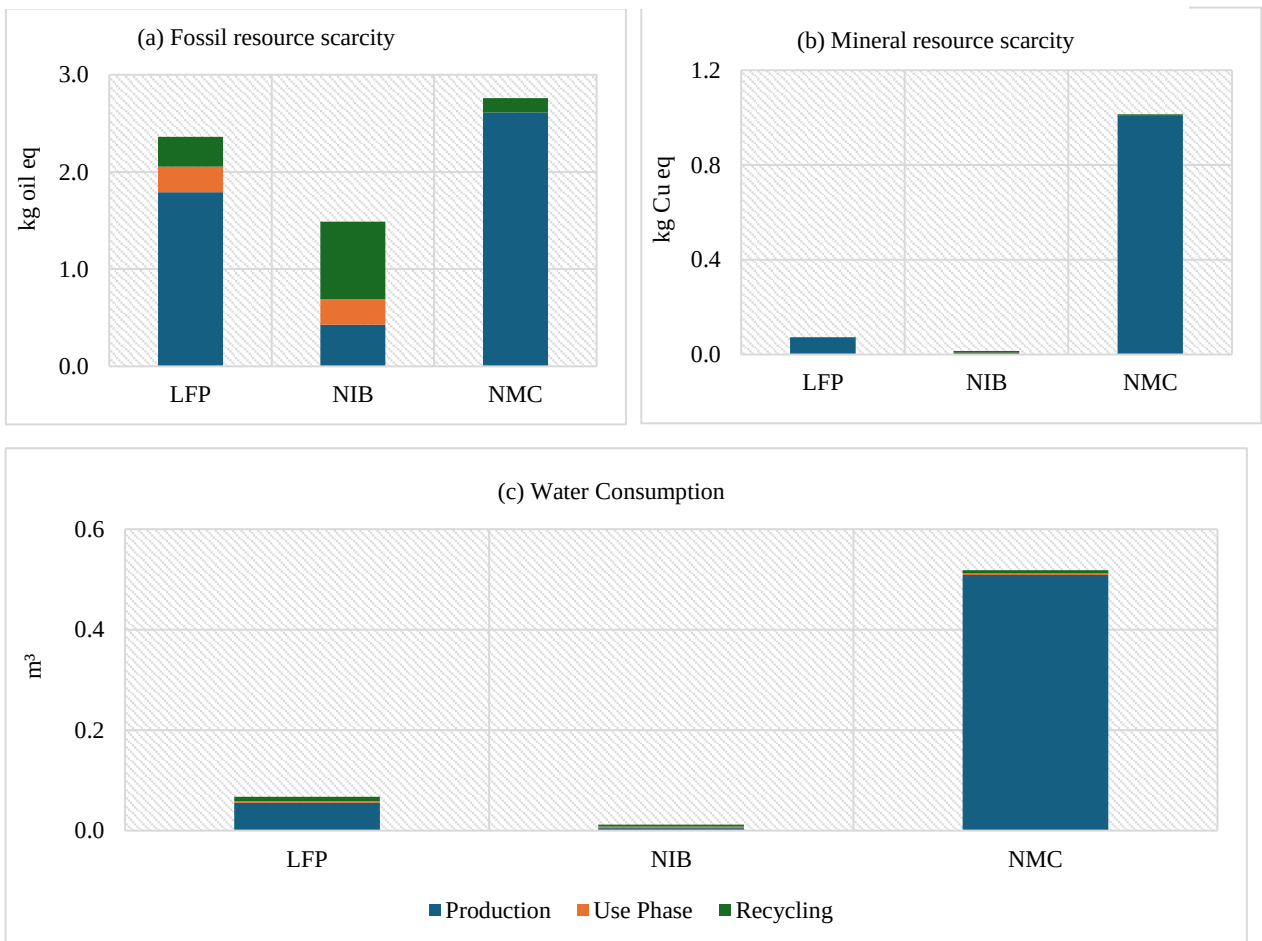


Figure 2 Resource depletion-related impact categories, (a) fossil resource scarcity, (b) mineral resource scarcity, (c) water consumption

1.4 Global warming

The findings showed that the production phase was the most significant contributor to global warming for all battery types, which represented the intensity of carbon intensity of electricity and material production processes. The NMC battery had the highest total global warming impacts, followed by LFP and NIB (Figure 3a). Such a trend implied that the overall global warming impact was strongly influenced by production-related emissions, while electricity use during charging remained similar across the batteries. The comparatively lower global warming of NIB was associated with its lower production-phase emissions, while the NMC battery showed highest production-related emissions, due to the energy-intensive mining and refining of nickel, cobalt, and manganese. The LFP battery demonstrated moderate impacts compared to the NMC battery, which can be explained by its simpler cathode chemistry and lower dependence on critical transition metals, although its energy-intensive production processes still contributed significantly. Similar results were presented, and raw material processing was identified as a major contributor to greenhouse gas emissions in NMC batteries. In addition, it was emphasized that the inclusion of cleaner energy sources to charge could significantly reduce the total greenhouse gas emissions, especially in LFP and NIB chemistries [21-24]. Thus, the effect of global warming was observed to be highly dependent on the carbon content of the electricity mix and the battery material composition. There was a significant difference in the end-of-life phase between battery chemistries. The NIB battery was identified to have the highest global warming impacts in the recycling process, which was mainly explained by the fact that it was processed through the pyrometallurgical process which requires a lot of energy, often from fossil fuels. However, the LFP and NMC batteries, which mostly undergo hydrometallurgical recycling, showed lower impacts, as this process is performed at lower temperatures with a reduced carbon footprint.

1.5 Fine particulate matter

The production phase was dominant in the formation of fine particulate matter because much of the particulate emissions were linked to energy-intensive manufacturing processes. The NMC battery had the greatest total

potential, followed by LFP and NIB (Figure 3b). The high impact of NMC was attributed to its production-related energy demand, which contributed to the emission of particulate matter. The LFP battery also showed notable impacts, mainly associated with material processing and manufacturing, while the NIB battery exhibited the lowest total particulate matter formation. The significantly larger contribution in the recycling stage of NIB originated from energy-intensive metal recovery and thermal treatment processes. Furthermore, the NIB battery was found to have lower overall particulate matter emissions, as its production phase required comparatively less energy. All these findings confirmed that the formation of particulate matter during battery production is highly sensitive to the energy source and processing methods [13, 23, 24]. The battery end-of-life stage for NIB remained a major source of particulate matter emissions, as the pyrometallurgical recycling process produces fine particles because of high-temperature applications, which are not safe for human respiratory health. The LFP and NMC recycling stages led to relatively lower particulate matter emissions.

1.6 Human carcinogenic toxicity

The most significant human carcinogenic toxicity effect was observed in the NMC battery, followed by LFP and NIB (Figure 3c). For the NMC battery, the production phase also contributed largest role, mainly due to the mining and processing of nickel and cobalt, which are known to be carcinogenic. In the case of LFP, the production phase played substantially, mainly because of energy-intensive material processing and upstream industrial activities associated with battery manufacturing. For the NIB battery, the end-of-life phase showed a relatively higher contribution, while the use phase contribution remained limited and was related to electricity generation during operation. The recycling phase also contributed to the overall impact, particularly for NIB, where pyrometallurgical recycling led to a higher potential for human carcinogenic toxicity. This was caused by the possible release and exposure to hazardous substances during high-temperature treatment. Overall, the production and recycling processes in battery systems were identified as the main sources of human carcinogenic toxicity,

depending on battery chemistry and recycling technology.

1.7 Non-human carcinogenic toxicity

The human non-carcinogenic toxicity impact was highest for the NMC battery, primarily driven by the production phase, including the production of nickel, cobalt, and manganese particulates, along with acid leachates and solvent residuals during cathode material preparation (Figure 3d). For LFP and NIB batteries, the production phase also contributed most to this toxicity, while the use phase contribution remained relatively small, as emissions from electricity generation were limited compared to manufacturing-related processes. The overall impact of recycling was small, although in the case of NIB, toxicity was slightly affected by energy-intensive recycling processes, rather than by material composition. These findings support the idea that metal extraction, material processing, and production-related energy emissions are the major non-carcinogenic toxicants in lithium- and sodium-based batteries [25].

1.8 Ionizing radiation

The examination estimated the effect of ionizing radiation and found that the contribution of the NMC battery was the highest, particularly during the manufacturing period, compared to other chemistries. This impact was primarily attributed to energy use and radioactive waste generation associated with nickel and cobalt extraction and processing. The LFP battery showed the second-highest impact, while the NIB battery had the lowest impact, mainly due to their lower dependence on these metals and relatively simpler manufacturing processes. The use stage also contributed to radiation effects, particularly when the share of nuclear electricity was high and the share of coal sources was minimum (Figure 3e), [26]. The LFP battery showed a relatively higher contribution in its end-of-life stage, primarily as a by-product of the hydrometallurgical recycling process, which is electricity-intensive. The primary contributor was the high-temperature treatment that requires substantial grid electricity. The NIB and NMC batteries, which were mainly associated with lower end-of-life radiation impacts, therefore exhibited a smaller footprint in this category.

1.9 Ozone formation, human health

The results indicated that ozone formation was mainly determined by the production and end-of-life treatment emissions. The NIB battery had the highest total contribution among the three chemistries, followed by LFP and NMC (Figure 3f). The main reason for this was the high end-of-life emissions of NIB, leading to higher releases of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) which are involved in the formation of tropospheric ozone. On the other hand, the production phase of NMC battery was a major contributor in this category, due to energy-intensive material processing, like aluminum foil, copper foil and rolling oil production, which are known sources of nitrogen oxides emissions. The higher total value of NIB reflected its higher recycling-related emissions, while the NMC battery showed a slightly higher impact than LFP, primarily associated with its production-related emissions. This trend has also been described, with NIB batteries exhibiting higher ozone formation potential on average than nickel-enriched cathode systems [27]. Overall, these results indicated that the electricity mix and energy efficiency are the most crucial factors affecting the impacts of ozone formation. The recycling of NIB battery contributed noticeably to the creation of ozone formation, as the pyrometallurgical process is a significant source of nitrogen oxides, which are precursors of smog and can cause respiratory problems. On the other hand, the end-of-life processes of LFP and NMC produced lower emissions, since their recycling relies on controlled hydrometallurgical processes.

1.10 Stratospheric ozone depletion

In the case of stratospheric ozone depletion, the production phase is found to be the leading contributor, primarily due to emissions of chlorofluorocarbons, halons, and nitrogen oxides. These emissions are generated during battery production through energy-intensive material processing and manufacturing activities. The NMC battery showed the highest potential for ozone depletion, followed by LFP, while NIB exhibited the lowest impact among the three batteries (Figure 3g). The relatively higher contribution of the recycling stage in NIB compared to its production phase was associated with emissions from the recycling process, which were related to energy utilization during metal

recovery and solvent evaporation. The ozone-depleting impact of NMC during production was substantially higher, due to the release of halogenated compounds and other ozone-depleting precursors during metal refining

processes. The results align with previous research, which shows that NMC batteries cause more stratospheric ozone depletion than LFP batteries because of their complex cathode manufacturing processes [28].

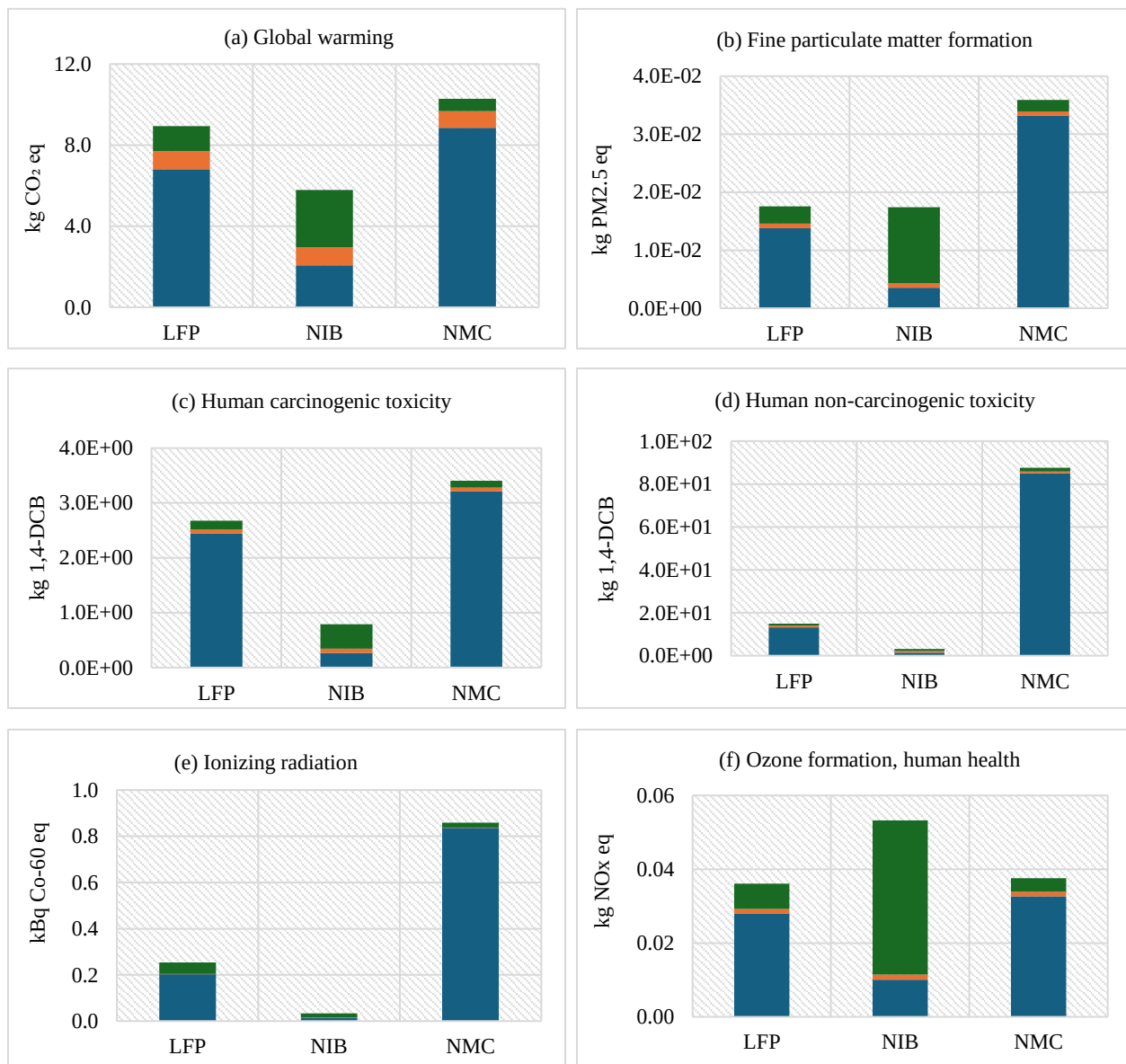


Figure 3 Human health-related impact categories, (a) global warming, (b) fine particulate matter, (c) human carcinogenic toxicity, (d) non-human carcinogenic toxicity, (e) ionizing radiation, (f) ozone formation terrestrial ecosystem, (g) stratospheric ozone depletion

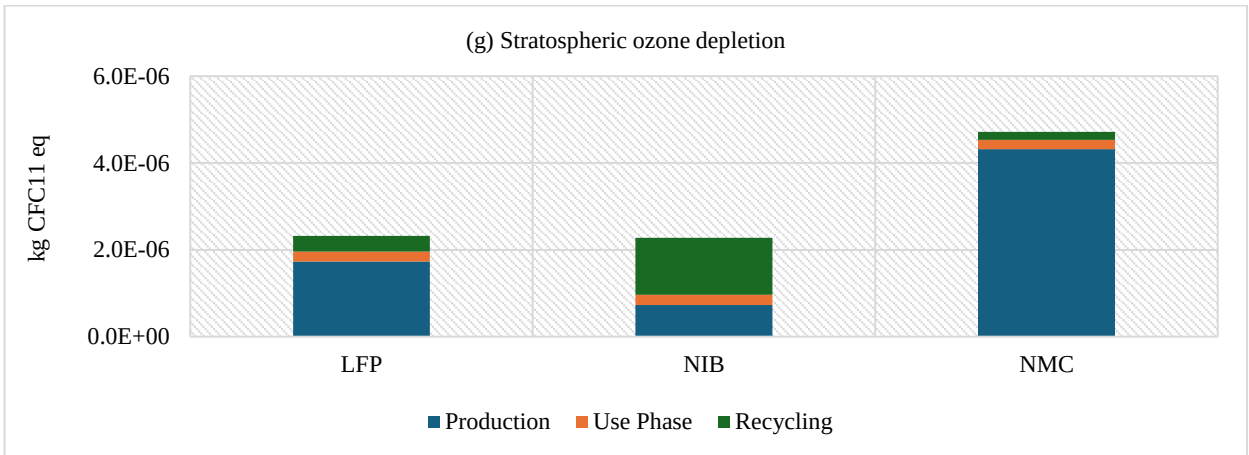


Figure 3 Human health-related impact categories, (a) global warming, (b) fine particulate matter, (c) human carcinogenic toxicity, (d) non-human carcinogenic toxicity, (e) ionizing radiation, (f) ozone formation terrestrial ecosystem, (g) stratospheric ozone depletion

1.11 Freshwater eutrophication

The largest contribution to eutrophication for all batteries occurred during the production phase, while the use phase showed a smaller contribution. This contribution was caused by phosphate emissions, which occurred during upstream fuel production and industrial activities in the electricity and material supply chains, specifically in fossil-based electricity generation and maintenance activities [29]. In NMC, the high impact of the production phase was due to wastewater discharge caused by effluent phosphorus from metal production [30, 31]. The highest total eutrophication was indicated by the NMC battery, followed more distantly by LFP, while NIB showed the lowest impact (Figure 4a). The lower total impact of NIB was associated with its reduced material intensity and lower phosphorus-related emissions across the life cycle. Similarly, it was mentioned that batteries were associated with varying rates of eutrophication depending on grid dependency and water management practices for sodium-ion and lithium-ion batteries [15, 32]. Their results revealed that further development of wastewater treatment has the potential to lessen freshwater eutrophication throughout battery life cycles, given that upstream phosphate emissions are minimized.

1.12 Marine Eutrophication

In the case of marine eutrophication, the production and end-of-life phases were the most

identified as the dominant contributors, while the use phase showed a relatively minor contribution across all battery chemistries. The NMC battery showed the highest overall impact, while the LFP battery showed a moderate impact and the NIB battery exhibited the lowest net emissions (Figure 4b). The lowest impact observed for the NIB battery was mainly attributed to lower nitrogen-related emissions across all life-cycle stages, particularly during the production and recycling phases. In contrast, the NMC battery demonstrated the highest marine eutrophication potential, which was primarily driven by its production and especially recycling stage, as reflected by its substantially higher recycling contribution compared to LFP and NIB. The moderate impact of the LFP battery was mainly associated with emissions from the production phase, while its recycling-related contribution remained considerably lower than that of NMC. The higher impacts observed for the NMC battery during production and recycling were associated with metal mining, chemical leaching, and recovery processes, which release nitrogen- and ammonia-related compounds into aquatic environments. These findings confirm that nutrient-based emissions originating from energy- and material-intensive battery production and recycling processes are the primary contributors to marine eutrophication. In comparison, LFP batteries demonstrate lower water-related environmental burdens than NMC batteries, while NIB batteries provide the most

environmentally favorable performance, thereby reducing the marine eutrophication potential in EV battery systems [30, 33].

1.13 Terrestrial Acidification

The production phase dominated terrestrial acidification, especially in NMC and LFP batteries, while the recycling phase played a major role for NIB batteries. This dominance was largely linked to the emission of sulfur dioxide and nitrogen oxides through energy-intensive material processing and electricity production from fossil fuels. The highest total impact was obtained with the NMC battery, followed by NIB, while LFP showed the lowest overall impact, which highlights the importance of material intensity and production-related emissions (Figure 4c). In the case of the NMC battery, the production stage played a significant role, since the extraction of metals and the refining of nickel and cobalt lead to the generation of acidifying emissions. The LFP battery showed a comparatively lower total impact, mainly because of its lower material intensity and reduced reliance on highly acidifying metal refining processes. The trend observed shows that the nature of acidifying emissions is mainly determined by manufacturing energy demand, as well as the chemical nature of the cathode materials [34]. The NIB battery was a significant contributor to acidifying emissions during the end-of-life stage, as the pyrometallurgical process caused emissions of sulfur oxides, which lead to acid rain and soil acidification. In comparison, recycling of the NMC and LFP batteries produced lower effects, because their hydrometallurgical processes operate at lower temperatures and use controlled chemical leaching instead of burning, which limits the release of these pollutants.

1.14 Ozone Formation (Terrestrial Ecosystems)

The formation of tropospheric ozone was mainly contributed by the production and recycling phases. Similar to the ozone formation (human health), the NIB battery had the highest impacts in terms of ozone formation (terrestrial ecosystem), whereas the difference between the LFP and NMC results is negligible (Figure 4d). The NIB battery exhibited a higher potential for ozone formation, which can be attributed to its

significantly higher recycling-related emissions, particularly from pyrometallurgical treatment, compared to NMC and LFP across its life cycle. In NMC and LFP, the production phase was playing a crucial role. This finding indicates that the formation of tropospheric ozone was strongly influenced by the raw material extraction, processing, and transformation in these two batteries. Similar conclusions were made, and it was emphasized that NIB batteries can show higher ozone formation potential when recycling-related emissions are substantial, whereas batteries generally exhibit lower impacts due to lower material intensity and more controlled recycling processes [25, 27, 34].

1.15 Terrestrial Ecotoxicity

The terrestrial ecotoxicity results show a different variation among the three battery chemistries. The NMC battery posed the highest overall impact, followed by NIB and LFP (Figure 4e). The most influential contribution to NMC occurred at the production stage, primarily because of the large amounts of toxic metals (nickel, cobalt, and manganese) used and the environmental costs of mining and refining. Another phase affecting all types of batteries was the use phase, which was responsible for airborne metal emissions during the production of electricity, although its contribution was minor compared to production and recycling. The recycling stage in the NIB battery showed a notable effect, which was mainly caused by operations involving the processing of sodium salts and chemical recovery, resulting in its total recycling-related ecotoxicity being higher than both LFP and NMC. Recent research established that NMC cathode manufacturing is the primary contributor to terrestrial ecotoxicity throughout EV battery life cycles due to the toxicity of metals and the release of waste [34, 35]. On the other hand, the impact of toxicity in LFP batteries was significantly lower because cobalt and nickel, which have severe effects on soil quality and ecotoxicology, are not present in the structure.

1.16 Freshwater ecotoxicity

The NMC battery shows the highest freshwater ecotoxicity during the production stage. It was determined that the production phase was the dominant contributor for the NMC

battery, suggesting that manufacturing and extraction of raw materials had significant impacts on freshwater ecosystems (Figure 4f). The production-related impacts were largely due to metal refining operations and chemical washing involved in the production of nickel and cobalt. Meanwhile, the use phase represented a comparable contribution in LFP and NIB batteries, mainly because of electricity production and grid emissions during the charging cycles, particularly from copper and zinc compounds released due to wear and corrosion in the electricity grid, which contribute to freshwater ecotoxicity. Although smaller than production impacts, the recycling phase contributed a relatively small amount to freshwater ecotoxicity across all chemistries. These findings were also observed in other studies pointing to the prevalence of transition metals and electrolyte residues as the primary sources of freshwater toxicity during battery production [18, 36].

1.17 Marine ecotoxicity

The maximum marine ecotoxicity was observed in the NMC battery, followed by LFP and NIB, respectively (Figure 4g). The production stage was predominant in the case of NMC, indicating that metal processing and solvent releases influenced marine ecosystems. The use and recycling stages of the NIB battery showed noticeable contributions despite its low production impact, indicating that electricity consumption and material recovery processes can continue to release toxic substances into water bodies. The LFP battery showed moderate production-related impacts but relatively low contributions from the use and recycling stages, which confirms that its iron-based chemistry is less harmful to marine

systems when compared to nickel- and cobalt-based alternatives [13, 36].

1.18 Land use

The NMC battery showed the highest effect on land use followed by LFP and NIB, respectively (Figure 4h). The production phase stands as the main contributor to NMC's environmental effects because mining for nickel and cobalt leads to large-scale land usage and results in deforestation and soil degradation [2]. In the case of LFP batteries, the production phase remained dominant, while for NIB batteries, the recycling phase prevailed, reflecting the impact of sodium recovery and associated material processing on land use. The impact of recycling was not very significant overall, but it was more evident in NIB because of the treatment of sodium and other metals. These findings indicate that the main factors driving land transformation in the life cycle of lithium- and sodium-based batteries are material extraction and end-of-life material processing, along with energy generation [3, 36].

2. Endpoint results

The endpoint assessment revealed that the indicators of human health, ecosystem quality, and resource availability showed significant differences across NMC, NIB, and LFP batteries. The variations were mostly attributed to material composition, energy consumption in the mining process, and recycling efficiency. In general, the end-of-life phase had a moderate impact, where hydrometallurgical recycling minimized effects, whereas pyrometallurgical recycling, especially that of NIB, posed larger risks to human health and resources.

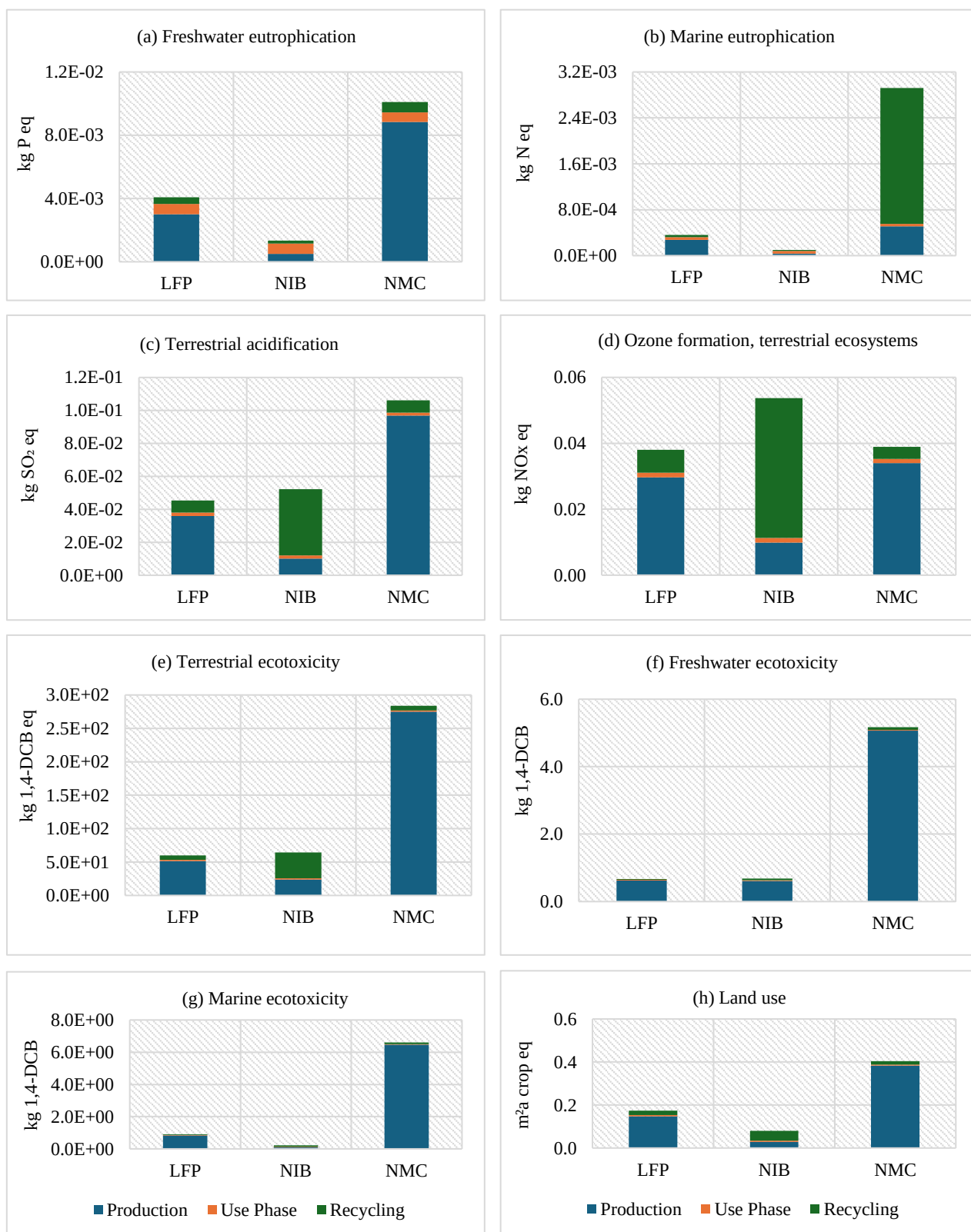


Figure 4 Ecologically related impact categories, (a) freshwater eutrophication, (b) marine eutrophication, (c) terrestrial acidification, (d) ozone formation, terrestrial ecosystems, (e) terrestrial ecotoxicity, (f) freshwater ecotoxicity, (g) marine ecotoxicity, (h) land use

2.1 Human health damage

The findings indicated that the production of the NMC battery made the greatest contribution in the human health category compared to the other stages (Figure 5a). This is explained by the fact that electricity-intensive manufacturing processes are widely used, and the production stage dominates the total impact. The energy demand associated with material processing and cell manufacturing contributes to releases of toxic compounds and greenhouse gases, which further endanger human exposure. These processes are associated with emissions of sulfur dioxide, particulates, and volatile organic compounds, all of which are linked to respiratory diseases and cardiovascular diseases. The NMC battery showed the highest total human health impact while LFP exhibited the second-highest total impact, and NIB the lowest, with its production phase still remained the main contributor, reflecting the influence of material processing and energy use. The NIB battery exhibited the lowest total impact, while its effects were relatively higher at the recycling stage, predominantly due to electricity consumption during recycling. Indirect emissions exacerbate human health risks in regions that primarily rely on fossil fuels for electricity production. The NIB battery exhibited higher impacts at the end-of-life stage, mainly because recycling processes contributed more to the total impact, even though it has a simpler material composition, does not contain toxic transition metals, and consumes less energy in its production. The end-of-life phase had the greatest contribution for NIB because of energy-intensive pyrometallurgical recycling, under which process-related emissions and residue handling may emit harmful gases unless properly managed [25, 27, 37]. In contrast, hydrometallurgical recycling is more efficient, trapping metals safely and minimizing possible human exposure. LFP and NMC showed lower end-of-life contributions, and the recycling processes are not complicated.

2.2 Ecosystem quality damage

The production phase was found to be the largest contributor in the ecosystem damage category for NMC and LFP batteries, whereas the recycling phase was the largest contributor for NIB [13, 34, 38]. This predominance is due to the

extraction and refining of metals and material-intensive manufacturing, which cause emissions leading to acidification, eutrophication, and ozone formation. For NMC, the production phase contributed the highest ecosystem damage among all batteries, while LFP showed lower but still noticeable production-related effects, (Figure 5b). Nickel and cobalt mining activities lead to heavy metal run-off, soil erosion, and contamination, causing degradation of aquatic and terrestrial ecosystems and disturbing biodiversity. The results also indicate that the geographical origin of resources and the carbon intensity of the local power network are significant factors in causing ecosystem harm. In addition, inadequate EV battery end-of-life regulatory frameworks, particularly the absence of biodiversity protection measures and clear recycling mandates, may further negatively affect ecosystem quality [3, 39]. NIB has shown a noticeable effect on the ecosystem at the end-of-life stage, which is caused by metal residues and process effluents during the pyrometallurgical treatment. The recycling effects of LFP and NMC are also minimal, indicating that the recycling of these materials, particularly via hydrometallurgical processes, does not release significant amounts of toxic substances into the soil or water.

2.3 Resource Depletion damage

The resource depletion category revealed that the NMC and LFP battery was by far the most resource-intensive, especially at the production stage, because it relied on scarce metals such as lithium, nickel, cobalt, and manganese (Figure 5c). The mining and subsequent handling of these metals not only increase the rates of depletion but also require high energy inputs, which cause other environmental burdens [13, 21, 40]. The LFP battery showed the second-highest resource depletion impact, mainly driven by the production phase, although its total impact remained lower than NMC and higher than NIB. The NIB battery presented greater contributions to the recycling stage, mainly because of increasing energy demands and underdeveloped recycling technologies. The existing approaches to sodium-ion recycling have low recovery rates, resulting in higher losses and additional strain on resource extraction. Conversely, the NIB battery

was least affected by resource depletion in the production stage because it is based on abundant natural resources, such as sodium and iron-based materials. The recycling stage contributed most to NIB, due to the pyrometallurgical recovery

process, which is less efficient and leads to greater resource loss. The end-of-life stage of NMC and LFP contributed minimally because hydrometallurgical recycling efficiently reclaims metals, reducing resource depletion.

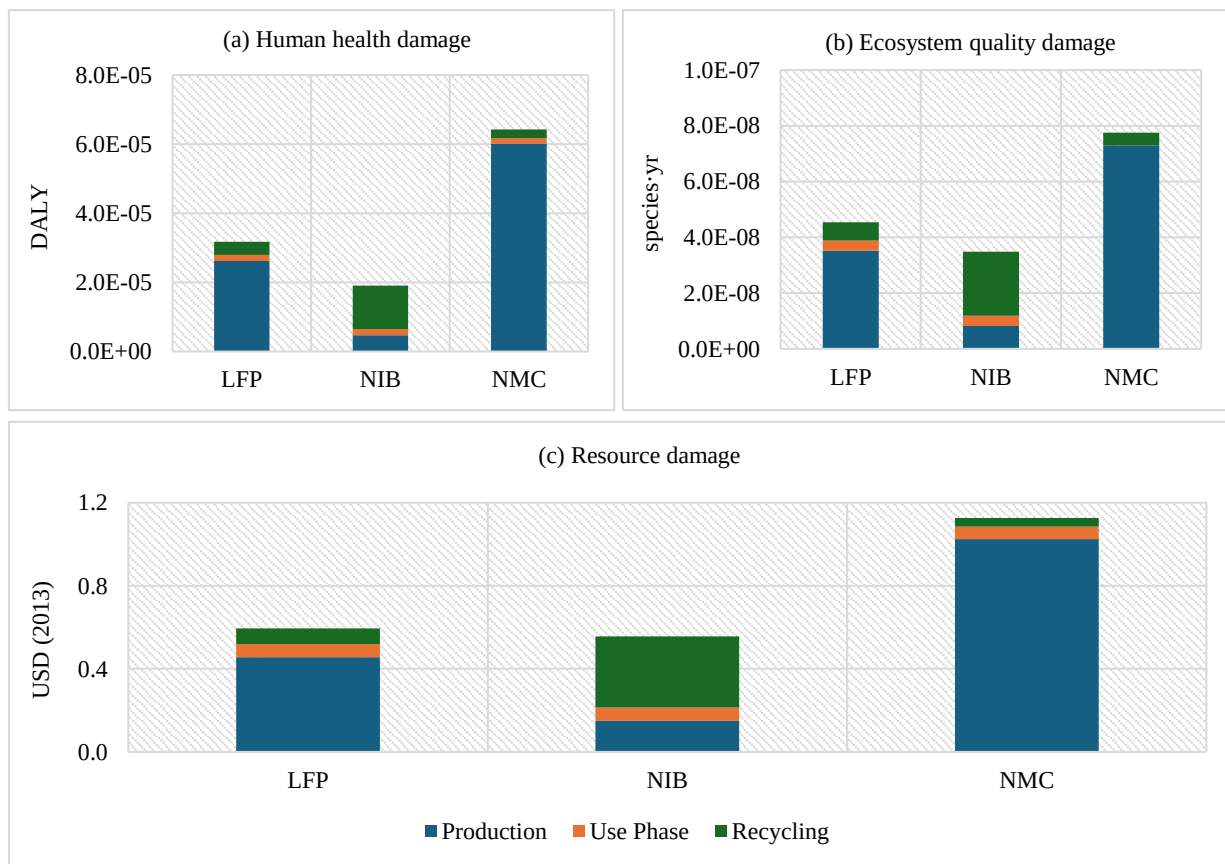


Figure 5 Comparison of endpoint results: (a) damage to human health damage, (b) ecosystem quality damage, (c) resource damage

3. Sensitivity Analysis

The sensitivity analysis was performed by considering a variability of $\pm 10\%$ percent in the battery production phase indicates a steady and almost linear response of endpoint impacts for all battery technologies (see Figure 6). In the case of the human health endpoint, the effects were proportional to the production burdens, where NMC had the highest and NIB the lowest values in all scenarios. The same linear patterns were observed in terms of damage to the ecosystem quality with NMC

showing the greatest potential impacts, then LFP and NIB respectively. The impacts in terms of resource scarcity showed NMC having the most pronounced impacts and NIB the least. Notably, the relative ranking of battery technologies did not change in any of the sensitivity cases, which implies that variability in the production phase influences the magnitude of the impact considerably but does not change the comparative conclusions of the study.

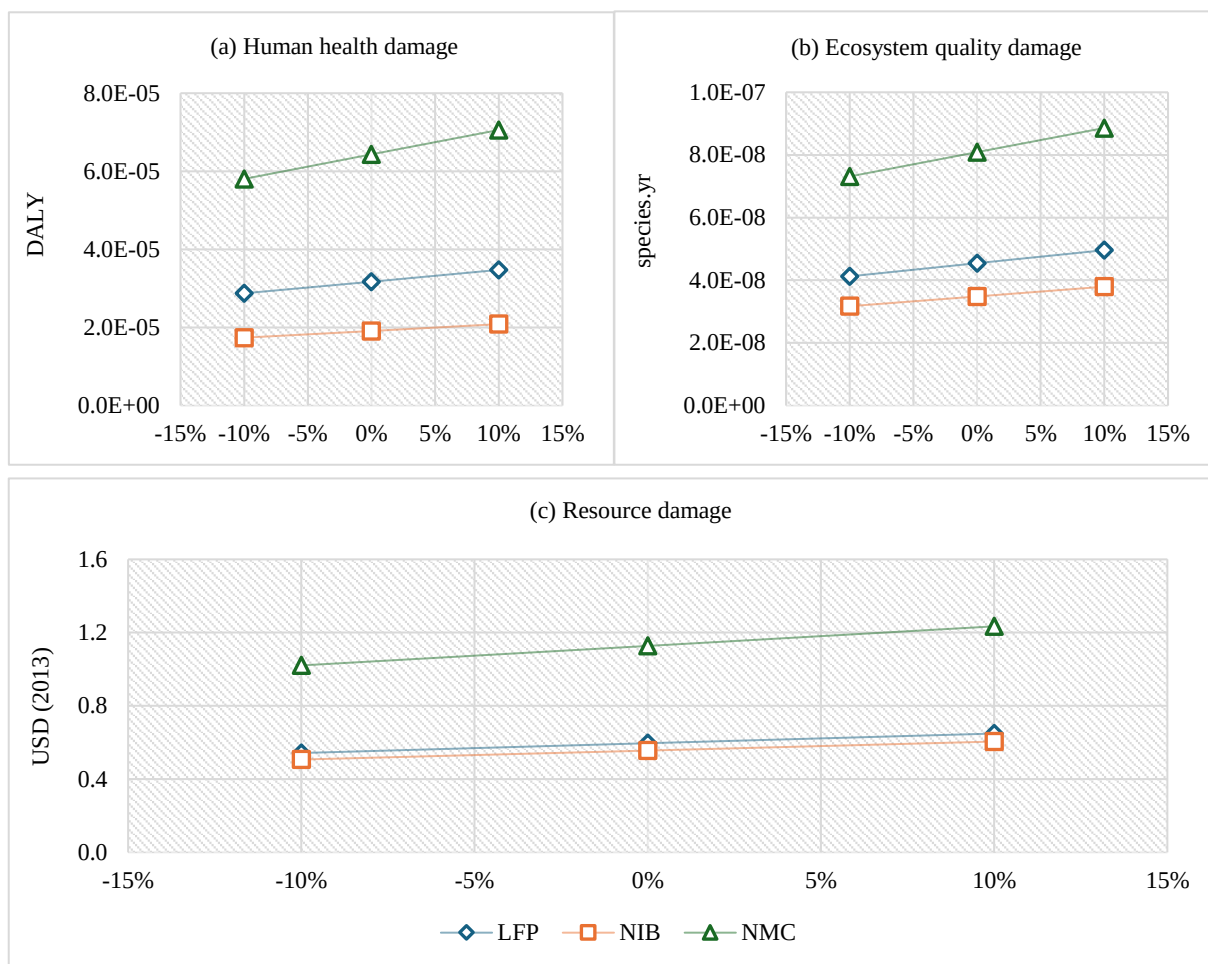


Figure 6 Sensitivity analysis of endpoint impact results considering $\pm 10\%$ Change in Battery Production Phase

Conclusions

In this study, the life cycle assessment methodology is employed to compare the environmental effects of NMC, LFP, and NIB batteries in their entire life cycle, beginning with the extraction of raw materials in China, their use in Thailand, and finally the recycling in China. Comparison analysis has been done to establish the major causal factors of environmental effects, as well as to determine the trade-offs between the three battery chemistries.

The findings indicate that the production stage is the primary cause of environmental impact of all types of batteries, especially for NMC, as it requires a lot of energy to extract and refine nickel, cobalt, and manganese. LFP

exhibits moderate environmental performance in the process of production, and it owes this quality mainly to its simpler material composition and a lesser dependence on critical minerals. NIB has better environmental effects in the production process and has a higher future adoption potential as it utilizes the abundant resources of sodium and does not use any critical metals. There is a need to optimize production technologies to minimize the environmental burdens further.

In use phase, both NIB and LFP have similar increased emissions particularly because of the extensive consumption of fossil fuels as a form of electricity, and NMC experiences relatively lower emissions because of the reduced energy usage due to its high energy density. NIB has the most significant

effects at the end-of-life stage due to the application of pyrometallurgical recycling, as residual sodium-based compounds, process slag, and high-temperature combustion emissions may emit toxic gases and particulate matter unless the process is closely monitored.

On the other hand, hydrometallurgical recycling is more effective, allowing safer recovery of metals and reducing human and ecological exposure. The effects of NMC and LFP in recycling are not very high, as they contain fewer hazardous metals and are easier to recycle. Additionally, classification of batteries and selective recycling to improve recovery efficiency and lower environmental burdens for all chemistries can be further enhanced.

Finally, the sensitivity analysis revealed that the considered variability in battery production phase ($\pm 10\%$) does not affect the environmental ranking of NMC, LFP, and NIB batteries, confirming the reliability of the comparative LCA results. The future studies may focus on quantitative uncertainty analyses to further assess the robustness of the LCA results.

Recommendations

Based on the results of this assessment, it is proposed that the manufacturing processes of NMC, LFP, and NIB batteries should be optimized to reduce water consumption, energy consumption and emissions, especially during the extraction and purification of critical material for NMC batteries. The increased use of renewable energy in battery manufacturing and operation in Thailand and China should be prioritized to reduce the impact of fossil fuels, related impacts, particularly for NMC and LFP chemistries. The recycling strategies should emphasize hydrometallurgical processes, as they exhibit lower emissions and better product recovery compared to pyrometallurgical, especially for the LFP and NMC batteries. Furthermore, selective classification of batteries prior to recycling could enhance resource recovery efficiency and mitigate ecological and human health risks. In addition, incorporating LFP and NIB batteries whenever possible will reduce the overall environmental impact as

they reduce the dependence on critical raw materials extraction, lightweight synthetic materials, and low energy consumption, which will facilitate sustainable EV adoption in Thailand and similar regions.

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Annexes - Inventory Data for the Life Cycle Assessment

The life cycle inventory of this study, which includes production, use, and end-of-life stages, was obtained from scientific literature. Inventory data for nickel-manganese-cobalt (NMC) batteries were taken from [3], While sodium-ion (NIB) and lithium iron phosphate (LFP) batteries were derived from [13].

1. Inventory data for NIB batteries

A1. Inventory data for NIB battery pack

	Parameter name	Amount	Unit
Input	Electricity	3.53E+01	kWh
	NIB battery cell	8.03E-01	kg
	BMS	5.60E-02	kg
	Shell	1.90E-1	kg
	Natural gas	3.65E-01	kg
Output	NIB Battery pack	1.00E+00	kg
	Waste heat	1.27E+1	MJ

A2. Inventory data for NIB battery cell

	Parameter name	Amount	Unit
Input	Cathode	2.16E-01	kg
	Anode	2.92E-01	kg
	Separator	1.69E-02	kg
	Electrolyte	1.17E-01	kg
	Cell container	1.97E-01	kg
	Nitrogen	8.39E-03	kg
	Infrastructure	3.20E-10	p
	Electricity	2.91E+00	kWh
Output	Heat	2.10E+01	MJ
	NIB Battery cell	7.99E-01	kg
	Waste heat	4.69E-01	MJ

A3. Inventory data for NIB Cell container

	Parameter name	Amount	Unit
Input	Casing	4.84E-01	kg
	Nylon ₆ for sealings	5.21E-03	kg
Output	Cell container	2.47E-01	kg

A4. Inventory data for NIB Electrolyte

	Parameter name	Amount	Unit
Input	Ethylene carbonate	1.04E-01	kg
	DMC	2.60E-02	kg
	NaPF ₆ (salt)	1.72E-02	kg
Output	Electrolyte	1.47E-01	kg

A5. Inventory data for NIB NaPF₆ (salt)

	Parameter name	Amount	Unit
Input	Sodium fluoride production	3.73E-02	kg
	Phosphorus pentachloride	2.32E-01	kg
	Hydrogen fluoride	4.73E-01	kg
	Nitrogen	1.46E-04	kg
	Lime	8.70E-01	kg
	Electricity	6.33E-02	kWh
Output	limestone residue	1.02E+00	kg
	Wastewater	4.22E-04	kg
	Phosphorus trichloride	3.08E-02	kg
	NaPF ₆	1.17E-01	kg
	NaF recycled	4.96E-03	kg
	Waste heat	2.28E-01	MJ

A6. Inventory data for NIB DMC

	Parameter name	Amount	Unit
Input	Electricity	4.66E-04	kWh
	Ethylene carbonate	1.73E-01	kg
	Methanol	1.26E-01	kg
	Heat	1.79E-02	MJ
	DMC	1.77E-01	kg
Output	Ethylene glycol	1.22E-01	kg

A7. Inventory data for NIB Cathode

	Parameter name	Amount	Unit
Input	Active material	2.31E-01	kg
	Carbon black	4.91E-03	kg
	Tetrafluoroethylene	4.78E-03	kg
	Polyethylene	4.85E-03	kg
	N-methyl-2-pyrrolidone	8.59E-04	kg
	Heat	7.21E-02	MJ
	Aluminum foil	4.92E-02	kg
Output	Electricity	5.40E-04	kWh
	1-Methyl-2-pyrrolidinone	8.59E-04	kg
	Cathode	2.70E-01	kg
	Waste heat	7.21E-02	MJ

A8. Inventory data for NIB Active material

	Parameter name	Amount	Unit
Input	Na ₂ CO ₃	4.70E-01	kg
	MnO ₂	3.50E-01	kg
	NiCO ₃	2.87E-01	kg
	Mg(OH) ₂	2.35E-02	kg
	N-methyl-2-pyrrolidone	8.59E-04	kg
	Heat	9.05E+00	MJ
	TiO ₂	3.22E-02	kg
	Electricity	2.63E-02	kWh
Output	Active material	8.54E-01	kg
	Carbon dioxide	3.01E-01	kg
	Waste heat	9.15E+00	MJ

A9. Inventory data for NIB Mg(OH)₂

	Parameter name	Amount	Unit
Input	Electricity	4.90E-02	kWh
	Sodium chloride	2.91E+00	kg
	Hydrated lime	3.30E-02	kg
	Magnesium mineral extraction	1.79E-02	kg
	Mg (OH) ₂	2.75E-02	kg
Output	Waste heat	1.77E-01	MJ

A10. Inventory data for NIB NiCO₃

	Parameter name	Amount	Unit
Input	NaHCO ₃	4.77E-01	kg
	NiSO ₄	4.37E-01	kg
	Water	2.68E+00	kg
	Heat	8.80E-01	MJ
	Electricity	3.76E-03	kWh
Output	NiCO ₃	3.36E-01	kg
	NiCO ₃ in effluent	4.27E-03	kg
	Na ₂ SO ₄ in effluent	6.52E-02	kg
	Carbon dioxide	3.01E-01	kg
	Waste heat	7.69E-01	MJ

A11. Inventory data for NIB Anode

	Parameter name	Amount	Unit
Input	Hard carbon	2.92E-01	kg
	Carbon black	9.45E-03	kg
	Carboxymethyl cellulose (CMC)	8.83E-03	kg
	Styrene-butadiene rubber (SBR)	3.80E-03	kg
	Water	1.26E-01	kg
	Heat	4.05E-01	MJ
	Aluminium foil	1.02E-01	kg
	Electricity	7.52E-07	kWh
Output	Anode	3.65E-01	kg
	Waste Water	1.26E-01	kg
	Waste heat	4.09E-01	MJ

A12. Inventory data for NIB Styrene-butadiene rubber (SBR)

	Parameter name	Amount	Unit
Input	Butadiene	7.82E-03	kg
	Styrene	2.61E-03	kg
	Emulsifier	2.84E-04	kg
	Cyclohexane	1.04E-04	kg
	Water	1.87E-02	kg
	Cooling water	2.60E-03	m ³
	Heat	1.43E-01	MJ
	Sodium persulfate	5.24E-05	kg
	Electricity	5.72E-03	kWh

Output	SBR	1.04E-02	kg
	Waste Water	1.87E-02	kg
	NM VOC	1.50E-04	kg
	Waste heat	1.64E-01	MJ

A13. Inventory data for NIB Hard carbon

	Parameter name	Amount	Unit
Input	Coke	9.13E-01	kg
	Nitrogen	7.21E-01	kg
	Water	1.43E-01	kg
	Heat	1.51E+00	MJ
	Electricity	1.47E-02	kWh
Output	Hard carbon	8.01E-01	kg
	CO ₂	6.72E-02	kg
	NO	3.73E-02	kg
	NO ₂	3.01E-03	kg
	SO ₂	4.03E-02	kg
	Waste heat	1.56E+00	MJ

2. Inventory data for LFP batteries

A14. Inventory data for LFP battery pack

	Parameter name	Amount	Unit
Input	Electricity	2.67E+01	kWh
	Water	7.95E-03	kg
	LFP battery cell	8.03E-01	kg
	BMS	1.66E-02	kg
	Shell	1.33E-01	p
Output	LFP Battery pack	1.00E+00	kg

A15. Inventory data for LFP battery cathode material

	Parameter name	Amount	Unit
Input	Iron phosphate	2.41E+00	kg
	Water	5.78E-01	kg
	Lithium carbonate	6.02E-01	kg
	Glucose	2.41E-01	kg
	Nitrogen	2.42E-02	kg
Output	CO ₂	4.12E+00	g
	Dust	2.31E-01	g
	Suspended solids	1.64E-02	g
	Phosphorus	1.20E-04	g
	Cathode material	2.41E+00	kg

A16. Inventory data for LFP battery Iron Phosphate

	Parameter name	Amount	Unit
Input	Electricity	8.43E+00	kwh
	Steam	1.93E+01	kg
	Iron powder	8.99E-01	kg
	Sulfur acid	1.62E+00	kg
	Phosphoric acid	1.84E+00	kg
	Ammonia	4.26E+00	kg
	Hydrogen peroxide	9.04E-01	kg
	Desalted water	2.05E+01	kg
	Ammonia	2.22E+00	g
	Dust	7.93E-01	g
Output	Sulfuric acid mist	4.89E-01	g
	Chemical Oxygen Demand (COD)	2.22E-00	g
	Biological Oxygen Demand (BOD)	2.23E-01	g
	Ammonia nitrogen	3.13E-03	g
	Suspended solids	8.87E-02	g
	Iron phosphate	2.41E+00	kg

A17. Inventory data for LFP battery Lithium carbonate

Parameter name		Amount	Unit
Input	Steam	3.71E+00	kg
	Hard coal	1.28E+00	kg
	Sulfuric acid	1.19E+00	kg
	Sulfur acid	4.76E-01	kg
	Limestone	4.46E-01	kg
	Sodium hydroxide	1.21E-01	kg
	Sodium carbonate	1.12E+00	kg
	Ultrapure water	1.07E+00	kg
Output	SO ₂	4.80E+00	g
	CO ₂	1.89E+02	g
	Dust	7.49E-01	g
	Sulfuric acid mist	7.68E-03	g
	Chemical Oxygen Demand (COD)	9.63E-03	g
	Suspended solids	9.36E-01	g
	Lithium carbonate	6.02E-01	kg

A18. Inventory data for LFP battery anode material

Parameter name		Amount	Unit
Input	Electricity	9.36E-01	kWh
	Natural gas	1.99E-02	kg
	Natural Graphite	9.94E-01	kg
	Water	7.68E-01	kg
	Asphalt	1.11E-01	kg
Output	Non-methane hydrocarbons	7.46E-01	g
	Dust	4.39E-01	g
	Benzopyrene	1.48E-06	g
	Soot	1.76E-01	g
	Anode material	1.05E+00	kg

A19. Inventory data for LFP battery Electrolyte

Parameter name		Amount	Unit
Input	Electricity	2.76E+00	kWh
	Natural gas	1.57E-01	kg
	Steam	1.15E+01	kg
	Pure water	6.70E-01	kg
	Nitrogen	4.89E-01	kg
	Sodium hydroxide	7.08E-02	kg
	Water	1.24E+00	kg
	CO ₂	8.45E+02	g
Output	Dust	4.96E-02	g
	Fluoride	8.82E-03	g
	Hydrogen fluoride	7.42E-02	g
	Hydrogen chloride	1.94E-01	g
	Volatile Organic Compounds (VOC)	3.40E-01	g
	Chemical Oxygen Demand (COD)	1.30E-01	g
	Fluoride	4.32E-03	g
	Suspended solids	1.25E-01	g
	Ammonia nitrogen	1.27E-02	g
	Electrolyte	1.88E+00	kg

A20. Inventory data for LFP battery separator

Parameter name		Amount	Unit
Input	Electricity	4.22E+00	kWh
	Polypropylene	1.88E-01	kg
	Polyethylene	9.44E-05	kg
	Aluminum oxide	3.75E-01	kg
	Carboxymethylcellulose sodium	3.75E-06	kg
	Aqueous acrylic acid	4.69E-02	kg
	Water	4.83E-01	kg
	Volatile Organic Compounds (VOC)	9.36E-01	g
Output	Dust	1.78E-02	g
	Chemical Oxygen Demand (COD)	5.76E-03	g
	Battery Separator	2.82E+01	m ²

A21. Inventory data for LFP battery copper foil

	Parameter name	Amount	Unit
Input	Electricity	1.12E+01	kWh
	Natural gas	2.49E-04	kg
	Copper	9.04E-01	kg
	Concentrated sulfuric acid	1.46E-02	kg
	Hydrochloric acid	1.21E-04	kg
	Tartaric Acid	1.02E-04	kg
	Active carbon	3.02E-04	kg
	Cobalt Sulphate Hexahydrate	6.04E-04	kg
	Zinc Sulphate Heptahydrate	6.04E-04	kg
	Carboxyethyl cellulose	1.21E-04	kg
	3-Carboxy-1-propanesulfonate	6.04E-05	kg
	Water	1.01E+01	kg
Output	Sulfuric acid mist	6.38E-01	g
	Copper	3.38E-04	g
	Cobalt	4.47E-05	g
	Copper foil	9.04E-01	kg

A22. Inventory data for LFP battery aluminum foil

	Parameter name	Amount	Unit
Input	Electrolytic aluminum	7.97E-01	kg
	Water	1.72E+00	kg
	Diatomite	2.48E+00	kg
	Rolling Oil	7.84E+00	kg
	Non-methane hydrocarbons	1.79E+00	g
Output	Chemical oxygen demand (COD)	2.98E-02	g
	Suspended solids	5.93E-04	g
	Ammonia nitrogen	5.86E-04	g
	Aluminum foil	6.02E-01	kg

A23. Inventory data for LFP battery Shell foil

	Parameter name	Amount	Unit
Input	Electricity	6.58E-01	kWh
	Stretching oil	5.26E-02	kg
	Water	2.88E-03	kg
	Aluminum	1.32E-01	kg
Output	Shell	1.75E+00	P

3. Inventory data for NMC batteries

A24. Inventory data for NMC battery cathode materials

A2.4. Inventory data for NMC battery cathode materials				
	Parameter name	Unit	Amount	
Input	Energy and Power	Electricity	kWh	
	Materials	Ternary precursor	kg	4.32E+00
		Water	kg	6.21E+00
		Lithium carbonate	kg	1.77E+00
		Oxygen	m³	2.76E-01
	Nano-alumina	kg	4.54E-02	
Output	Atmospheric Pollutant	CO₂	kg	1.05E+00
		Dust	g	3.19E-01
		Cobalt	g	1.01E-01
		manganese	g	1.52E-01
		Nickel	g	2.35E-01
	Water pollutants	Biological Oxygen Demand (BOD)	g	1.93E-01
		Chemical Oxygen Demand (COD)	g	7.45E-01
		Suspended solids	g	5.87E-01
		Ammonia nitrogen	g	1.16E-01
Production	Cathode material	Kg	4.62E+00	

A25. Inventory data for NMC battery Ternary precursor

	Parameter name	Unit	Amount
Input	Energy and Power	Electricity	4.35E+00
		Natural gas	m ³
		Nickel sulfate	kg
	Materials	Cobalt sulfate	kg
		Manganese sulfate	kg
		Water	kg
		Ammonia	kg
		Sodium hydroxide	Kg

Output	Atmospheric Pollutant	Nitrogen	kg	1.04E-01
		SO ₂	g	3.52E-01
		Dust	g	7.20E-01
		Nitrogen oxides	g	3.43E-01
	Water pollutants	Ammonia	g	6.88E+01
		Chemical Oxygen Demand (COD)	g	3.89E+00
		Suspended solids	g	3.11E-01
		Ammonia nitrogen	g	5.63E-01
		Production	Ternary precursor	kg

A26. Inventory data for NMC battery Manganese sulfate

		Parameter name	Unit	Amount
Input	Energy and Power		Electricity	kWh
	Materials	Manganese dioxide	kg	1.64E+00
		Pyrite	kg	1.64E-01
		Concentrated sulfuric acid	kg	9.26E-01
		Hydrogen peroxide	kg	5.52E-04
		Sodium sulfate	kg	2.71E-02
		Sodium sulfide	kg	1.08E-02
		Biomass fuel	kg	3.25E-01
		Sodium hydroxide	kg	1.42E+01
		Water	kg	1.62E+00
		Manganese carbonate	kg	5.41E-02
Output	Atmospheric Pollutant	CO ₂	g	2.30E+01
		Dust	g	1.42E-02
		Sulfuric acid mist	g	1.15E-02
		Nitrogen oxides	g	3.32E-01
	Water pollutants	Chemical Oxygen Demand (COD)	g	3.30E-02
		Suspended solids	g	1.62E-03
		Ammonia nitrogen	g	5.59E-02
	Production		Manganese sulfate	kg
				1.65E+00

A27. Inventory data for NMC battery Nickel sulfate

11.27. Inventory data for Ni-Me battery Nickel sulfate				
		Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh	1.25E+01
		Hard coal	kg	3.42E+01
	Materials	Laterite nickel ore	kg	2.47E+02
		Calcium hydroxide	kg	1.30E+01
		Sodium hydroxide	kg	2.01E+01
		Water	kg	1.52E-02
		Flake alkali	kg	1.82E+00
		Extracting agent	kg	5.06E-02
		Calcium carbonate	kg	3.55E-01
		Hydrogen peroxide	kg	8.87E-01
		Sulfuric acid	kg	4.91E+00
		Concentrated sulfuric acid	kg	1.68E+02
Output	Atmospheric Pollutant	SO ₂	g	7.84E+01
		Dust	g	8.65E+01
		Nitrogen oxides	g	7.37E+01
		Sulfuric acid mist	g	9.39E+00
	Water pollutants	Chemical Oxygen Demand (COD)	g	5.70E+00
		Ammonia nitrogen	g	7.50E-01
	Production	Nickel sulfate	kg	7.84E+00

A28. Inventory data for NMC battery Cobalt sulfate

		Parameter name	Unit	Amount
Input	Energy and Power		Electricity	kWh
	Materials	Hard coal	kg	1.11E+01
		Cobalt concentrate	kg	3.57E+01
		Concentrated sulfuric acid	kg	6.76E+00
		Sodium sulfite	kg	2.18E+00
		Water	kg	1.83E+02
		Sodium carbonate	kg	3.11E-01
		Calcium triple superphosphate	kg	8.51E-01
		Sodium chlorate	kg	1.04E-01
		Hydrochloric acid	kg	2.40E+01
		Sulfuric acid	kg	4.91E+00
Output	Atmospheric Pollutant	Sodium hydroxide	kg	2.36E+01
		Ammonia	kg	1.50E-01
		Oxalic acid	kg	3.73E-01
		Ammonium bicarbonate	kg	4.79E+00
	Water pollutants	Sodium sulfide	kg	2.45E-01

		Extracting agent	kg	5.54E-02
		Calcium oxide	kg	3.68E+00
Output	Atmospheric Pollutant	SO ₂	g	7.09E+01
		Dust	g	2.27E+01
		Nitrogen oxides	g	3.00E+01
		Ammonia	g	3.77E-01
		Sulfuric acid mist	g	3.37E+00
	Water pollutants	Chemical Oxygen Demand (COD)	g	7.86E+00
		Suspended solids	g	2.55E+00
		Biological Oxygen Demand (BOD)	g	1.11E-01
		Ammonia nitrogen	g	5.57E-02
	Production	Cobalt sulfate	kg	2.75E+00

A29. Inventory data for NMC battery Lithium carbonate

		Parameter name	Unit	Amount
Input	Energy and Power	Steam	kg	1.09E+01
		Hard coal	kg	3.77E+00
	Materials	sulfuric acid	kg	3.50E+00
		Sulfur acid	kg	1.40E+00
		Limestone	kg	1.31E+00
		Sodium hydroxide	kg	3.56E-01
		Sodium Carbonate	kg	3.56E+00
		Ultrapure water	kg	3.13E+00
Output	Atmospheric Pollutant	SO ₂	g	1.41E+01
		CO ₂	g	5.56E+02
		Dust	g	2.20E+00
		Nitrogen oxides	g	7.86E+00
	Water pollutants	Sulfuric acid mist	g	2.24E-02
		Chemical Oxygen Demand (COD)	g	2.83E-02
		Suspended solids	g	2.83E-02
	Production	Lithium carbonate	kg	1.77E+00

A30. Inventory data for NMC battery anode material

		Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh	2.74E+01
		Natural gas	kg	4.50E-02
	Materials	Natural Graphite	kg	2.25E+00
		Water	kg	1.74E+00
		Asphalt	kg	2.51E-01
Output	Atmospheric Pollutant	Non-methane hydrocarbons	g	1.69E+00
		Dust	g	9.94E-01
		Benzo[a]pyrene	g	3.36E-06
		Soot	g	3.98E-01
	Production	Anode material	Kg	2.37E+00

A31. Inventory data for NMC battery Electrolyte

		Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh	3.01E+01
		Natural gas	kg	1.71E-01
		Steam	kg	1.25E+01
	Materials	Pure water	kg	7.30E-01
		Nitrogen	kg	5.32E-01
		Sodium hydroxide	kg	7.71E-02
		Water	kg	1.35E+00
Output	Atmospheric Pollutant	SO ₂	g	7.84E+01
		CO ₂	g	9.20E+02
		Dust	g	5.40E-02
		Fluoride	g	9.61E-03
		Hydrogen fluoride	g	8.08E-02
	Water pollutants	Hydrogen chloride	g	2.11E-01
		Volatile Organic Compounds (VOC)	g	3.70E-01
		Chemical Oxygen Demand (COD)	g	1.42E-01
		Fluoride	g	4.70E-03
		Suspended solids	g	1.36E-01
		Ammonia nitrogen	g	1.38E-02
	Production	Electrolyte	kg	2.05E+00

A32. Inventory data for NMC battery separator			
	Parameter name	Unit	Amount
Input	Energy and Power	Steam	kg
	Materials	Polypropylene	kg
		Polyethylene	kg
		Aluminum oxide	kg
		Carboxymethylcellulose sodium	kg
		Aqueous acrylic acid	kg
		water	kg
	Atmospheric Pollutant	Volatile Organic Compounds (VOC)	g
	Water pollutants	Dust	g
		Chemical Oxygen Demand (COD)	g
		Suspended solids	g
Output	Production	Battery Separator	m ²

A33. Inventory data for NMC battery copper foil			
	Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh
	Materials	Natural gas	kg
		Copper	kg
		Concentrated sulfuric acid	kg
		Hydrochloric acid	kg
		Tartaric Acid	kg
		Active carbon	kg
		Cobalt Sulphate Hexahydrate	kg
		Zinc Sulphate Heptahydrate	kg
		Carboxyethyl cellulose	kg
		3-Carboxy-1-propanesulfonate	kg
		Water	kg
	Atmospheric Pollutant	Sulfuric acid mist	g
	Water pollutants	Volatile Organic Compounds (VOC)	g
		Copper	g
		Cobalt	g
Output	Production	Copper foil	kg

A34. Inventory data for NMC battery aluminum foil			
	Parameter name	Unit	Amount
Input	Materials	Electrolytic aluminum	kg
		Water	kg
		Diatomite	kg
		Rolling Oil	kg
	Atmospheric Pollutant	Non-methane hydrocarbons	g
	Water pollutants	Chemical Oxygen Demand (COD)	g
		Suspended solids	g
		Ammonia nitrogen	g
Output	Production	Aluminum foil	kg

A35. Inventory data for NMC battery shell			
	Parameter name	Unit	Amount
Input	Materials	Electricity	kWh
		stretching oil	kg
		Water	kg
	Production	Aluminum	kg
		Shell	P

A36. Inventory data for the LFP batteries assembly phase			
	Parameter name	Unit	Amount
Input	Materials	Electricity	kWh
		Battery cell	P
		Battery management systems	P
		Water	kg
	Production	Shell	P
		LFP Battery	P

4. Inventory data for use phase

A37. Background Parameters of NIB, LFP, and NMC battery life cycle models

Parameter name	NIB	LFP	NMC	Unit
Vehicle mass	1625	2,380	2,021	kg
Battery mass	558	600	531	kg
Battery capacity	57.0	57.0	63.8	kWh
Energy density	102	95	120	Wh/kg
Electricity consumption (Pv)	19.5	19.5	19.94	kWh/100km
Total mileage (Dv)	200000	200000	200000	km
Battery charge and discharge efficiency	90	90	95	%
Energy input to deliver 1 kWh of energy (loss from charge-discharge)	1.1	1.1	1.05	kWh
Total energy (use phase)	24,400	39,000	39,880	kWh
Grid mix electricity (use phase)	27,111	43,333	41,052	kWh

5. Inventory data for the recycling phase NIB, LFP & NMC

A38. Inventory data for hydrometallurgical recycling process of NIB

	Parameter name	Amount	Unit
Input	Electricity	1.41E-01	kWh
	Reagent	2.50E-02	kg
	Used battery of NIB	1.00E+01	kg
	Water	7.20E-01	kg
	H ₂ SO ₄	2.13E-01	kg
	Lime	1.16E-01	kg
Output	Non-Fe-Co-metals	1.05E-01	kg
	Aluminum	9.59E-02	kg
	Copper	9.38E-03	kg
	NiCO ₃	8.71E-02	kg
	MnO ₂	1.07E-01	kg
	Mg (OH) ₂	6.74E-03	kg
	TiO ₂	1.09E-02	kg
	SO ₂	4.50E-06	kg
	VOC	2.50E-06	kg
	Solid suspension	1.20E-05	kg
	Chemical Oxygen Demand (COD)	3.00E-05	kg
	Total hydrocarbon	1.00E-08	kg
	Plastic to refining	5.82E-02	kg
	Residue to landfill	2.02E-01	kg

A39. Inventory data for pyrometallurgical recycling process of NIB

	Parameter name	Amount	Unit
Input	Electricity	8.00E-01	kWh
	Used battery of NIB	1.00E+00	kg
	NaOH	2.10E-01	kg
	Water	1.10E+00	kg
Output	Non-Fe-Co-metals	1.05E-01	kg
	Aluminum	9.57E-02	kg
	Copper	9.36E-03	kg
	NiCO ₃	8.71E-02	kg
	MnO ₂	1.07E-01	kg
	TiO ₂	1.09E-02	kg
	SO ₂	4.80E-05	kg
	Dust	1.04E-05	kg
	CO ₂	2.03E+00	kg
	Plastic to refining	5.82E-02	kg

A40. Inventory data for hydrometallurgical recycling process of LFP batteries

	Parameter name	Amount	Unit
Input	Energy and Power		
	Natural gas	3.40E-02	kg
	Used battery of LFP	1.75E-02	P
	Hydrochloric acid	4.04E+00	kg
	Thick water	5.61E+00	kg
	Magnesium hydroxide	5.85E-01	kg
Output	Sodium hydroxide	4.26E-01	kg
	Dust	3.03E-01	g
	Sulfuric acid mist	8.11E-02	g
	Hydrogen chloride	5.43E-02	g
	Production		
	Lithium chloride solution	8.90E+00	kg

A41. Inventory data for Physical recycling process of LFP batteries

		Parameter name	Amount	Unit
Input	Energy and Power	Electricity	3.65E+01	kWh
		Used battery of LFP	1.75E-02	P
	Materials	Liquid Nitrogen	3.80E+01	kg
		DMC Solvents	1.93E+00	kg
		Lithium carbonate	1.53E-01	kg
		Nitrogen	4.92E-01	kg
		Glucose	1.45E-03	kg
	Atmospheric Pollutant	Hydrogen fluoride	2.10E-01	g
		Dust	6.51E+00	g
		Volatile Organic Compounds (VOC)	2.44E+00	g
Output	Production	Graphite	1.05E+00	kg
		Aluminum	5.26E-01	kg
		Copper	8.42E-01	kg
		Battery Separator	4.52E-01	kg
		Plastic Parts	1.11E-01	kg
		Shell	1.75E-02	P
		Electrolyte	1.04E+00	kg
		Cathode material	2.32E+00	kg

A42. Inventory data for hydrometallurgical recycling process of NMC batteries

		Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh	1.86E+01
		Steam	kg	1.20E+01
	Materials	Used battery of NMC	P	1.57E-02
		Sodium chloride	g	6.75E+01
		Water	kg	8.31E+01
		Sulfuric acid	kg	1.27E+00
		P ₂ O ₄	kg	3.94E-03
		P ₅ O ₇	kg	1.45E-03
		Hydrochloric acid	kg	2.40E+01
		Sulfonated kerosene	kg	1.37E-02
		Sodium sulfide	kg	1.33E-02
Output	Atmospheric Pollutant	Ammonia	kg	4.17E-01
		Sodium hydroxide	kg	8.84E-01
		Hydrogen fluoride	g	4.38E-01
		Dust	g	4.38E-01
		Hydrogen sulfide	g	2.29E-02
		Ammonia	g	8.59E-02
	Water pollutants	Sulfuric acid mist	g	3.75E-02
		Chemical Oxygen Demand (COD)	g	1.03E+01
		Suspended solids	g	1.24E+02
		Biological Oxygen Demand (BOD)	g	3.64E+00
		Nickel	g	4.75E-02
		Cobalt	g	4.38E-02
		Manganese	g	4.75E-02
		Lithium	g	3.98E+00
		Ammonia nitrogen	g	5.96E-01
	Production	Cathode material	kg	1.25E+00

A43. Inventory data for pyrometallurgical recycling process of NMC batteries

		Parameter name	Unit	Amount
Input	Energy and Power	Electricity	kWh	6.67E+00
		Used battery of NMC	P	1.57E-02
	Materials	Sodium hydroxide	kg	2.92E+00
		Coke	kg	1.10E+00
		Limestone	kg	1.00E+00
		Slag Agent	kg	1.00E+00
Output	Atmospheric Pollutant	Hydrogen chloride	g	1.67E+01
		Sulfuric acid	g	2.50E+01
		Dust	g	4.17E-02
		Soot	g	3.86E-02
		SO ₂	g	2.00E-02
		CO ₂	kg	2.03E+00
	Production	Nickel	kg	1.39E+00
		Cobalt	kg	1.42E+00



The Role of Street Trees in Mitigating Particulate Matter Pollution: A Case Study of PM_{2.5} and PM₁₀ Concentrations in Urban Street Canyon

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Abstract

This study evaluates the effectiveness of street trees in reducing particulate matter (PM_{2.5} and PM₁₀) concentrations in an urban street canyon along Sukhumvit Road, Samut Prakan Municipality, Thailand. Field measurements were conducted at pedestrian level (1.5 m height) across three sidewalk microenvironments: beneath tree canopies, between trees, and in open, non-vegetated areas. Real-time particle counters monitored PM levels, temperature, humidity, and wind speed over a two-week period. Results demonstrated consistently lower PM concentrations on sidewalk with street trees. Relative Difference in Concentration (RDC) analysis revealed negative values for 70.8% of PM_{2.5} (17/24) and 75.0% of PM₁₀ (18/24) measurements, with average reductions of 3.74% and 4.11%, respectively, beneath tree canopies. Statistical analysis (ANOVA) confirmed significant PM₁₀ reduction ($p = 0.030$), while PM_{2.5} differences were marginally non-significant ($p = 0.058$). Tree canopies also moderated microclimate conditions, lowering ambient temperature by 0.33°C and wind speed by 0.83 m/s compared to non-vegetated areas. These findings highlight street trees as effective, sustainable interventions for urban air quality improvement, particularly for coarse particle (PM₁₀) mitigation. The study provides actionable insights for urban planners and policymakers advocating nature-based solutions in high-density built environments.

Keywords : street trees; PM_{2.5}; PM₁₀; urban; street canyon

Introduction

Rapid urbanization in Thailand has reshaped economic and social systems while markedly increasing environmental pressures in metropolitan areas. Densification, expanded transport networks, industrial activity, and construction have together elevated emissions of particulate matter (PM), making PM_{2.5} and PM₁₀ central indicators in national air-quality management. The World Health Organization's 2021 Global Air Quality Guidelines highlight the disproportionately large health risks of fine particulates and set annual PM_{2.5} targets far below current levels observed in Thai cities. National monitoring consistently reports frequent exceedances of Thailand's 24-hour ambient PM_{2.5} standard (37.5 µg/m³), particularly

during the cool season, with recurrent peaks across the Bangkok Metropolitan Region [1]. This chronic pattern highlights the persistence of particulate pollution in densely populated areas, where limited urban ventilation intensifies pollutant accumulation and cardiopulmonary health risks. Consequently, population exposure to PM remains a significant public-health concern, underscoring the urgent need for place-based mitigation strategies tailored to high-density urban environments.

The use of green infrastructure to mitigate particulate pollution and improve urban environmental quality has received growing attention in recent years. Street trees and vegetative barriers are increasingly recognized as effective nature-based solutions (NbS) for reducing near-road air pollution. Empirical

studies have reported strong associations between urban green-space coverage and lower ambient particulate matter concentrations [2-5]. In particular, the role of street trees in reducing the adverse effects of particulate matter in urban areas has been increasingly recognized. However, their influence on particulate dynamics within dense, built-up areas remains complex and highly context-dependent, varying with vegetation characteristics, and prevailing meteorological conditions [6]. Their effectiveness in capturing particulate matter and influencing local airflow, which may either enhance or inhibit pollutant dispersion depends on various factors [7-8].

Numerous field studies support the premise that increased vegetation coverage generally correlates with lower particulate pollution levels in urban settings [3, 5, 9]. Acting as natural biofilters, trees intercept airborne particles and absorb gaseous pollutants while modifying wind velocity, turbulence, and thermal conditions that affect pollutant dispersion [10]. These effects arise through interactions between vegetation, airflow, and particulate matter, whereby trees modify local wind patterns and facilitate the removal of both fine and coarse particles through deposition processes. Although studies report significant $PM_{2.5}$ reductions from these processes, outcomes vary widely with vegetation characteristics and canyon form [11-12]. For example, Gromke et al. [13] reported that larger tree crowns and reduced spacing between street trees can elevate PM concentrations along canyon walls due to restricted airflow. Similarly, tree-lined avenues can even increase concentrations compared to tree-free streets [14, 15]. These conflicting findings highlight the dual role of street trees. While trees can act as protective barriers against traffic emissions at the pedestrian level, their planting designs critically influence wind dynamics and pollutant dispersion [16]. Consequently, optimizing green infrastructure requires careful consideration of these trade-offs to maximize air quality benefits.

Meteorological conditions add another layer of complexity to this relationship. Parameters such as humidity, temperature, precipitation, and wind speed and direction differentially influence

PM behavior across particle sizes [17, 18]. As shown by Xu et al. [19], these variables govern the spatiotemporal variability of particulate pollution by regulating accumulation and dispersion. Additionally, large-scale weather patterns and various meteorological factors interact with local meteorological conditions to shape $PM_{2.5}$ and PM_{10} dynamics in urban environments [10-22]. Since vegetation also modifies local microclimates, particularly through effects on wind flow and humidity, understanding the interplay between meteorology and vegetation is essential for accurately assessing the effect of trees in street canyons.

In this context, this study examines the impact of street trees on particulate matter concentrations through direct field measurements of $PM_{2.5}$ and PM_{10} in street canyons with and without tree cover in Samut Prakan Municipality, a high-density urban area experiencing worsening particulate pollution. While many existing studies examine tree-air quality interactions primarily through numerical simulations or idealized modeling scenarios, this research focuses on tree effects under real-world urban conditions. The main objective is to assess how the presence or absence of street trees influences air quality at the pedestrian level, with particular emphasis on $PM_{2.5}$ and PM_{10} . Concurrent measurements of wind speed, air temperature, and relative humidity were conducted to identify key microclimatic drivers and support the interpretation of observed pollution patterns. Over the past three years, Samut Prakan has recorded an average of approximately 30 annual exceedances of the national $PM_{2.5}$ standard [23], underscoring the urgency of developing evidence-based and context-specific mitigation strategies. The findings are expected to inform climate-sensitive urban design and air-quality management by clarifying the functional role of street trees in mitigating particulate pollution within tropical urban environments.

Methodology

Study area

This study examines the impact of street trees on $PM_{2.5}$ and PM_{10} levels along Sukhumvit Road, a major traffic corridor in Samut Prakan

Municipality. Meteorological data from the urban district of Samut Prakan recorded a mean air temperature of 28.4°C, relative humidity of 74%, and a mean wind speed of 3.89 m/s. In 2022, the highest 24-hour average PM_{2.5} concentration reached 108 µg/m³, nearly triple Thailand's 24-hour standard (37.5 µg/m³), while the annual mean likewise exceeded the national limit (15 µg/m³). These violations correlate with the area's characteristics, including its high building density, diverse land-use activities, and consistently heavy traffic volume throughout the day. According to the Department of Highways (2022), the average daily traffic volume on Sukhumvit Road (Bearing-Tai Ban section) was 20,985 vehicles per day. Passenger cars formed the majority, followed by larger passenger vehicles and light-duty trucks, reflecting the corridor's mixed-use and commuter-dominated traffic pattern.

Structurally, Sukhumvit Road is a six-lane, concrete-paved arterial road with opposing traffic directions and an aspect ratio of approximately 0.5. Land uses along the corridor comprise commercial buildings, government offices, residential areas, industrial zones, and institutional facilities, with several segments featuring high-rise structures such as condominiums. Most buildings are low-rise, typically two to four stories in height, although open spaces such as parking lots and vacant parcels are also present. In many parts of the corridor, buildings are positioned close to the sidewalk with an average setback of about 2 m, forming a semi-enclosed street canyon. Additionally, an elevated rail structure runs above the roadway. Vegetation cover varies along the corridor, some sections are densely planted with trees, while others lack greenery entirely (**Figure 1**). This spatial variability provides a framework for assessing the effects of tree cover on air quality across both vegetated and non-vegetated sections.

Methods

To investigate the effect of street trees, sampling sites with similar background

concentrations were selected along Sukhumvit Road. Field measurements were carried out on the sidewalks of three segments of Sukhumvit Road in Samut Prakan Municipality, as shown in **Figure 2**. Since the road runs north to south, each sampling point was placed on the sidewalk within the street canyon on the leeward side of the prevailing wind direction to minimize the direct influence of roadside trees on pollutant concentrations [24].

Data Collection and Analysis

To achieve the research objectives, this study investigates the influence of street trees on particulate matter (PM) concentrations by measuring PM_{2.5}, PM₁₀, and microclimatic variables using real-time particle counters. The CEM DT-9880 was used for these measurements (**Figure 2**). The CEM DT-9880 utilizes a laser light-scattering principle to detect particle concentrations and incorporates built-in sensors that enable PM_{2.5}, PM₁₀, air temperature, and relative humidity to be collected simultaneously within the same device. The instrument records particulate matter with an accuracy of ±5% and microclimatic variables with an air-temperature accuracy of ±0.5°C (±1°F), and a humidity accuracy of ±2.5%, ensuring synchronized and consistent measurements across all sampling points. Wind speed was measured separately using a Hot Wire/Air Velocity Meter, which operates based on a hot-wire thermal anemometry principle. In each street segment, PM_{2.5}, PM₁₀, and microclimatic parameters were simultaneously recorded at three sidewalk sampling points: beneath tree canopies (BTC), between two trees (BWT), and in open areas without trees (WT). Both particulate matter and microclimatic data were logged at five-minute intervals, resulting in 12 measurements per hour and 132 measurements per day for each sampling point. Data collection was conducted between 20 January and 7 February 2022, from 07:00 to 18:00, on both weekdays and weekends, with five sampling days per street segment over a two-week period covering all three segments.

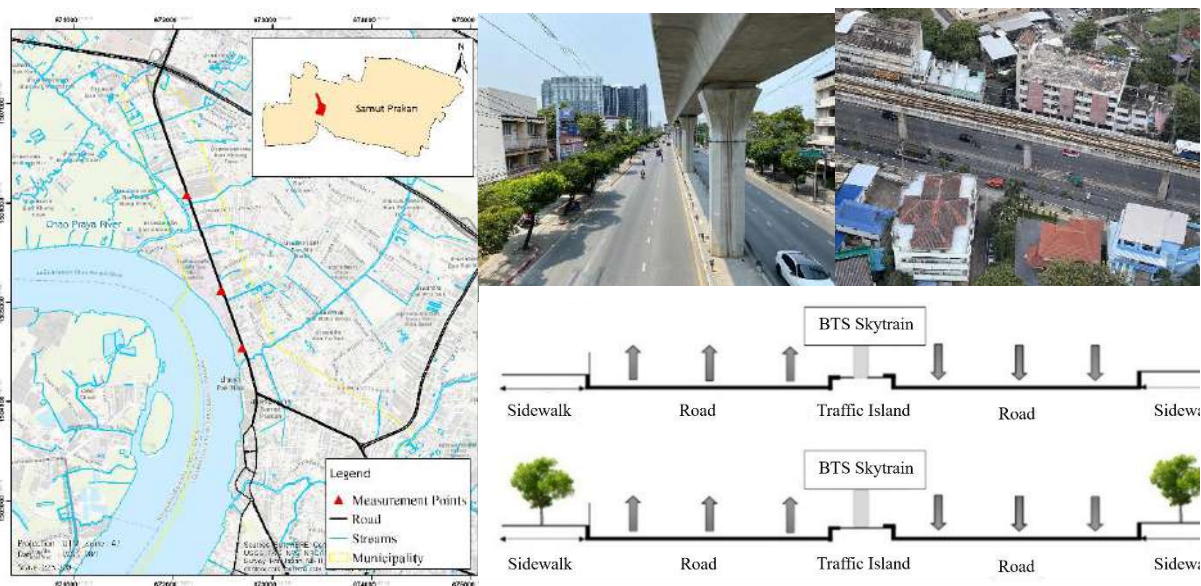


Figure 1 Study area and measurement locations along Sukhumvit Road, Samut Prakan Municipality

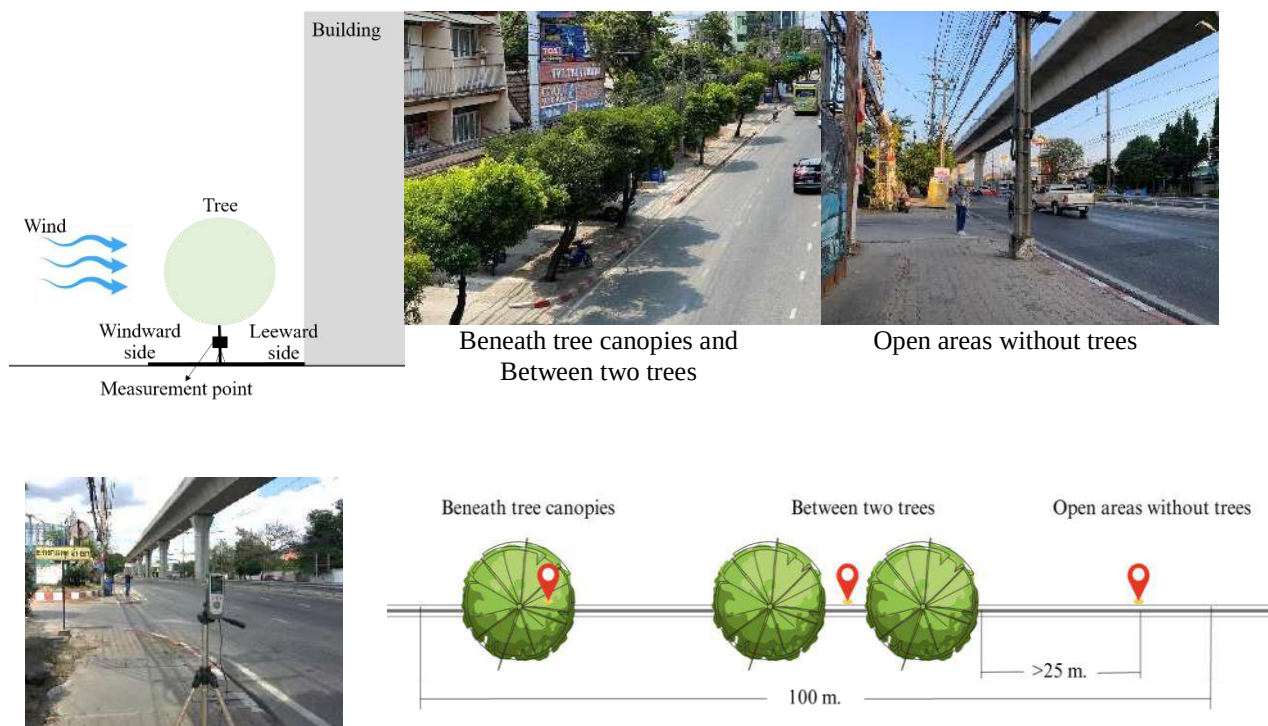


Figure 2 Field measurements were carried out on the three segments of sidewalks with three sampling points per road segment: (1) beneath tree canopy, (2) between two trees, and (3) in open areas without trees

The relative difference in concentration (RDC) was used to quantify the influence of street trees on particle concentrations (PM_{2.5} and PM₁₀) at pedestrian level [20]. RDC was calculated as the difference in particle concentrations between tree-covered and open areas, as shown in Equation (1). Positive RDC values indicate that particle concentrations are higher at tree-covered locations compared to open areas without trees, suggesting an increase in air pollution. Conversely, negative RDC values reflect lower particle concentrations at the tree-covered sites, indicating an improvement in air quality relative to open areas. Statistical analysis was performed using one-way ANOVA and the least significant difference (LSD) test to evaluate the effects of street trees on PM concentrations and microclimatic variables, using SPSS software.

$$RDC = \frac{C_{tree} - C_{ref}}{C_{ref}} \times 100$$

where C_{tree} is the particle concentration at area with tree/between trees ($\mu\text{g}/\text{m}^3$)

C_{ref} is the particle concentration at area without tree ($\mu\text{g}/\text{m}^3$)

Results and Discussions

PM Concentration and PM_{2.5}/PM₁₀ Ratio

PM_{2.5} and PM₁₀ concentrations along Sukhumvit Road were analyzed using hourly field data collected between 7:00 AM and 6:00 PM over a two-week period. The spatiotemporal variability of the PM_{2.5}/PM₁₀ ratio was examined based on these hourly measurements to better understand the dynamics of particulate matter distribution throughout the day. The results revealed that peak particulate concentrations occurred during morning rush hours (7:00–9:00 AM) across all sampling points. Beneath tree canopies, PM_{2.5} and PM₁₀ peaked at 45.70 $\mu\text{g}/\text{m}^3$ and 73.47 $\mu\text{g}/\text{m}^3$, respectively, at 7:00 AM, before gradually declining to their lowest levels at noon (35.24 $\mu\text{g}/\text{m}^3$ for PM_{2.5} and 56.00 $\mu\text{g}/\text{m}^3$ for PM₁₀ at 12:00 PM). Open areas without tree cover exhibited similar diurnal trends but with slightly higher concentrations, reaching maxima of 47.05 $\mu\text{g}/\text{m}^3$ (PM_{2.5}) and 74.96 $\mu\text{g}/\text{m}^3$ (PM₁₀) at 7:00 AM and minima of

34.80 $\mu\text{g}/\text{m}^3$ (PM_{2.5}) and 55.82 $\mu\text{g}/\text{m}^3$ (PM₁₀) at 2:00 PM. The most pronounced variability was observed between trees, where peak concentrations were highest (48.91 $\mu\text{g}/\text{m}^3$ PM_{2.5} and 77.48 $\mu\text{g}/\text{m}^3$ PM₁₀ at 8:00 AM). Across all sites, particulate matter concentrations were consistently lowest during early afternoon hours (12:00–2:00 PM), as illustrated in **Figure 3**.

PM_{2.5}/PM₁₀ ratios were subsequently calculated (Figure 3). The results indicate that the ratios across the three sites—beneath tree canopies, between two trees, and in open areas without trees—ranged from 0.620 to 0.657, 0.623 to 0.636, and 0.574 to 0.640, respectively. The highest ratio (0.657) was observed beneath tree canopies, suggesting that street trees may selectively reduce PM₁₀ through leaf deposition, thereby increasing the relative proportion of PM_{2.5} [25–26]. In contrast, open areas without trees exhibited a narrower ratio range (0.623–0.636), indicating greater stability, likely due to the absence of vegetation-driven particle filtration [27]. The most variable ratios (0.574–0.640) were recorded between trees, where the lowest value (0.574) suggests intermittent PM₁₀ dominance. This variability may result from airflow disturbances in tree gaps, which could promote coarse particle resuspension or uneven pollutant dispersion [28].

PM Concentration and RDC

Figure 4 presents the hourly PM_{2.5} and PM₁₀ concentrations along Sukhumvit Road, accompanied by their corresponding RDC values. The results demonstrate that street trees significantly influence particulate matter levels. The highest reduction of PM_{2.5} beneath trees was found at 10:00 AM (RDC_BTC = -12.49%), and at 8:00 AM for between two trees (RDC_BWT = -13.99%). These times correspond with relatively lower PM_{2.5} concentrations at vegetated sites compared to tree-free areas. A similar trend is evident for PM₁₀ concentrations, where the most pronounced reductions occurred at 10:00 AM as well, with beneath tree canopies reaching -11.87% and between two trees as low as -14.16%. These values are slightly more substantial than those observed for PM_{2.5} at the same time, suggesting that tree canopies and vegetated areas are particularly effective at capturing larger particulate matter. In addition, as

shows in **Figure 4**, during the early morning hours (7:00–9:00 AM), $\text{PM}_{2.5}$ concentrations beneath trees were occasionally comparable to or slightly higher than those in treeless area (WT), particularly at 9:00 AM. This may be due to limited airflow under the canopy, which can temporarily trap pollutants. This pattern reversed

after 9:00 AM, when PM concentrations at non-vegetated sites exceeded those at vegetated locations. The temporal variations in RDC values reflect dynamic interactions between traffic emissions, wind patterns, and vegetation structure.

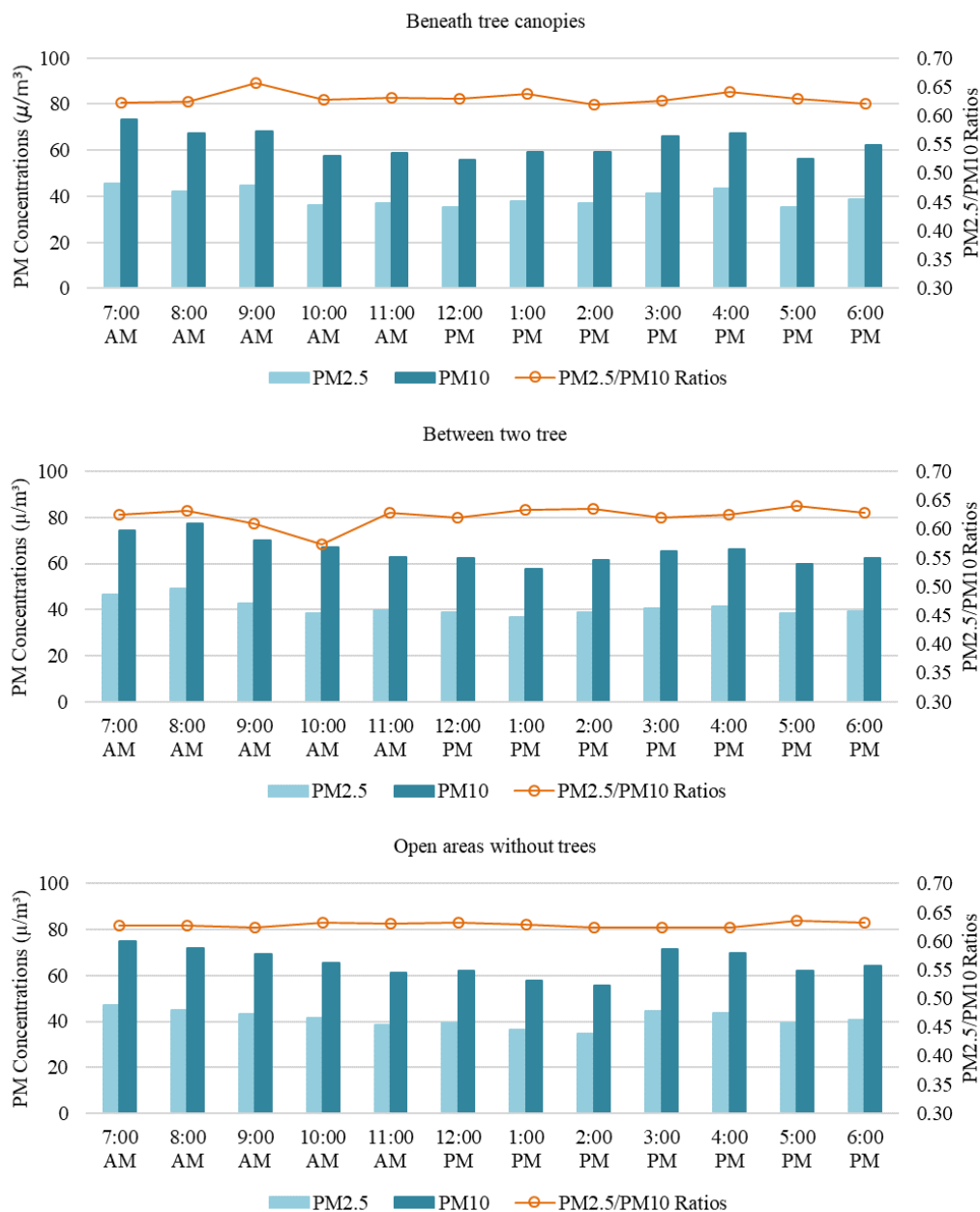


Figure 3 Hourly average PM Concentrations and ratios of the $\text{PM}_{2.5}/\text{PM}_{10}$ on Sukhumvit Road

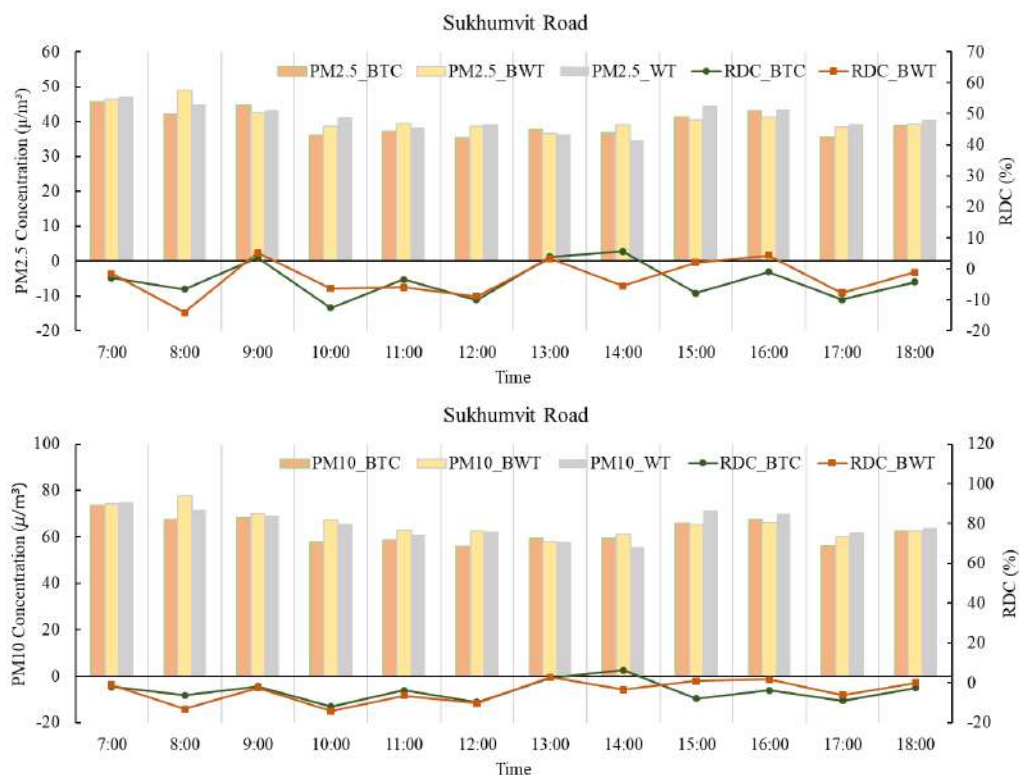


Figure 4 illustrates the $PM_{2.5}$ and PM_{10} concentration from 7:00 a.m. to 6:00 p.m. on Sukhumvit Road. BTC, BWT and WT represent Beneath Tree Canopy, Between Two Trees, and Without Tree

As illustrated in **Figure 5**, the RDC values for $PM_{2.5}$ and PM_{10} along Sukhumvit Road were predominantly negative, indicating lower particulate matter concentrations at vegetated locations compared with tree-free areas. Specifically, 17 out of 24 RDC values for $PM_{2.5}$ (9 beneath tree canopies [BTC] and 8 between trees [BWT]) were negative, while 18 out of 24 values for PM_{10} exhibited the same pattern. On average, $PM_{2.5}$ concentrations decreased by approximately 3.74% beneath tree canopies and 2.99% between trees, whereas PM_{10} concentrations decreased by about 4.11% and 4.27%, respectively.

These results demonstrate that both fully and partially vegetated areas contribute to particulate matter reduction relative to tree-free zones, with the most pronounced effect observed for PM_{10} . This pattern is consistent with previous studies showing that the particulate removal efficiency of street trees depends strongly on particle size [22, 29]. Coarse particles (PM_{10}) were substantially lower in vegetated areas than in non-vegetated

locations, as they are more readily removed through deposition onto leaf surfaces, whereas fine particles ($PM_{2.5}$) remain suspended in the atmosphere for longer periods [30]. Overall, the results underscore the efficacy of urban vegetation—particularly tree canopies—in mitigating particulate pollution, with a more substantial effect observed for coarse particles (PM_{10}) than for fine particles ($PM_{2.5}$).

Microclimatic Conditions under Different Street Tree Configurations

Field measurements of air temperature, relative humidity, and wind speed were conducted across three micro-environments: beneath tree canopies (BTC), between two trees (BWT), and open areas without trees (WT). The results reveal clear variations in microclimatic conditions among the three settings. Beneath tree canopies, the average air temperature was 31.07 °C, relative humidity was 59.79%, and wind speed was 1.55 m/s. In the areas between two trees, the average temperature was slightly lower at 31.02 °C, relative humidity

was 59.20%, and wind speed increased to 2.17 m/s. In contrast, open areas without tree cover exhibited the highest average temperature (31.40

°C), a marginally lower relative humidity (59.11%), and the highest wind speed (2.63 m/s), as shown in **Figure 6**.

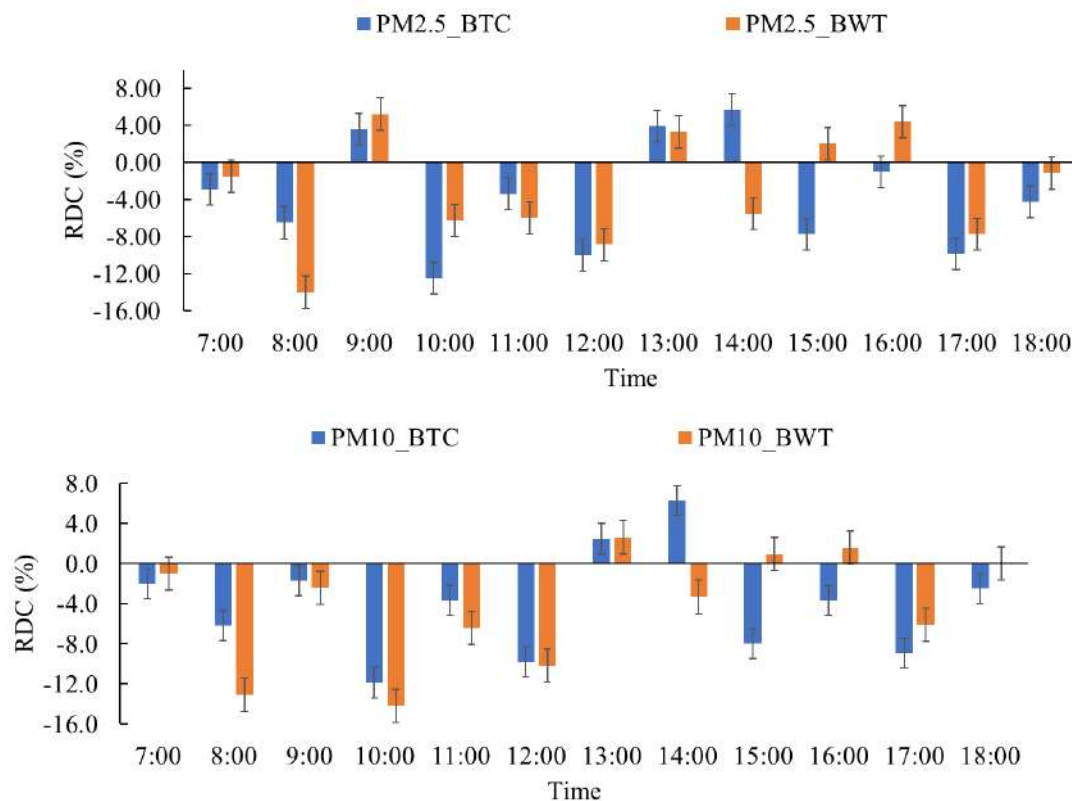


Figure 5 RDC values for PM_{2.5} and PM₁₀ at different times on Sukhumvit Road. Where BTC, BWT and WT represent Beneath Tree Canopy, Between Two Trees, and Without Tree, respectively

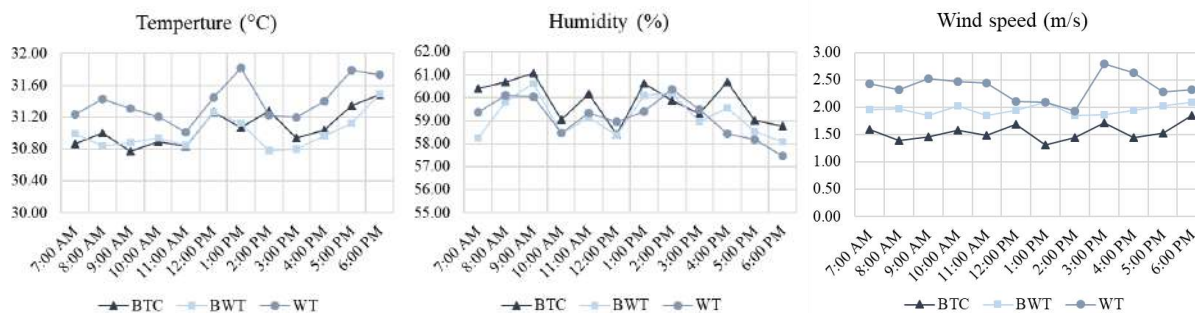


Figure 6 Diurnal variations in air temperature (°C), relative humidity (%), and wind speed (m/s) measured across three micro-environments: beneath tree canopies (BTC), between trees (BWT), and open areas without tree cover (WT) along Sukhumvit Road

Table 1 summarizes the hourly mean values, maxima, and minima of PM_{2.5}, PM₁₀, and associated meteorological parameters across the three micro-environments: beneath tree canopies (BTC), between two trees (BWT), and open areas without trees (WT). Overall, mean PM_{2.5} concentrations ranged from 39.53 µg/m³ under tree canopies to 41.13 µg/m³ in open areas, while PM₁₀ concentrations ranged from 62.69 µg/m³ to 65.59 µg/m³, indicating slightly higher particulate matter levels in non-vegetated and partially vegetated locations. Correspondingly, wind speed was lowest beneath tree canopies (1.54 m/s) and highest in open areas (2.36 m/s), suggesting that reduced airflow under tree cover may limit particulate dispersion. In contrast, air temperature exhibited minimal spatial variation among the three settings; however, marginally higher temperatures in open areas likely reflect increased surface heating and enhanced vertical mixing, conditions that typically favor pollutant dilution.

Effects of Street Trees on Particulate Matter and Microclimate

ANOVA was conducted to determine whether there were variations in PM concentrations and microclimate among the sampling points (beneath tree canopy, between two trees, and open areas without trees). The results revealed differences in particulate matter concentrations (PM_{2.5} and PM₁₀) across the three sampling points. For PM_{2.5}, the mean concentration was lowest under tree canopies (39.45 µg/m³), slightly higher in open areas (41.00 µg/m³), and comparable between trees (40.71 µg/m³). The one-way ANOVA shows

that these differences were not statistically significant at the 0.05 level ($p = 0.058$), indicating that while trees may slightly reduce PM_{2.5} levels, the effect was not strong enough to be conclusive. In contrast, PM₁₀ concentrations showed clearer variation across sites. The lowest mean was observed under tree canopies (62.51 µg/m³), followed by the between trees (64.84 µg/m³), and highest in open areas (65.18 µg/m³). The ANOVA test for PM₁₀ yielded a statistically significant result ($p = 0.030$), suggesting that tree canopies significantly reduce PM₁₀ levels compared to open areas. These findings indicate that street trees are more effective at mitigating larger particles (PM₁₀), possibly due to their capacity to intercept coarse dust particles, while the effect on finer particles like PM_{2.5} may be influenced by additional factors such as wind flow and atmospheric dispersion.

The results revealed significant effects of tree canopies on the urban microclimate. Trees significantly reduced air temperature ($F = 13.168$, $p < 0.001$), with the lowest mean temperature observed under tree canopies (31.07°C), compared to areas without trees (31.40°C, $p < 0.001$). Wind speed was also significantly lower beneath tree canopies (1.54 m/s) than in areas without trees (2.37 m/s, $p < 0.001$) and between trees (2.08 m/s, $p < 0.001$). However, no significant difference was found in relative humidity across the three sampling conditions ($F = 1.873$, $p = 0.154$). Mean differences in microclimatic variables (temperature, humidity, and wind speed) were further examined using LSD post hoc multiple comparisons (see **Table 2**).

Table 1 Hourly summary statistics of PM_{2.5}, PM₁₀, and associated meteorological variables across vegetated and non-vegetated street environments

Area	Parameter	PM _{2.5} (µg/m ³)	PM ₁₀ (µg/m ³)	T (°C)	RH (%)	WS (m/s)
BTC	Average ± SD	39.53 ± 3.71	62.69 ± 5.62	31.07 ± 0.23	59.82 ± 0.93	1.54 ± 0.15
	Max	45.70	73.47	31.49	61.08	1.85
	Min	35.24	56.00	30.77	58.21	1.31
BWT	Average ± SD	40.80 ± 3.58	65.59 ± 5.84	31.77 ± 0.21	59.18 ± 0.87	1.96 ± 0.09
	Max	48.91	77.48	31.50	60.61	2.10
	Min	36.62	57.83	30.79	58.10	1.85
WT	Average ± SD	41.13 ± 3.70	65.48 ± 6.02	31.40 ± 0.26	59.14 ± 0.86	2.36 ± 0.24
	Max	47.05	74.96	31.82	60.38	2.79
	Min	34.80	55.82	31.01	57.49	1.93

BTC, BWT and WT represents Beneath Tree Canopy, Between Two Trees, and Without Tree, respectively.

Table 2 LSD multiple comparison tests for determining the effect of trees on the concentration of PM and Microclimate

Comparison (I - J)	Dependent variables									
	PM _{2.5}		PM ₁₀		Temperature		Humidity		Wind speed	
	M-diff (I-J)	Sig	M-diff (I-J)	Sig	M-diff (I-J)	Sig	M-diff (I-J)	Sig	M-diff (I-J)	Sig
BTC-BWT	-1.25703	0.070	-2.33636	0.016*	-0.33151	0.000*	0.64693	0.106	-0.25846	0.000*
BTC- WT	-1.55095	0.027*	-2.67384	0.008*	-0.39319	0.000*	0.69348	0.083	-0.54061	0.000*
BWT-WT	0.29396	.676	0.33747	0.934	-0.06168	0.088	-0.04655	0.907	0.28214	0.000*

BTC, BWT and WT represents Beneath Tree Canopy, Between Two Trees, and Without Tree, respectively. M-Diff represents the mean difference *The Mean difference is significant at the 0.05 level (P value= 0.05)

The findings confirm that tree canopies significantly reduce PM_{2.5} and PM₁₀ concentrations while simultaneously lowering air temperature and wind speed, highlighting their important role in regulating the urban microclimate. These results are consistent with previous studies demonstrating that urban trees strongly influence local thermal conditions by providing shade and reducing surface and near-ground air temperatures, particularly at the pedestrian level [31]. For example, Zender-Świercz et al. (2024) [32] reported that tree planting can reduce air temperature at a pedestrian height of 1.5 m by approximately 1.83-2.48 °C.

In this study, the presence of trees was negatively correlated with air temperature, which in turn influenced PM_{2.5} and PM₁₀ concentrations within the street canyon. Temperature exhibited a statistically significant relationship with PM_{2.5}, however, the direction of this relationship remains inconclusive. While some studies report lower PM_{2.5} concentrations at reduced temperatures [33-34], others have observed a positive correlation between temperature and particulate matter [17, 35]. This inconsistency suggests that temperature alone does not govern PM variability and that other factors such as wind conditions, street geometry, and vegetation characteristics, play a more dominant role in particulate matter dispersion and accumulation. Additionally, the observed reduction in wind speed is consistent with existing literature describing the role of trees as windbreaks that attenuate airflow and reduce

turbulence within street canyons [36]. Although tree canopies may decrease wind speed, the results highlight a dual effect of urban vegetation, reflecting both aerodynamic modification and enhanced pollutant deposition processes [13, 37]. Along Sukhumvit Road, the presence of medium-height trees (approximately 6-8 m), positioned below the building eave level, appears to preserve ventilation corridors within the street canyon. This configuration allows for sufficient air exchange while promoting particulate deposition on foliage, thereby achieving a balance between aerodynamic performance and pollution removal efficiency.

Although the results indicate that variations in PM concentrations are associated with tree-regulated microclimatic conditions, the overall relationship between humidity and tree presence was weak and statistically insignificant, in contrast to the effects observed for temperature and wind speed. This limited variation can be attributed to the high baseline humidity typical of tropical urban environments, where atmospheric moisture is often near saturation, thereby constraining the potential influence of additional moisture from vegetation through transpiration [38-39]. Moreover, the influence of trees on ambient humidity depends on canopy density, continuity, species characteristics, and soil moisture availability. In roadside planting conditions, where tree cover is often sparse or spatially discontinuous, the evapotranspirative contribution may be insufficient to produce measurable changes in

ambient humidity [31, 40]. These factors likely explain the absence of statistically significant differences in humidity between tree-covered and non-tree scenarios observed in this study.

Conclusions

This study examined the impact of street trees on PM_{2.5} and PM₁₀ concentrations within a high-density street canyon in Samut Prakan. The results indicate that tree-covered locations effectively mitigate particulate matter pollution at the pedestrian level (1.5 m), with the lowest concentrations observed beneath tree canopies, followed by areas between trees and locations without tree cover. The findings further suggest that street trees play a meaningful role in improving urban air quality, particularly through the reduction of PM₁₀. Given the significant reduction in PM₁₀ and the observed mitigation trends for PM_{2.5} under tree canopies, urban policymakers should consider integrating tree planting into air quality management strategies, especially along high-traffic roads. Promoting the use of dense, broad-leaved species with effective canopy coverage may enhance the interception of airborne particles while improving thermal comfort for pedestrians. However, as this study was conducted on a specific stretch of Sukhumvit Road in Samut Prakan Municipality, its generalizability may be limited. To strengthen policy development, future research should expand the geographic scope to include multiple urban districts with varying built environments and vegetation types, and integrate dynamic traffic data across diverse urban contexts to further strengthen the evidence base for tree-based air quality interventions.

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Water-Saving Green Roofs for Pollinators

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Abstract

Appropriately designed green roofs can function as water-saving irrigation systems and pollinator habitats. In this study, we evaluated a rooftop irrigation system using reclaimed water (simulated by diluted seawater up to 18 dS m⁻¹) to sustain vegetation (turf grass *Cynodon dactylon* and the Crassulacean acid metabolism [CAM] species *Sedum kamtschaticum* and *S. oryzifolium*) under drought and salinity stress. A stress factor, the time integral of the soil water potential that exceeds a threshold for normal growth, was used to quantify the accumulated plant stress. Moderate stress reduced total evapotranspiration but increased water use efficiency in CAM plants, indicating trade-offs between irrigation frequency and plant water use. Saline irrigation led to cation accumulation in leaves (Na⁺, Ca²⁺, Mg²⁺, and K⁺). Additionally, leaf extract electrical conductivity [ECleaf] was more reliable for assessing plant salt stress than drainage water electrical conductivity. However, ECleaf is not an absolute stress detector. Rather, it is a relative indicator that requires species-specific calibration. These findings support an integrated design framework that balances substrate properties, plant selection, climate conditions, and irrigation scheduling. Key recommendations include prioritizing drought- and salt-tolerant species (especially CAM plants) to reduce water demand, optimizing irrigation intervals to mitigate stress, and adopting renewable energy for automated irrigation. Integrating pollinator-friendly planting with efficient reclaimed water reuse can enhance the sustainability and resilience of green roof ecosystems. However, pollinator-habitat benefits remain theoretical. This demonstrates the need for direct field validation of flowering and visitation responses.

Keywords : green roof; pollinator habitat; reclaimed water reuse; saline irrigation; drought stress; Crassulacean acid metabolism; water-use efficiency

Introduction

Urban rooftop agriculture and green roofs provide greenery, thermal regulation, and habitats for pollinators and biodiversity [1]. For instance, bees pollinate flowering plants and sustain urban ecosystems [2]. Plant diversity and floral abundance strongly influence their diversity and syrphid fly visitation [3]. Urban microclimates, often warmer, benefit thermophilic bees [4]. This

suggests that tropical rooftops can serve as alternative habitats in the presence of vegetation and features such as beehives. Rooftop beekeeping also produces honey for educational purposes and sale [5,6]. However, maintaining bee-friendly vegetation increases irrigation demand, a challenge in water-scarce cities.

In tropical monsoon climates such as Thailand, green roofs face long dry seasons followed by intense rains. Prolonged drought

necessitates non-potable irrigation, whereas heavy rainfall flushes accumulated salts from substrates. This strong seasonality and limited maintenance capacity complicate the provision of year-round pollinator support.

Reclaimed water, particularly secondarily treated domestic graywater from sinks, baths, and laundry, is a practical non-potable source for green roof irrigation. Salinity in irrigation water indirectly affects pollinator support. Specifically, elevated salt concentrations stress vegetation, consequently reducing growth and flowering intensity. This limits the availability of floral resources for pollinators [7]. In addition, raindrop splash erosion and wind-driven particle transport can cause the loss of thin green roof substrates, especially when vegetative cover is incomplete [8]. Substrate loss reduces rooting depth and can clog drainage outlets. These issues become particularly relevant when intense early-monsoon rains fall on partially exposed substrates after the dry season.

Rising urban populations further strain water supplies, resulting in the use of non-potable irrigation (**Figure 1**). Graywater (the primary reclaimed water source considered in this study) and harvested rainwater can significantly reduce potable water-use [9]. In one reuse system

(**Figure 1**), reclaimed water undergoes aerobic and anaerobic treatment [10]. It is stored in a primary tank and subsequently pumped (via renewable energy) to rooftop tanks for irrigation.

The application of such systems in multistory buildings is feasible, as they support well-managed vegetation [11]. However, salinity remains a challenge: even treated water contains residual salts, especially sodium. These salts are costly to remove and accumulate in shallow substrates, thereby stressing plants [12].

Green roof plants must withstand drought and salinity, especially in regions with prolonged dry seasons or competing water demands that restrict the use of freshwater irrigation. Although saline irrigation methods exist for field crops [13, 14], green roof conditions—thin substrates and shallow root zones—are more challenging.

Stress elimination would require intensive management and constant monitoring (**Figure 2**), which is unrealistic for most owners. A more practical strategy is to allow controlled stress to reduce water and labor needs. However, data on the stress tolerance of green roof species are limited, partly because of difficulties in the quantification of cumulative stress.

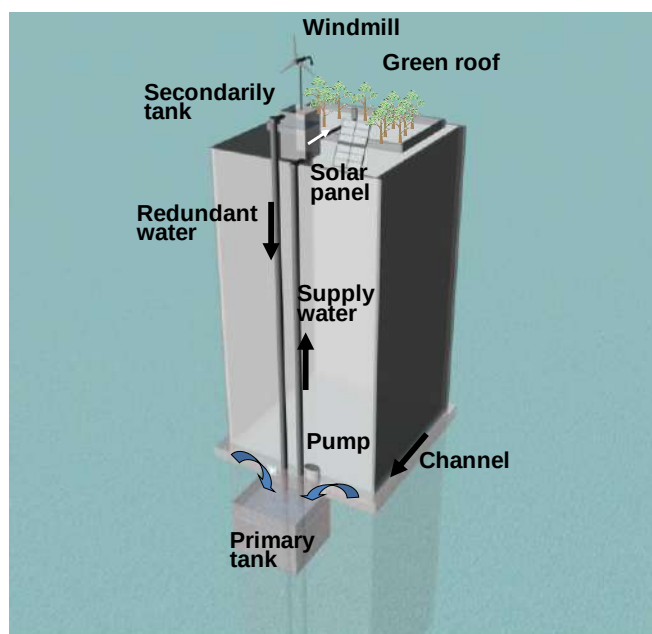


Figure 1 Schematic of reclaimed water collection, treatment/storage, and rooftop reuse for irrigation

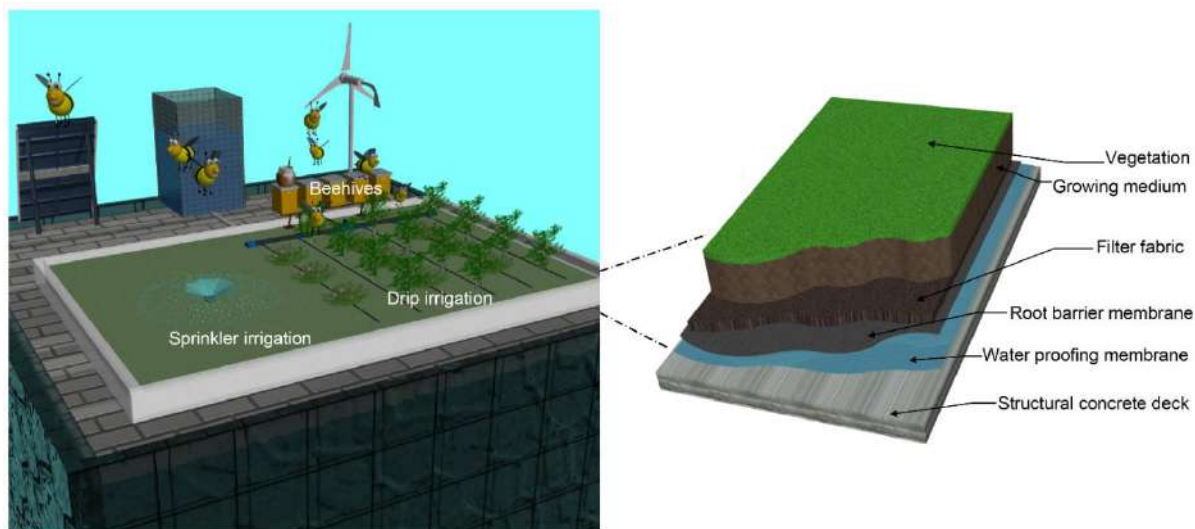


Figure 2 Schematic layout of gray water irrigation for vegetation with beehives (Left) and thin substrate layers of a representative green roof system (Right)

In this study, we aimed to quantify plant stress on a green roof based on the “stress factor” concept. We further sought to evaluate its effects on water use and growth [15]. Finally, we propose strategies for integrating pollinator-friendly habitats with water-saving irrigation, enabling water conservation in rooftops while supporting flowering plants for pollinators.

Materials and Methods

Experimental Conditions

A controlled irrigation experiment was conducted in a glasshouse during the hot summer to simulate the tropical rooftop conditions typical of Thailand’s monsoon cities and pollinator-oriented green roofs. The average temperature and relative humidity were 32 °C and 66%, respectively. Plastic pots (200-cm² surface area) served as micro-green roofs. Each pot contained a 20 cm layer of engineered green roof substrate over 10 cm of coarse perlite gravel for drainage purposes. The gravel acted as a filter, and the bottom of the pot functioned as a root barrier, with drainage outlets collecting excess water (**Figure 1**). Pots were placed on a sand bed where the surface sand temperature exceeded 50 °C to simulate rooftop heating, and a thin insulating cushion moderated heat transfer to

reproduce dry-season heat loads relevant to bloom suppression and substrate desiccation.

Although the present pot-scale experiment focused on water-use dynamics and salt accumulation, substrate integrity under rainfall is a parallel concern for operational green roofs. **Figure 3** shows photographs of related experiments conducted in the same glasshouse facility using the same plant species and engineered substrate as those in this study. The glasshouse slope installation (**Figure 3a**) accommodated *S. kantschaticum* on six substrate types—including the engineered green roof medium used in this study—at two inclinations (20° and 30°); it was further equipped with overhead nozzles capable of simulating rainfall. A separate rainfall simulation experiment (**Figure 3b–e**) quantified splash erosion from the same substrate under 40 mm h⁻¹ artificial rainfall delivered from a height of 12 m for approximately 1 h. Bare substrate (**Figure 3c**) showed substantial splash-driven soil loss; detached particles were deposited on the inner walls of the surrounding collection tray. Partial vegetative cover by turfgrass (Left) and *S. oryzifolium* (Right) (**Figure 3d**) reduced but did not eliminate splash loss. In contrast, complete canopy closure (≥100% cover) by *S. oryzifolium* (Left) or a nonwoven-sheet ground cover with *S. oryzifolium* (Right) (**Figure 3e**) virtually eliminated visible splash

erosion. These observations confirm that vegetative cover plays a decisive role in protecting thin green roof substrates from raindrop-impact erosion, a factor with direct implications for the irrigation management strategies discussed below.

Irrigation regime

Diluted seawater with electrical conductivity (EC) levels ranging from 0.7 dS m^{-1} (freshwater) to 18 dS m^{-1} (high salinity) was used as a salinity proxy for reclaimed water. This range was selected to establish dose–response relationships; the lower range ($0.7\text{--}2.0 \text{ dS m}^{-1}$) is representative of treated domestic graywater, whereas the upper range represents worst-case scenarios. Two irrigation regimes were applied: frequent (every 1–3 days) and intermittent (5–17 days) [16]. We imposed a zero-rain condition to simulate a

worst-case Thai dry-season window; multi-week rain-free periods (approximately 41 consecutive days across all experimental periods) occur in inland regions. Accordingly, we did not simulate rainfall (freshwater) events. Such rains would episodically leach salts in real roofs and temporarily raise soil water potential (**Figure 4c**).

Evapotranspiration (ET) was monitored by weighing the pots before irrigation. The irrigation volume equaled $1.2 \times \text{ET}$ loss to permit partial salt leaching, creating a 20% drainage surplus [17]. The drainage volume and EC were recorded to estimate the salt balance. Soil moisture was inferred from the pot weight, and root-zone salinity was assessed using a mass balance of salt inputs (irrigation) and outputs (drainage), adjusted for soil water content. Small evaporation pans near the pots provided reference evaporation data.

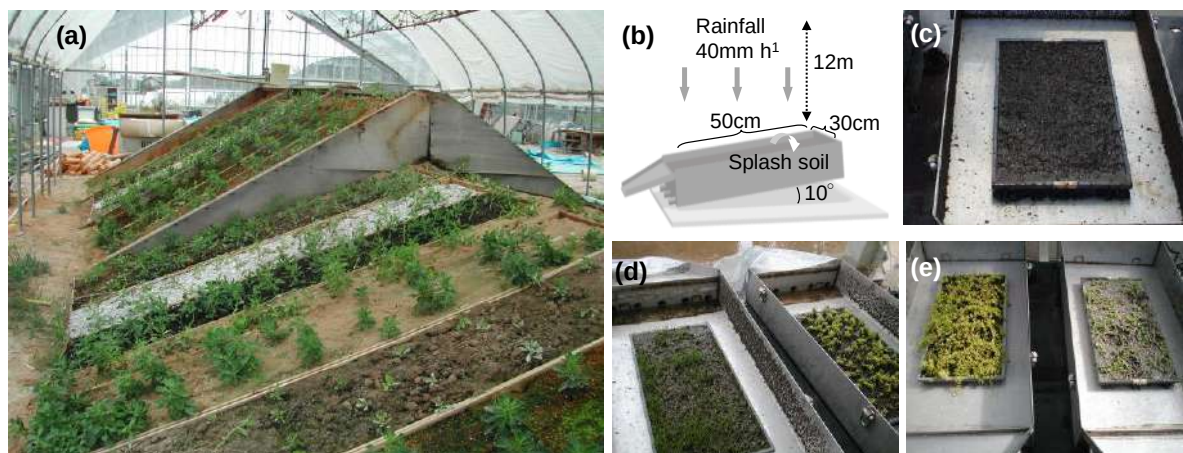


Figure 3 Photographs of related experiments conducted in the same glasshouse facility.

(a) Slope experiment: *S. kamtschaticum* cultivated on six different substrates at two contrasting inclinations; overhead nozzles allow rainfall simulation.

(b) Schematic and overview of the rainfall simulation setup: artificial rain was delivered onto substrate trays from a height of 12 m at 40 mm h^{-1} for approximately 1 h.

(c) Bare substrate after rainfall simulation, showing substantial splash-driven soil loss deposited on the inner walls of the surrounding collection tray.

(d) Partial vegetative cover: turfgrass (left) and *S. oryzifolium* (right) with incomplete canopy closure; splash erosion was reduced compared with bare substrate but remained visible.

(e) Complete vegetative cover ($\geq 100\%$): *S. oryzifolium* (left) and nonwoven-sheet ground cover with *S. oryzifolium* (right); virtually no splash erosion was observed.

All experiments used the same engineered green roof substrate as that in the present study.

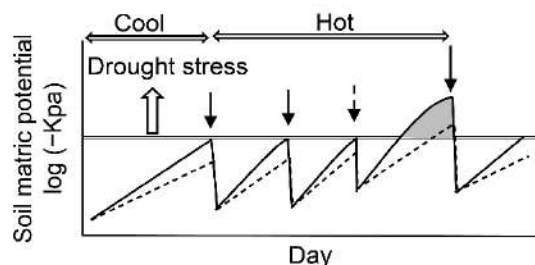
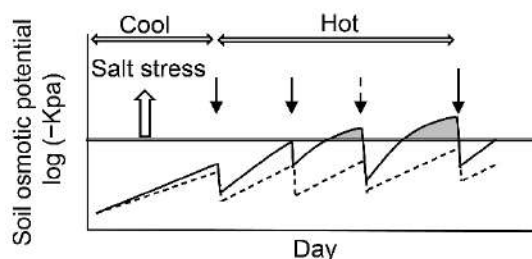
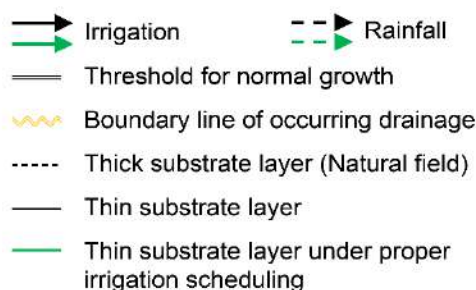
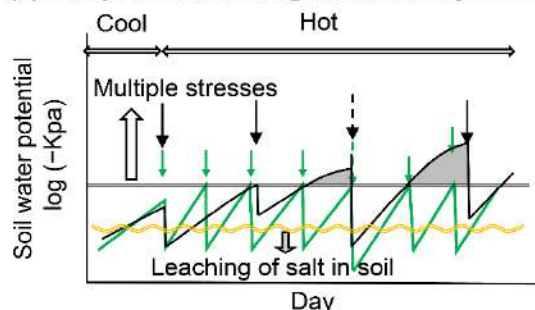
(a) Soil droughtness**(b) Soil salinity****(c) Complex of the drought and salinity in soil**

Figure 4 Illustration of the drought/salinity stress factor, defined as the time-integrated exceedance of soil water potentials beyond growth thresholds

Plant stress assessment

Plant stress was assessed using a stress factor (S) method (**Figure 4**). Soil water potential has two components: matric (related to moisture/drought) and osmotic (related to salinity) potential. Matric potential was derived from soil moisture using a predetermined soil water retention curve, and the osmotic potential was estimated via a linear conversion from EC. The threshold for plant stress was selected as pF 3.0 (approximately -1 kPa), a widely accepted threshold demarcating the limit of readily available water [14, 18]. If the soil matric potential was wetter than the threshold for plant stress, we considered drought stress to be zero; if drier, the excess (in time and magnitude) contributed toward drought stress (Figure 4a). Similarly, salinity stress accumulated when soil salinity (EC) exceeded the plant tolerance threshold (Figure 4b). The total stress factor S was then calculated by integrating the portions of the matric and osmotic potentials that exceeded their respective thresholds (Figure 4c). In

simpler terms, S (MPa-day) represents the cumulative “amount” of water stress (drought plus salinity) experienced by the plant during the experiment [14]. The selected thresholds represent general agronomic benchmarks rather than species-specific calibrations. Thus, S may not perfectly capture differential stress sensitivity across species.

Plant selection and measurements

For sustainable green roofs that use reclaimed water, selecting plants with high drought and salt tolerance while retaining nectar/pollen potential for pollinators, is essential. We focused on three species in this study: one turfgrass species and two succulents.

In tropical regions, *Cynodon dactylon*, *S. kamtschaticum*, and *S. oryzifolium* typically flower between June and September, June and August, and May and July, respectively. Flowering was not observed during our short experimental period; actual phenology under saline irrigation on green roofs may differ from these reference ranges.

C. dactylon (Bermuda grass) is commonly used on roofs because of its resilience; it tolerates moderate salinity and drought and grows naturally in salt-affected habitats (up to 19.9 dS m⁻¹) [19]. In contrast, turfgrass tolerates stress less effectively than Crassulacean acid metabolism (CAM) succulents under extreme conditions [20]. The succulent species *Sedum kamtschaticum* and *S. oryzifolium* use CAM, an adaptation that facilitates water conservation. CAM plants open their stomata at night (when evaporation demand is low) to fix CO₂ into organic acids. They close their stomata during the day while completing photosynthesis internally [21, 22]. This metabolism and water storage significantly reduce transpiration losses in fleshy leaves. These traits enable CAM plants to thrive in thin, dry substrates with minimal irrigation. For example, *Sedum* species can maintain metabolic activity during drought by shifting to CAM and avoiding excessive salt uptake [23]. Owing to these advantages, CAM succulents are ideal for water-limited roofs. However, an all-succulent roof may not provide the best forage for bees. Thus, including some stress-tolerant flowering herbs or grasses can improve the habitat value. *C. dactylon* can bloom and provide pollen, though not as much as wildflowers. This mix reflects Thai monsoon reality: resilient species carry the dry season, whereas flowering herbs enhance rainy-season forage. In addition to their role in habitat provision, dense canopies formed by these species also protect thin substrates from splash erosion (**Figure 3c–e**).

Before starting the irrigation treatments, healthy specimens of each species were cultivated and transplanted into the experimental pots to ensure that the planting density was sufficient to cover the soil surface before the experiment began. The plants were established using non-saline water before initiating the abovementioned irrigation regimes.

Monitoring plant responses

Plant growth and stress indicators were evaluated at the end of the experiment. Above-ground biomass was harvested and oven-dried at 80 °C for 72 h to determine the dry matter

yield (DM). Plant tissue salt accumulation was analyzed by grinding dried shoot material to powder using a mixer mill [24]. A known powder mass was mixed with deionized water and shaken for >24 h to extract soluble salts. The EC of the filtered supernatant was measured to determine the leaf water EC (EC_{leaf}), which reflects the tissue's salt concentration. To account for differences in plant water content, we expressed EC_{leaf} based on the water content using an inversely proportional adjustment. We further measured the concentrations of key cations (Na⁺, K⁺, Ca²⁺, and Mg²⁺) in the leaf extract using the same atomic absorption spectroscopy procedures [24]. Because flowering was not observed during the short trial, canopy biomass served as a proxy for habitat capacity under dry versus rainy analogs.

Results and Discussions

Stress factor

The treatments successfully generated various stress conditions, as reflected in the calculated stress factor (S) values (**Figure 5**). *C. dactylon* experienced the largest S range under intermittent (extensive) irrigation with high salinity, reaching a maximum of 126 MPa·day under water stress alone. In contrast, the two CAM succulents showed considerably lower S values, with a maximum of 34 MPa·day. No significant difference in S was observed between frequent vs. intermittent irrigation at equal salinity. This indicates that CAM plants avoided most of the drought stress by closing their stomata early and markedly reducing water use under dry or saline conditions. The grass, with C3 metabolism, continued to transpire until the soil water was largely depleted, resulting in higher water stress during dry intervals. Frequent saline irrigation alleviated some stress in *C. dactylon*; its S value under frequent 18 dS m⁻¹ irrigation was approximately 67% lower than that under intermittent 18 dS m⁻¹. From a practical standpoint, short-term intensive watering can buffer the dry season to preserve the canopy and prospective bloom sites. Salinity stress accumulated gradually and was partly offset by reduced water demand under stress. However,

this buildup can erode mid-dry-season habitat quality (cover and floral potential) in the absence of seasonal rain.

Water use efficiency (WUE)

Total water use (cumulative ET) was inversely correlated with stress factors (**Figure 5**). Well-watered *C. dactylon* had the highest total evapotranspiration (TET) (574 mm), which sharply declined to 172 mm as *S* increased. CAM species had inherently lower water use and weaker correlations with *S*. Furthermore, they reduced water use under stress via stomatal closure and CAM-idling, whereas *C. dactylon* continued to use water at a moderate rate until stress became markedly high. This reflects a fundamental trade-off: CAM plants conserve water at the expense of growth, whereas grass maintains function for longer but risks dehydration.

WUE refers to the ratio of biomass produced to water used. **Figure 6** shows the relative WUE against the stress factor. WUE increased with increasing stress in CAM plants,

reaching up to 2.1 times that of the control. However, this reflects reduced water consumption rather than maintained or improved biomass production. In absolute terms, DM decreased with increasing stress for all species. Therefore, the higher WUE should not be interpreted as improved productivity. The regression slope of WUE vs. *S* for CAM plants was approximately 12 times steeper than that for *Cynodon*.

C. dactylon showed stable WUE compared to that of CAM species, reaching 1.2 at the highest stress levels. This design trade-off is important: infrequent saline watering saves water but reduces canopy cover, whereas frequent irrigation sustains biomass but increases water use. Reduced canopy cover under stress also leaves substrates more exposed to splash erosion during subsequent rainfall events (cf. **Figure 3c vs. 3d–3e**), thereby creating a feedback loop in which water-saving strategies may indirectly compromise substrate integrity.

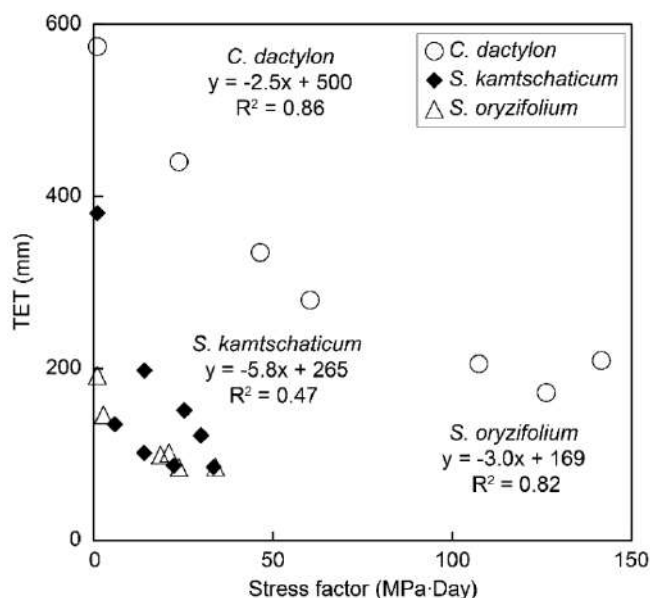


Figure 5 Relationship between stress factor and total evapotranspiration (TET) for Crassulacean acid metabolism (CAM) species (*S. kamschaticum*, *S. oryzifolium*); dashed: turf (*C. dactylon*). Linear regressions are shown

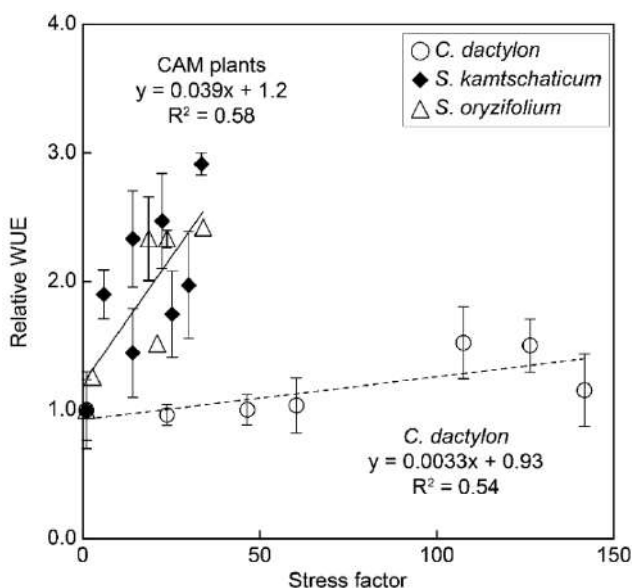


Figure 6 Relative water use efficiency (WUE) (baseline = 1.0 under frequent 0.7 dS m⁻¹). Solid lines: Crassulacean acid metabolism (CAM) species (*S. kamschaticum*, *S. oryzifolium*); dashed: turf (*C. dactylon*). Lines depict linear regressions

Salt accumulation in leaves

Leaf ion concentrations were measured to assess species-specific responses to salinity (Figure 7, frequent irrigation treatments). As expected, total cation content increased with irrigation water salinity across all species. *C. dactylon* consistently accumulated more Na^+ than the *Sedum* species, likely because of higher transpiration. However, the leaf Na^+ ratio relative to irrigation water was only 0.04-0.21, indicating that all species excluded most salt [25].

Potassium remained the dominant cation under all conditions [26]. Under stress treatments, the CAM plants maintained approximately 1.9-2.1 times higher K levels than the grass. *S. kamtschaticum* showed tissue damage under some high-salinity treatments, possibly because of temporary CAM cycle breakdown. In contrast, *S. oryzifolium* appeared to avoid this by rapidly entering dormancy as stress intensified.

ECleaf was proportionally correlated with total cation content. However, CAM leaves showed only 28%-55% of the EC values of grass leaves. ECleaf serves as a relative indicator of tissue salt loading rather than an absolute stress threshold. Its relationship with physiological endpoints requires species-specific calibration. Factors such as tissue water content, leaf age, and seasonal variation may affect ECleaf values independently of actual salt stress. Therefore, we recommend using ECleaf as a screening tool in conjunction

with visual assessment, rather than as a standalone diagnostic.

Salinity stress may indirectly affect pollinator communities, primarily through reduced floral resource quantity: salt-stressed plants produce fewer flowers, smaller floral displays, and less nectar. A recent review [7] noted the lack of studies on direct salinity–pollinator effects; the effects are most likely mediated through changes in plant chemistry and floral resource provision. Water stress, which often co-occurs with salinity, substantially reduces nectar volume in bee-pollinated species [27]. These indirect effects reinforce the importance of maintaining substrate salinity at tolerable ranges.

Over multiple seasons, cumulative salt deposition during dry periods may progressively alter substrate chemistry, even with monsoon leaching. Long-term salt accumulation could shift species composition toward more halophytic communities [28, 29], and substrate organic matter decomposition may alter water-holding capacity. Plant succession, including gradual dominance of stress-tolerant species, could reduce floral diversity if not actively managed. Furthermore, repeated wetting–drying cycles combined with salt crystallization may degrade substrate physical structure, thereby increasing susceptibility to erosion during subsequent rainfall.

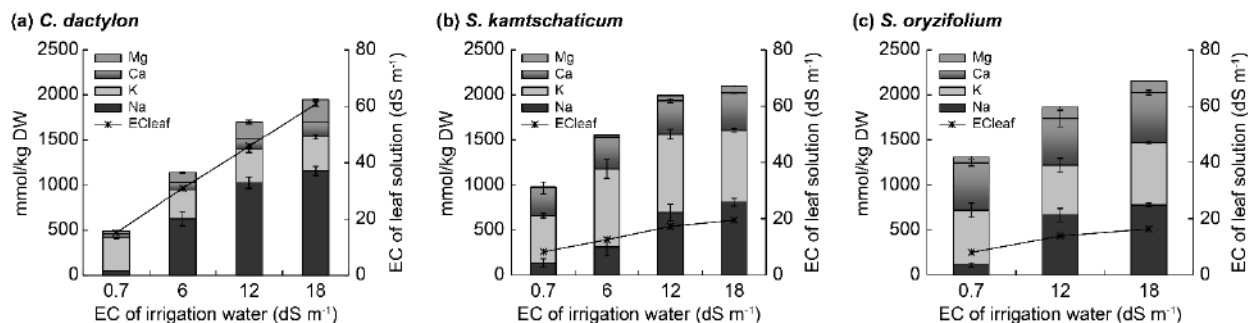


Figure 7 Leaf cation concentrations (Mg^{2+} , Ca^{2+} , K^+ , and Na^+) and EC under frequent irrigation at different salinity levels; DW = dry mass

Operational strategy matrix for Thai monsoon roofs

Green roof irrigation and management strategies vary globally. Thailand faces a pronounced monsoon rhythm: a long, hot and dry season followed by months of heavy rainfall. This seasonality directly shapes rooftop vegetation.

We constructed a 2×2 operational strategy matrix to facilitate the applicability of our experimental findings (**Figure 8**). This matrix is a conceptual synthesis derived from experimental observations and has not been field-validated. Thus, it should be treated as a decision-support heuristic rather than a prescriptive protocol.

A practical rule is to anchor in a Passive Habitat quadrant during the monsoon season and then carry a Resilient Base during the dry season. In the Passive Habitat quadrant (Rainy/Fresh $\times$ Low operation), native wildflowers thrive with rainfall alone; clearing of gutters or drains is often sufficient to prevent waterlogging. The splash erosion results (**Figure 3**) underscore the importance of this drain maintenance: substrate particles detached by monsoon rainfall can accumulate in drainage outlets, and even moderate vegetative cover may not fully prevent splash-driven particle transport (**Figure 3d**). Therefore, regular drainage checks serve a dual purpose—prevention of waterlogging and removal of eroded substrate material that could obstruct water flow. If resources are sufficient, managers can move upward into the High Diversity or Intensive Care quadrants to enrich flowering. Nonetheless, the system remains functional and pollinator-supportive even without such inputs.

Although CAM species provide reliable green cover during drought, their reduced growth rate and suppressed flowering under stress may limit nectar and pollen availability. Consequently, an all-CAM roof may sustain vegetation but underperform as a pollinator habitat during extended dry periods. Thus, mixed plantings with stress-tolerant flowering herbs are recommended.

Although designed for Thailand's monsoon seasonality, the matrix logic is transferable to other climates. Practitioners in other monsoon or semi-arid climates can map their local dry and wet seasons onto the

horizontal axis and adjust the species palette to locally available drought- and salt-tolerant species.

Limitations and future directions

This study had some limitations. First, experiments were conducted on pot-scale micro-green roofs in a glasshouse. Actual rooftop dynamics (wind, rainfall, and advection) may alter drying, leaching, and heat loads. At full-roof scale, wind exposure would accelerate substrate drying and deposit salt on foliage. Furthermore, heterogeneous substrate depths would create spatial variability in moisture and salinity regimes. Substrate erosion, which is absent in pot experiments, becomes a significant concern at full scale. As demonstrated in the companion experiments (**Figure 3**), raindrop splash can detach and displace substantial amounts of substrate material from thin green roof media, particularly under incomplete vegetative cover (**Figure 3c–3d**). Therefore, maintaining adequate canopy cover through appropriate irrigation management serves both a habitat function and an erosion-control function.

Second, reclaimed water was modeled using diluted seawater to isolate ionic effects. Actual reclaimed water typically contains residual nutrients (N and P), dissolved organic matter, and microbial communities that may alter growth and salt transport. The ionic composition also differs: reclaimed water generally has higher Ca^{2+} and HCO_3^- relative to Na^+ than seawater. Therefore, future studies should validate these findings using actual treated wastewater.

Third, the stress factor (S) used general agronomic thresholds (pF 3.0 [14, 18]) that may not capture species-specific responses. Thus, future studies should validate S against leaf water potential and stomatal conductance. Furthermore, leaf-extract EC was only used as a proxy of tissue salinity, consequently necessitating calibration across species.

Fourth, the species palette was narrow, the trial was short, and flowering/pollinator visitation were not measured. Therefore, pollinator-habitat inferences remain conceptual. Conclusions on pollinator habitats are based on the assumption that sustained vegetative cover serves as a prerequisite for subsequent floral resource provision.

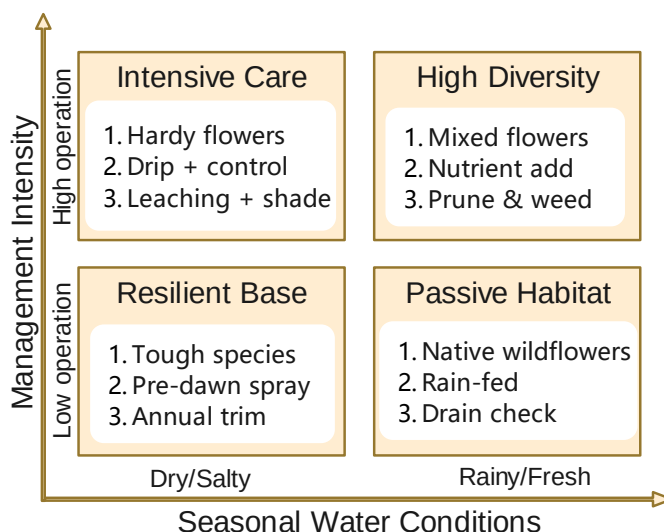


Figure 8 Operational strategy matrix for pollinator-friendly green roofs under monsoon climates:
A conceptual framework linking seasonal water conditions and management intensity

Urban rooftop environments also subject plants and pollinators to additional stressors that were not simulated in the present study. These include reflected thermal radiation, urban heat island effects, and air pollutants (e.g., NO_x , particulate matter), which may interfere with floral scent signals that are important for pollinator navigation.

Future studies should test full-scale roofs across Thai dry/rainy seasons using reclaimed water (with rainwater blending), validate S and EC proxies against plant water potentials, expand to native Thai wildflowers, track flowering phenology and pollinator visitation, and compare drip vs. micro-spray with planned leaching to maintain year-round habitat while minimizing water use.

Conclusions

The synergy of a suitable substrate, resilient plants, climate-responsive design, and smart irrigation control can produce green roofs that use minimal water while sustaining diverse vegetation for urban pollinators. Our research shows that certain plants can adapt under saline and limited water inputs by reducing their water use and tolerating moderate salt accumulation. Beyond habitat provision, maintaining vegetative cover also protects thin substrates from splash erosion, linking irrigation management to

long-term substrate integrity. Urban designers can develop environmentally sustainable and ecologically beneficial green roofs by harnessing these natural adaptations and complementing them with thoughtful engineering. However, the pollinator-habitat benefits inferred in this study remain conceptual, as flowering and pollinator visitation were not directly observed. Future studies should refine this approach by testing herbaceous species and wildflowers that attract pollinators. Nonetheless, our findings provide a foundation for the advancement of such designs, bringing us closer to green roofs that function as urban oases for biodiversity while conserving fresh water.

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CR Disaster MAN: A Training Curriculum Model for Area-Based Flood Disaster Management and Evaluation Outcomes in Chiang Rai Province

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Abstract

This study aimed to design and evaluate the CR Disaster MAN (Chiang Rai Disaster Management and Networking) curriculum to address the lack of area-specific disaster preparedness training in Chiang Rai province. The curriculum integrates disaster management principles, adult learning theory, community-based disaster risk management, psychological group processes, and resilience enhancement. The research employed a one-group pretest–posttest design with 200 samples, including community leaders, volunteers, government and local personnels in flood risk areas in Chiang Rai province. Data were collected using a knowledge test, satisfaction questionnaire, and training program evaluation. All collected data were analyzed using a descriptive statistics and paired sample T-test.

Results showed statistically significant improvement in disaster management knowledge after training ($p < .001$). Satisfaction with content, instruction, and technology support was at “the highest level” ($M = 4.60$, $S.D. = 0.54$). The modular design and participatory approach enable transferability to other flood-risk areas in Thailand. The study highlights the importance of structured, evidence-based training models in strengthening area-based disaster management competency.

Keywords : Disaster management; Adult learning; Community engagement; Systematic resilience; CR Disaster MAN

Introduction

Chiang Rai is one of Thailand’s most flood-prone province, located on a river basin with an annual rainfall is 1,200-2,000 mm. [1]. Flood-risk districts such as Mueang and Mae Sai consistently encounter riverine and flash floods due to hydrological, environmental, and urbanization factors. Prior studies indicate limitations in existing flood management, including gaps in data accuracy, insufficient technical personnel, and weak community-level engagement [2].

Despite integrated flood management planning, challenges persist due to incomplete datasets, governance limitations, and inadequate public participation. Consequently, the development

of area-specific training programs is essential to enhance disaster preparedness and strengthen community resilience [3].

The CR Disaster MAN curriculum was developed to address these gaps. However, evidence-based evaluation of such localized training initiatives remains limited. This study aims to design the CR Disaster MAN area-based flood disaster management curriculum, to evaluate the effectiveness of the curriculum through pre- and post-test knowledge assessment, and to assess participants’ satisfaction with the curriculum. By applying 5 theories to (1) the Disaster Management concept guides the curriculum structure across the modules on preparedness, mitigation, response, and recovery [4], (2) the Psychological

Training Groups support experiential learning and group interaction activities [5], (3) the Adult Learning Theory ensures that learning is problem-centered and relevant to real-world contexts [6], (4) the Community-Based Disaster Risk Management (CBDRM) approach frames community participation, the integration of local wisdom, and collaborative planning [7], and (5) the Resilience Theory strengthens long-term recovery capacity and adaptive skills [8]. Each framework's principles were mapped directly to training modules including surveillance, early warning, evacuation planning, community mapping, and post-flood recovery.

Methodology

Research Design

This article is partial research promoting the CR Disaster MAN disaster management platform, funded by Thailand Science Research and Innovation (TSRI) and Program Management Unit on Area Based Development (PMUA). A pre-experimental one-group pretest–posttest design was used to evaluate knowledge improvement and satisfaction after participating in the CR Disaster MAN curriculum.

Population and Sample

The population consisted of individuals who had roles in flood management in Chiang Rai province, including (1) community leaders and volunteers from flood-prone areas; (2) personnel from local administrative organizations and relevant agencies, and agencies concerned with disaster prevention and mitigation, e.g., the Department of Disaster Prevention and Mitigation, municipalities, Subdistrict Administrative Organizations, and rescue volunteers; and (3) representatives of civil society organizations participating in risk management and disaster recovery. This population plays important roles in flood response and management, as they are field-level practitioners who systematically use data for decision-making and apply practical skills.

The sample consisted of 200 purposively selected individuals from flood-prone areas. Notably, 39% were aged 51 years or older. This group was intentionally included because older adults in northern rural communities commonly serve as community leaders, village heads, and disaster volunteers. Their experience

and local authority are crucial for decision-making and mobilizing community responses during floods.

Research Instruments

Three instruments were utilized in this research.

1. The “CR Disaster MAN” curriculum was developed by the researcher based on documents, textbooks, concepts, and theories related to disaster management, psychological groups, and adult learning. Only concepts and theories that were appropriate and consistent with area-based disaster management were selected to improve area-based flood management. The content validity and consistency were evaluated by three experts in psychology, education, measurement, and disaster management, resulting in the Index of Content Validity (IOC) of 0.80-1.00. Their recommendations were adopted before piloting the curriculum with a non-sample group for 24 hours to test the appropriateness of the steps, duration, and content, and to determine flaws and improvement before implementation. Content structure and training activities included five dimensions: (1) surveillance, (2) response, (3) relief, (4) recovery, and (5) community preparedness plan based on the participatory learning & action and integration of local wisdom and international disaster management concept.

2. Knowledge assessment form for the “CR Disaster MAN” flood management training was validated by three experts in psychology, education and measurement, and disaster management to validate the consistency of questions and terminology, and to assess content validity. The findings indicated an IOC of 0.60-1.00, discrimination index of 0.54-0.97, and reliability, Cronbach's Alpha of 0.97, which indicated high reliability. The assessment form consisted of two parts.

Part 1: General information of informant
This part collects basic information, such as gender, age, education level, marriage status, income, and personal contact, to explain the qualities of the sample. It has no impact on learning achievement measurement.

Part 2: Knowledge assessment form - 20 questions with four multiple-choice
This part covers knowledge about area-based flood management

3. Satisfaction assessment form for “CR Disaster MAN” flood disaster training curriculum. This information is used to measure the participants’ satisfaction with content, teaching methods, and benefits.

Data collection

The researcher conducted the data collection following five steps.

1. Preparation

The researcher coordinated with local administrative organizations, relevant agencies, and local community leaders in flood-prone areas to select samples based on the criteria. Then, the researcher asked for permission from participants and their organizations, and provided clear information about the objectives, scope, and rights of participants.

2. Pre-test

A total of 200 samples completed a knowledge test about disaster management, which has 20 questions with four multiple-choice, to collect their basic geographic information, including gender, age, educational level, income, and direct experience in flood management.

3. Training implementation

The researcher conducted the training following the CR Disaster MAN curriculum, which covered five dimensions: (1) Surveillance, (2) Response, (3) Relief, (4) Recovery, and (5) Community preparedness plan, which implemented participatory learning & action and learning exchange among participants.

4. Post-test

At the end of the training, the sample group completed the post-test, the same test as the pre-test, to compare results. The researcher collected the data on satisfaction with the training using the 5-Likert scale questionnaire (5 = Highest, 4 = High, 3 = Moderate, 2 = Low, 1 = Lowest). The satisfaction evaluated the content, instructor, training logistics, and appropriateness of time and venue.

5. Data validation

The researcher validated the completion of the questionnaire and all sets of tests and processed the data coding to prepare for the statistical analysis.

Data analysis

Data analysis was carried out systematically to ensure accurate results aligned with the research objective. Descriptive statistics and inferential statistics were utilized as follows.

1. Descriptive data analysis

Descriptive data analysis described general qualities of the population and sample group and validated the appropriateness of the data using statistics. Frequency and percentage explained participants’ general information, including gender, age, educational level, marriage status, income, and flood management experience. Mean and standard deviation (SD) summarized the tendency and distribution of the pre- and post-scores for knowledge, competency, and skills of the sample group.

2. Inferential data analysis

Inferential data analysis tested the research hypothesis and compared the training results using statistics. A paired samples t-test was used to compare pre- and post-test knowledge scores in disaster management, to assess whether the CR Disaster MAN curriculum enhanced knowledge and skills with statistical significance. A statistical significance level of .05 ($p < .05$) was used to identify whether the difference was statistically reliable or not.

Results and Discussions

General information of the sample group

General information of 200 samples comprised gender, age, educational level, status, and income. Descriptive data analysis was applied to examine the mean and percentage. Results shown in **Table 1**.

Table 1 Number and percentage of the sample group's information (n=200)

General information of the sample group	Number (prs.)	Percentage
1. Gender		
Male	134	67.00
Female	66	33.00
Total	200	100.00
2. Age		
15-20 years	8	4.00
26-30 years	9	4.50
31-35 years	6	3.00
36-40 years	17	8.50
41-45 years	41	20.50
46-50 years	41	20.50
51 years and above	78	39.00
Total	200	100.00
3. Educational level		
Primary school	42	21.00
Middle school	20	10.00
High school	56	28.00
Bachelor's degree	50	25.00
Master's degree	8	4.00
Vocational Cert./High vocational cert.	24	12.00
Total	200	100.00
4. Status		
Single	60	30.00
Married-Separate	8	4.00
Married-Living together	97	48.50
Divorce	13	6.50
Widowed	22	11.00
Total	200	100.00
5. Monthly income		
Under 5,000 THB	27	13.50
5,001-10,000 THB	70	35.00
10,001-15,000 THB	52	26.00
15,001-20,000 THB	17	8.50
20,001-25,000 THB	10	5.00
25,001 THB and above	24	12.00
Total	200	100.00

Table 1 shows that most samples were males (67.00%), with females accounting for 33.00%. Most of them were aged 51 years and above (39.00%), followed by those aged 41-45 and 46-50 years (20.50%), 36-40 years (8.50%), 26-30 years (4.50%), 15-20 years (4.00%), and 31-35 years (3.00%). The majority of them graduated from high school (28.00%), followed by bachelor's degree, primary school, vocational certificate/high vocational certificate, middle school, and master's degree (25.00, 21.00, 12.00, 10.00, and 4.00%, respectively). Most were married and living together, followed by single, widowed, divorced, and married and separated (48.50, 30.00, 11.00, 6.50, and 4.00%, respectively). Most of them earned 5,001-10,000 THB (35.00%), followed by 10,001-15,000 THB, under 5,000 THB, 25,001 THB and above, 15,001-20,000 THB, and 20,001-25,000 THB, respectively (26.00, 13.50, 12.00, 8.50, and 5.00%, respectively).

Therefore, Samples were predominantly older adults, reflecting community leadership roles in rural flood-prone areas. Lower formal education levels in some groups may influence learning pace, reinforcing the need for visual and activity-based training.

Study of “CR Disaster MAN” curriculum training results – pre- and post-test

To analyze pre- and post-test results of the “CR Disaster MAN” curriculum training, the researcher tested the primary agreement using the normality test with Kolmogorov–Smirnov; p was .06-.11. It illustrated that the mean of pre- and post-test scores in disaster management scores had normal distribution. Then, the researcher analyzed the basic statistics to analyze the t-test for dependent samples, as shown in **Table 2**.

Table 2 Mean and standard deviation (S.D.) of pre- and post-test scores in knowledge about disaster management (n=200)

Knowledge about disaster management	Before the test			After the test		
	M	S.D.	Level	M	S.D.	Level
Knowledge about disaster management	8.72	2.29	Low	14.14	1.67	High

Table 2 shows that the mean of pre-scores in knowledge about disaster management was low ($M = 8.72$ S.D. = 2.29), while the post-test scores was high ($M = 14.14$ S.D. = 1.67).

Therefore, Significant improvement was found ($M = 8.72$ to 14.14 , $p < .001$). This aligns with adult learning and experiential group-based methods.

Table 3 Comparison of pre- and post-test knowledge about disaster management

Knowledge about disaster management	Before the test		After the test		MD	t	p
	M	S.D.	M	S.D.			
Knowledge about disaster management	8.72	2.29	14.14	1.67	5.42	45.99*	.00

Table 3 shows that the mean of post-test scores in knowledge about disaster management increased with a statistical significance of .05. The research created a bar chart to clearly present the statistically increasing mean of post-test scores in knowledge, as shown in **Figure 1**.

Figure 1: Mean Knowledge Score Before and After Training

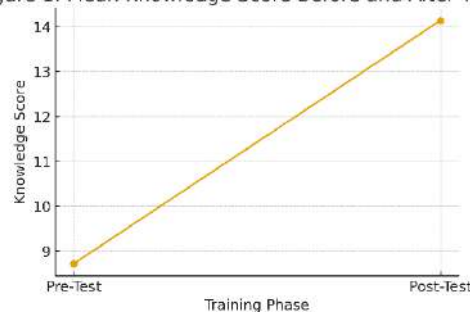


Figure 1 Mean of knowledge about disaster management before and after the training

Study the satisfaction with the “CR Disaster MAN” curriculum training

The researcher studied the satisfaction with the “CR Disaster MAN” curriculum training by analyzing mean and S.D., as shown in **Table 4**.

Table 4 Mean and S.D. of satisfaction with “CR Disaster MAN” curriculum training (n=200)

Satisfaction with training	M	S.D.	Level
Content is appropriate for the activity’s objectives.	4.67	0.65	Highest
The instructor has expertise in activity demonstration and facilitation.	4.69	0.61	Highest
The instructor conveys the content to be understood easily.	4.66	0.65	Highest
The instructor answers questions clearly and usefully.	4.70	0.58	Highest
The venue of activity is appropriate and convenient.	4.66	0.62	Highest
Equipment and technology are available and practical.	4.70	0.58	Highest
Registration and facilities are in order.	4.11	0.47	High
Activity duration is appropriate.	4.69	0.59	Highest
Overall satisfaction with the activity.	4.54	0.73	Highest
Overall satisfaction	4.60	0.54	Highest

Table 4 presents that the mean of overall participants’ satisfaction with the “CR Disaster MAN” training curriculum was 4.60, and the S.D. was 0.54, representing the highest level. When considered by aspects, the highest mean was the instructor answers questions clearly and usefully and equipment and technology are available and practical ($M = 4.70$, $S.D. = 0.58$), followed by the instructor has expertise in activity demonstration and facilitation and activity duration is appropriate ($M = 4.69$, $S.D. = 0.61$ and 0.59), content is appropriate for the activity’s objectives ($M = 4.67$, $S.D. = 0.65$), the instructor conveys the content to be understood easily and the venue of activity is appropriate

and convenient ($M = 4.66$, $S.D. = 0.65$, 0.62), and the overall satisfaction with the activity ($M = 4.54$, $S.D. = 0.73$), respectively. The lowest mean was for registration and facilities are in order ($M = 4.11$, $S.D. = 0.47$).

Although not statistically tested with ANOVA, observed patterns indicated that participants with previous flood experience showed slightly higher baseline knowledge, and overall satisfaction was at the highest level ($M = 4.60$, $SD = 0.54$). Instructor clarity and equipment availability scored highest.

Subgroup Analysis

Although the study did not employ formal statistical tests such as ANOVA due to the pre-experimental design, an observational subgroup analysis was conducted to explore patterns among demographic groups. The results suggested several noteworthy trends:

1. Age Groups

Participants aged 51 years and above demonstrated slightly higher pre-test scores compared to younger groups. This pattern is consistent with their longer experience in local flood response roles, such as village leaders and community volunteers. However, the magnitude of improvement from pre-test to post-test was similar across all age groups, indicating that the curriculum was effective regardless of age-related learning differences.

2. Education Levels

Participants with higher education (bachelor’s degree and above) showed marginally higher pre-test knowledge. Nevertheless, participants with lower education levels exhibited greater relative improvement after the training, suggesting that the experiential and activity-based learning approach effectively supported participants of diverse educational backgrounds.

3. Prior Flood Experience

Individuals with previous direct experience in flood response tended to score higher on the pre-test. After the training, the gap between experienced and inexperienced participants decreased substantially, indicating that the curriculum helped build foundational knowledge for those without past disaster management exposure.

4. Gender

No meaningful difference was observed between male and female participants in either

baseline knowledge or improvement trends. Overall, these subgroup observations support the conclusion that the CR Disaster MAN curriculum is suitable and effective across demographic groups, particularly in diverse rural contexts with mixed ages and education levels.

Discussions

The results on the “CR Disaster MAN” training curriculum illustrated that participants’ knowledge and skills in disaster management increased with a statistical significance after the training, from 8.72 to 14.14. Firstly, the increasing knowledge scores reflects the appropriateness of the curriculum design that aligns with the adult learning theory by [6]; adults learn effectively when the content is related to their direct experience, and it can be a solution in their real life. Therefore, an integration of experiential learning and problem-based learning within the curriculum is crucial for accumulating and developing participants’ spatial competencies and skills. Secondly, the CR Disaster MAN curriculum is comprehensively designed to include five aspects of the disaster management process: surveillance, response, mitigation, recovery, and community planning. This is consistent with the disaster management concept that emphasizes all-phase integration: preparedness, mitigation, response, and recovery [4]. The design enhances a participants’ holistic understanding, so they see the overall picture of disaster management clearly. Thirdly, the research findings exhibit the community engagement and resilience enhancement as the curriculum supports people and local leaders to engage in a risk assessment, planning, and actions, which is in line with the community-based disaster risk management (CBDRM) by [7]. In addition, it is consistent with the resilience theory by [8] that highlights strengthening adaptive and restorative capacity of the community during disasters. Consequently, the integration of local leaders and volunteers is critical for upgrading spatial resilience. Another key point is that the participants’ satisfaction was at “the highest level” ($M = 4.60$, $S.D. = 0.54$), particularly with the instructor’s expertise, availability of equipment and technology. This aligns with [9], who

pointed out that group learning elevated experiential exchange, co-learning, and behavioral competency development efficiently. As a result, the satisfaction reflects the quality of design and training facilitation that effectively fulfills the learners’ needs.

Anyhow, multiple limitations and challenges should be considered. For example, the mean of registration and facilitation was lower than other aspects, implying restrictions in system management. Additionally, most of the samples were elderly people (39% were 51 years old and above). For this reason, the learning and adaptation may differ from working-age participants, even though they have direct experience in disaster management. Therefore, it is necessary to design the learning activity to suit different age groups. After comparing with other relevant studies, the research results are in line with the work of Prabhakar [10], who reported that enhancing personnel competency via participation increased preparedness for disaster response. Moreover, results were in accordance with studies in the Thai context, which affirmed that developing the training curriculum and community networking were key factors for flood impacts mitigation, such as the study on flood preparedness literacy by [11], and flood resilience in Thailand by [12].

The findings signify the necessity for the government agencies, especially the Department of Disaster Prevention and Mitigation (DDPM) and local administrative organizations, to include the CR Disaster MAN curriculum in the enhancement planning for personnel competency in disaster management to set a sustainable training standard that elevates spatial management potential efficiently. In the policy perspective, it is recommended to allocate sufficient and continuous budget to support long-term training, especially in provinces with flood risk, such as floodplains in Northern and Central Thailand, which have repeated flooding issues [12]. In addition, the government sector should establish cross-collaboration between agencies, including the government, private, and civil society sector, to link a holistic data management, resource allocation, and disaster response [4]. In regard to operational recommendations, simulation exercises and field-based practice should be included to

enhance crucial skills for disaster management, such as decision-making skills, leadership, and communication skills during a crisis [9]. Furthermore, learning media and manuals that are appropriate for target groups, such as aging people, community leaders, or local administrative organization staff, should be made available for equal knowledge access [11]. In addition, the integration of digital technology and online platforms for surveillance and real-time reporting will facilitate the speed and precision of data communication [4]. Meanwhile, the voluntary networks for CBDRM should be supported to decentralize authority and responsibility within the community [7], and the CR Disaster MAN can be adapted to other disasters for academic purposes, e.g., landslide, wildfire, or cold hazard, to assess the appropriateness and for a complete curriculum. Additionally, a study on the role of demographic variables affecting the training efficiency should be considered [13] to improve activity patterns and the learning process to suit multiple needs within the different geographical and social contexts.

All in all, this research not only demonstrates the CR Disaster MAN curriculum efficiency but also emphasizes a significance of curriculum design that is founded on the integration of adult learning, holistic disaster management, community engagement, and systematic resilience concept. This curriculum serves as a role model for curriculum training development to upgrade disaster management potential in other high-risk areas across Thailand.

Therefore, results confirm that the combination of adult learning, group psychology, and CBDRM principles contributed to substantial learning gains. The most effective curriculum components were experiential mapping exercises, simulation-based response drills, and peer-learning group sessions.

However, behavioral change and resilience improvement were not directly measured, representing a limitation. The study relied on knowledge tests and self-reported satisfaction, which may not fully reflect long-term skill application.

Comparison with prior studies [2] shows that CR Disaster MAN is unique due to its integration of local wisdom and psychological group learning within a rural Thai context.

Conclusion

The CR Disaster MAN curriculum effectively strengthened area-based disaster management knowledge among participants in Chiang Rai province. The significant improvement in posttest scores and high satisfaction levels confirm its potential as a scalable training model for other flood-risk areas.

Research results reflect the efficiency of a training curriculum model for area-based flood disaster management in developing decision-making skills, leadership, and communication during the crisis. Based on the development process, people who have the roles related to flood management in Chiang Rai should establish and support the efficient disaster surveillance and reporting (flood) by having the local volunteers as a center for precision and swiftness. It should be the practical system that integrates cooperation to build the mechanism promoting systematic collaboration between the government sector and other sectors, aiming for inclusive and sustainable disaster management.

The policy provision should aim to include training curriculum. For example, the Department of Disaster Prevention and Mitigation (DDPM) and Provincial Administrative Organization (PAO) include the disaster training curriculum that covers decision-making, leadership, and communications skills in the personnel development plan. Moreover, the organizations should allocate a sufficient and constant budget, particularly for the areas with the risk of recurrent flooding.

The integrated collaboration between the government, private, and civil society should be promoted to link data and resource management and disaster response efficiently and cohesively.

Research and development for area-based disaster monitoring and reporting technologies should be supported constantly to obtain empirical data that is useful for policy planning and execution.

A longitudinal study should be conducted to assess the knowledge and skills obtained from the training, how they can be practical in the real flood situation, and how they can mitigate spatial losses.

Research methodology to confirm the empirical results that it can upgrade the

community's potential and competency in disaster management should be designed. A comparative study should be applied to compare the area with the training and that without the training. Similarly, the correlational research should be adopted to study the impact of the demographic factor on the direction and intensity of training effectiveness.

Research results should be extended to the predictive research using data from CR Disaster MAN. It will lead to a design of the model to predict the trend or influence on flood situation in other areas

Acknowledgement

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Green Supply Chain Management of Sustainable Rubber Industry

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Abstract

This study aims to analyze the supply chain of the natural rubber and rubberwood industry in Thailand across three levels: upstream, midstream, and downstream, and to propose guidelines for transitioning toward Green Supply Chain Management (GSCM).

The results indicate that the upstream stage generates greenhouse gas emissions of up to 6.4 tCO₂e from cultivation and approximately 35.90 kgCO₂e from chemical use. In the midstream stage, high energy consumption results in emissions of about 80.92 tCO₂e, with fuel and water usage averaging 0.033 and 0.028 gha/ton, respectively. In the downstream stage, emissions from electricity use and transportation are approximately 51.82 and 1.08 kgCO₂e, respectively. The GSCM approach can significantly reduce these impacts, for example, organic fertilizers can reduce emissions by 30–50%, biological inputs by 5–20%, and clean energy can reduce carbon emissions by approximately 0.9 kg CO₂/kWh.

Furthermore, integrating circular economy concepts, developing value-added products such as biofuels and recycled products, and promoting the role of consumers as “carbon stewards” contribute to the long-term sustainability of the rubber industry. The adoption of standards such as FSC and EUDR also enhances competitiveness in global markets, despite challenges related to costs and business adaptation.

Keywords : Rubber; Supply Chain; Green Supply Chain; Rubber Products; Green Products

Introduction

Natural rubber (*Hevea brasiliensis* Muell. Arg.) is an important economic crop for Thailand, particularly as the country is one of the world's leading producers and exporters of natural rubber. According to data from 2024, Thailand exported more than 2.4 million tons of natural rubber, generating over 500 billion baht in revenue, covering both raw rubber and rubber-based products [1]. China was the largest export destination, with a volume of 1,859,259 tons, valued at more than 22.7 billion baht [2]. However, the expansion of rubber plantation areas over the past two decades—especially into new regions such as northern Thailand—has had

environmental impacts, including land-use changes, deforestation, and a decline in biodiversity [3].

In the context of environmental change and global market pressures, Thailand has established development directions through its 20-Year National Strategy and the 13th National Economic and Social Development Plan. These emphasize environmentally friendly economic growth, the promotion of high-value agricultural industries, and efficient resource utilization. There have also been efforts to promote sustainable production and processing of natural rubber through the use of clean technologies, carbon emission reduction, and environmentally friendly products [4]. In this context, Green Supply Chain Management

(GSCM) plays a crucial role in reducing environmental impacts and enhancing the competitiveness of the natural rubber industry. This concept encompasses the entire supply chain—from raw material selection, production processes, and transportation to waste management—with the aim of integrating sustainability principles into every stage [5].

Most existing studies tend to focus on only certain segments of the supply chain, such as rubber plantations or processing factories, and lack a comprehensive system-level analysis that connects upstream, midstream, and downstream activities within a GSCM framework. Furthermore, there are limitations in studies of new rubber-growing areas such as northern Thailand, which have different ecological contexts, economic structures, and land-use patterns compared to traditional growing regions. In addition, there is a lack of analysis on structural supporting factors, such as environmental standards, green market mechanisms, and linkages to regional greenhouse gas reduction targets.

For northern Thailand, which is a newly established rubber-growing region and still in the early stages of supply chain development, studying green supply chain management models can help identify key potentials and supporting factors. This would lead to systematic approaches for developing rubber plantation management and rubber product industries in alignment with international

standards and current environmental change contexts.

Methodology

1. Data Collection on the rubber and rubberwood supply chains. Researchers gathered data on the rubber and rubberwood supply chains from related literature and previous research with a focus on analyzing existing supply chain diagrams to serve as a basis for further study including Kanthicha Khotsaenlee, Prayoon Tosanguan, Chutikarn Suklim and Asae-san Kasemarn. The analyzed supply chains were presented into various supply chain diagram formats, allowing systematic analysis and comparison with the green supply chain concepts.

2. Comparative Analysis of Conventional Supply Chain and Green Supply Chain. At this stage, the researcher conducts a comparative analysis between the conventional supply chain structure and the concept of the Green Supply Chain (Green Supply Chain Management: GSCM). The analysis considers various dimensions, such as efficient resource utilization, waste reduction, minimization of environmental impacts, and value addition in the production process. The results of this analysis will be used to propose guidelines for developing and improving the supply chain system of the natural rubber industry to be more sustainable and environmentally friendly.

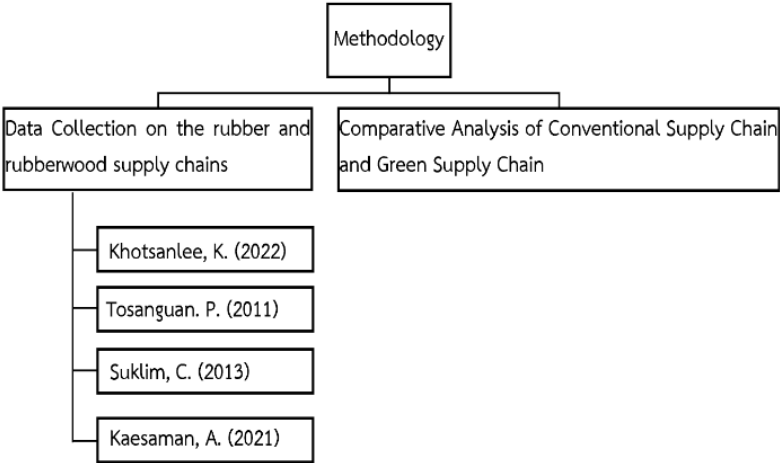


Figure 1 Methodology Map

The data collected will be analyzed to illustrate the supply chain structure of natural rubber and rubberwood production, which is divided into

- **Upstream** cultivation and maintenance, fertilizers, chemicals, and water use
- **Midstream** energy consumption, transportation, and water usage
- **Downstream** energy consumption and fuel usage

Results and Discussions

1. Rubber and Rubberwood Supply Chain

Based on the compilation of supply chain data for natural rubber and rubberwood products from various sources, along with comparative analysis (as illustrated in **Figure 1**), it was found that the supply chain of the natural rubber industry consists of three main groups: upstream, midstream, and downstream, as follows

1) Upstream Rubber farmers and primary buyers (e.g., raw latex, rubber lumps, logs, and twigs) were identified as the first stage. This sector was considered critical for ensuring quality control before products were transferred to the midstream stage. In Northern Thailand, farmers were observed to be in the early stages of industry development, although expansion was ongoing [6].

2) Midstream: Primary processing facilities (e.g., smokehouses, sawmills) and rubberwood product manufacturers were included in this stage. It was found to play a vital role in adding value to products from the upstream stage. For example, logs and twigs that were processed in FSC-COC (Forest Stewardship Council - Chain of Custody) certified sawmills into products are suitable for export [7].

3) Downstream: This stage comprised distributors and consumers at both national and international levels. Products certified by FSC were found to have increased value in international markets where sustainability is emphasized.

The comparative analysis between the conventional supply chain and the green supply chain found that the green supply chain approach played a role in reducing environmental impacts, such as the use of certified wood, waste management from production processes, and the promotion of alternative energy use. All these measures helped reduce greenhouse gas emissions and enhanced the product's image in the eyes of consumers.

In addition, environmentally friendly supply chain management aligned with the 20-Year National Strategy and the 13th National Economic and Social Development Plan, which emphasized sustainable production and consumption [8].

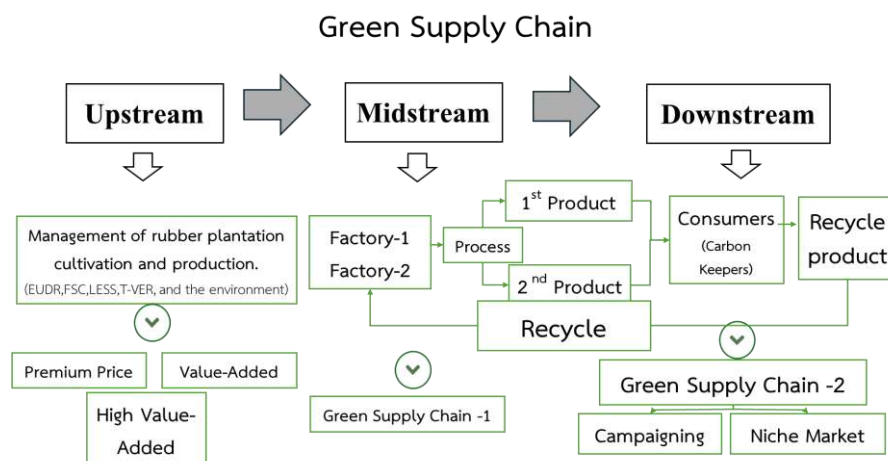


Figure 2 Rubber and Rubberwood Supply Chain

1.1 Upstream Information

Natural Rubber Cultivation

Successful rubber cultivation requires proper land preparation, planting materials, and appropriate planting methods. Determining the planting direction is important to reduce damage to rubber trees and to facilitate tapping and latex collection. Planting rows should be arranged perpendicular to the direction of water flow to minimize soil erosion and surface runoff. The rows should be at least 1.5 meters away from plantation boundaries, and each tree should have a planting area of no less than 20 square meters to prevent nutrient competition and promote proper growth. Common planting spacing in traditional rubber-growing areas includes 2.5×8 meters or 3×7 meters, while in new planting areas spacing such as 2.5×7 meters, 3×6 meters, or 3×7 meters may be used depending on soil fertility and site conditions [9].

Rubber can be cultivated using several methods, including budded stumps, budding in the field, and planting of polybag seedlings. Each method has different advantages, with polybag seedlings generally offering the highest success rate due to uniform growth and earlier tapping readiness. After planting, proper maintenance is required, such as fertilization to replace nutrients lost during latex production. Both chemical and organic fertilizers should be applied to enhance growth efficiency. Weed control is also necessary to reduce competition for nutrients and prevent the accumulation of pests and diseases [9].

Tapping is a crucial step in harvesting latex. Rubber trees are ready for tapping at around 7 years of age or when the trunk circumference reaches at least 50 cm at a height of about 150 cm above ground, with at least 70% of trees meeting the criteria. Proper tapping techniques must consider the depth and angle of the cut, as well as tapping frequency, to maintain tree health and ensure sustainable yield. Typically, half-spiral tapping is performed every other day, and tapping should not exceed 160 days per year to avoid long-term impacts on tree growth [9].

1.2 Midstream Information

The primary rubber processing industry involves transforming fresh latex into raw materials for downstream rubber product

manufacturing. Primary rubber products can be classified into five main types: ribbed smoked sheets (RSS), block rubber, crepe rubber, air-dried sheets, and concentrated latex. These are used as raw materials for finished products such as automobile tires, motorcycle tires, bicycle tires, rubber gloves, condoms, elastic bands, and industrial rubber hoses. The tire industry, in particular, relies heavily on raw rubber sheets, smoked sheets, and block rubber [9].

Raw rubber sheets are a key primary product that can be further processed into air-dried sheets or ribbed smoked sheets. Their price depends on quality, which requires cleanliness of latex, uniform thickness during rolling, and appropriate proportions of water and formic acid. Smallholder farmers often produce raw sheets themselves, while larger plantations may sell latex to processing factories. The production process includes filtering latex to remove impurities, adding formic acid to coagulate the latex, kneading and rolling it into sheets of about 3–4 mm thickness, and washing with clean water to remove residual impurities and acid. The sheets are then air-dried in the shade or dried in a kiln to prevent mold and extend shelf life [9].

Raw sheets can be further processed into ribbed smoked sheets, a widely used product in the rubber industry. The process involves cleaning, drying, and smoking at temperatures of approximately 50–60°C for 4–12 days. Afterward, impurities are removed, and the sheets are compressed into bales for easier transport and sale. Ribbed smoked sheets are an important midstream product due to their versatility as a raw material [9].

Additionally, block rubber, or Standard Thai Rubber (STR), is a key product in Thailand's rubber industry, especially STR 20, which has the highest export volume. The production process begins with raw materials such as cup lumps, rubber scraps, and raw sheets. These are cleaned, sorted, and chopped into small pieces, then dried using hot air at temperatures of about 100–120°C. The dried material is compressed into standard-sized blocks using hydraulic presses, making it suitable for storage and transportation. The final products are packaged and labeled according to international quality standards before export or distribution to rubber product manufacturers [10].

1.3 Downstream Information

Rubber Processing and Latex Industry

The downstream rubber processing industry transforms primary rubber products into finished goods for various markets. Primary rubber products—ribbed smoked sheets, block rubber, crepe rubber, air-dried sheets, and concentrated latex—serve as raw materials for manufacturing products such as automobile tires, motorcycle tires, bicycle tires, rubber gloves, condoms, elastic bands, and industrial rubber hoses. The tire industry is particularly dependent on raw sheets, smoked sheets, and block rubber [9].

Rubber products can be made from natural rubber, synthetic rubber, or blends of both. Natural rubber is used in both dry forms (e.g., sheets and blocks) and concentrated latex. Synthetic rubber is produced through polymerization of chemical precursors and is commonly used in industrialized countries due to its customizable properties, such as oil resistance, high-temperature resistance, and air retention [11].

Rubberwood Industry

The rubberwood industry is another important sector that utilizes rubber trees after they reach the end of their latex-producing life. It covers plantation management, logging of old trees, and processing into various products with economic, social, and environmental benefits. Rubberwood is widely used to produce furniture, toys, picture frames, particle board, medium-density fiberboard (MDF), and parquet flooring due to its favorable properties and low production cost [10].

Generally, rubberwood with a diameter greater than 6 inches is suitable for furniture and high-quality wood products, while smaller wood is used for MDF or particle board production. Currently, about 60% of Thailand's furniture industry relies on rubberwood as a raw material, with major export markets including Japan, the United States, and the United Kingdom [9].

Logistics System and Rubber Supply Chain

The logistics system for rubber in northern and northeastern Thailand is similar, as both are new rubber-growing regions. Farmers' products—such as raw sheets, cup

lumps, and rubber scraps—are typically sold through small local traders who collect products and pass them on to larger traders. These larger traders aggregate significant volumes and sell them to central rubber markets, particularly in Rayong Province. Prices received by farmers are usually 1–2 baht per kilogram lower than those at central markets [9].

Transportation of rubber products from northern Thailand to central markets or processing factories in the eastern region is primarily conducted by truck, passing through key provinces such as Chiang Rai, Phayao, Lampang, and Tak before reaching Rayong. Additionally, rubber is exported to China via border trade checkpoints. This logistics system plays a vital role in linking farmers' production with industrial sectors and international markets [11].

2. Comparative Analysis of Conventional Supply Chain and Green Supply Chain

From the comparative analysis between the conventional supply chain and the green supply chain, it was found that the green supply chain for rubber and rubberwood is distinguished from the conventional model by the integration of environmental standards such as FSC, T-VER, and CFP at all stages of production. This integration reduced environmental impacts and increased long-term sustainability, whereas the conventional supply chain focused on production volume and efficiency while often neglecting environmental considerations. The green supply chain also promoted local economies through the utilization of local resources and job creation, and it encouraged responsible consumption by consumers, particularly in their role as carbon keepers. Despite the constraints of higher costs and greater system complexity, the green supply chain enhanced competitiveness in the global market and served as a key mechanism for advancing Thailand's rubber industry toward sustainability in line with Net Zero targets. The details are as follows

2.1 Rubber and Rubberwood Conventional Supply Chain

Based on the supply chain structure of the FSC™ (Forest Stewardship Council) (as shown in **Figure 3**), it was found that the entire chain from upstream to downstream added both economic and environmental value, as follows:

1) Upstream: FSC-FM/COC-certified (Forest Management/Chain of Custody) farmers harvested rubber trees when latex production ceases (typically at 25–30 years of age) and separate them into logs and twigs for sale to FSC-COC-certified sawmills [12].

2) Midstream: FSC-COC-certified sawmills process logs and twigs into sawn timber and other value-added products, including sawn wood (for furniture and construction materials), rubberwood furniture (for export), wooden pallets, wood pellets for biomass energy, and woodchips and sawdust that can be further processed or used for renewable energy production.

3) Downstream: These rubberwood products are exported to international markets, particularly to countries that prioritize environmental standards, such as the European Union, Japan, and South Korea, which place high value on FSC-COC-certified products.

The application of FSC™ standards at every stage of the supply chain not only ensures transparency in sourcing from sustainable origins but also strengthens the international image of Thai products and increases access to premium markets. These findings are consistent with the “Green Supply Chain Management” concept, which emphasized environmental integration throughout the production and distribution processes. This approach reduced the environmental impacts of wood waste by reusing woodchips and sawdust for biomass energy and decreased the need for harvesting from natural forests, thereby benefiting overall the ecosystems [13].

2.2 Rubber and Rubberwood Green Supply Chain

The study of the rubber and rubberwood supply chain incorporating the green supply chain concept (as shown in **Figure 4**) revealed that environmental standards such as FSC, EUDR, and T-VER were integrated into all stages. The upstream stage was managed under FSC-FM/COC standards for sustainable rubber plantation operations, enabling the transfer of raw materials to FSC-COC-certified sawmills for processing into furniture or rubberwood products intended for export [14-15]. In the midstream stage, the circular economy concept was applied, whereby production waste was utilized as raw material for other processes, such as the production of wood pellets, in order to reduce waste and increase resource efficiency. In the downstream stage, consumer participation in post-consumer product management was promoted through activities such as recycling and product return programs, along with the provision of carbon footprint information to raise awareness of their role as a “carbon sequester.” This approach aligns with the concept of ‘Green Marketing with Engagement’ and contributes to progress toward the Net-Zero Emission goal [16]. Furthermore, the implementation of the green supply chain was found to create added value through premium pricing, brand image, and sustainable production efficiency, serving as a key strategy for enhancing the competitiveness of Thailand’s rubber industry in environmentally conscious global markets.

Sustainable Value Supply Chain of Rubber wood according to FSCTM Standard

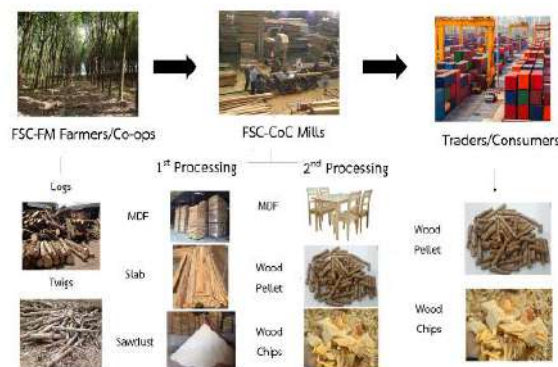


Figure 3 FSC certified Rubber and Rubberwood Supply Chain

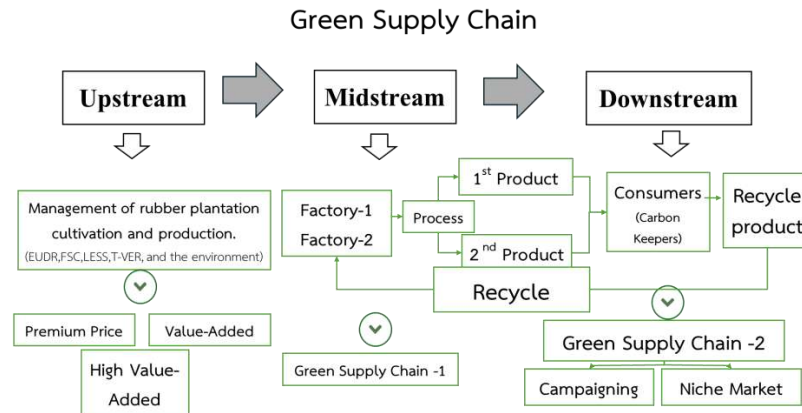


Figure 4 Rubber and Rubberwood Green Supply Chain

2.2.1 Classification of Green Supply Chain Mechanisms and Land Use in Different Rubber Plantation Models

The analysis (as shown in **Figure 5**) indicated that different types of rubber plantations are managed in ways that have varying effects on the green supply chain and land use, as follows

Conventional Rubber Plantations:

These are generally focused on yield quantity, with potential limitations in environmental management. Land use may not adequately consider biodiversity and community forests, and the potential for implementing LESS and T-VER mechanisms is often limited.

FSC-Certified Rubber Plantations:

Certification under FSC standards indicated that plantation management is conducted with environmental and social responsibility. Greater emphasis is placed on the conservation of community forests and biodiversity.

2.2.2 Linkages to Land Use, Community Forests, Biodiversity, and the Circular Local Economy

The management of rubber plantations certified under FSC and T-VER standards promotes sustainable land use, conservation of community forests, and the preservation of biodiversity, alongside the development of a circular community economy. Certified rubber plantation management is positively associated with efficient resource utilization,

local employment generation, and increased community economic value, compared to conventional rubber plantations, which may face limitations in these aspects.

Furthermore, the concept of the circular economy enables more efficient use of resources, waste reduction, and the development of value-added products. At the same time, rubber production systems also function as carbon sinks, creating opportunities for both farmers and consumers to participate as carbon stewards through mechanisms such as carbon credits.

Therefore, integrating these concepts and standards represents an important approach to enhancing the natural rubber industry in alignment with sustainable development and future greenhouse gas emission reduction goals.

2.2.3 Value Creation in Primary Processing and Environmental Impact Assessment

The analysis of the production process from natural rubber latex to primary products (latex and block rubber) indicates that the adoption of environmentally friendly technologies and production processes can significantly reduce environmental impacts. These practices also enable products to be evaluated and certified under schemes such as CFP (Carbon Footprint of Product), Eco Label, and LESS (Low Emission Support Scheme). Such certifications contribute to value creation by enhancing product sustainability and increasing market credibility.

Table 1 Comparison between the conventional supply chain and the green supply chain

	Supply Chain	Green Supply Chain
Upstream	<i>Hevea brasiliensis</i> cultivation Is reported to generate greenhouse gas emissions of up to 6.4 tCO ₂ e	The “Kaset Sanjorn” platform suggests that replacing chemical fertilizers with organic or bio-compost fertilizers can reduce nitrous oxide (N ₂ O) emissions by 30–50%.
	Use of chemicals (e.g., ammonium) results in emissions of approximately 35.90 kgCO ₂ e.	The United Nations Environment Program states that using biological alternatives (e.g., microbial pest control) can reduce greenhouse gas emissions by 5–20%, or about 0.1–0.5 tCO ₂ e per rai per year.
Midstream	Energy consumption results in emissions of 80.92 tCO ₂ e.	The Thailand Environment Institute notes that coal-based electricity emits approximately 0.9 kg CO ₂ per kWh, suggesting that reducing coal-based energy use can significantly lower emissions.
	Fuel consumption is about 0.033 gha per ton.	According to Bangkok Bank (2024), switching to electric vehicles for transportation can reduce energy and maintenance costs by 69.87%.
	Water usage is about 0.028 gha per ton.	The United Nations Environment Program indicates that using sensors and irrigation planning can reduce water usage by 20–40% and decrease greenhouse gas emissions by 0.2–0.7 tCO ₂ e per rai per year.
Downstream	Electricity consumption results in emissions of 51.82 kgCO ₂ e.	The Thailand Environment Institute reports that reducing coal-based electricity use can lower emissions by approximately 0.9 kg CO ₂ per kWh.
	Transportation fuel use generates about 1.08 kgCO ₂ e.	According to Bangkok Bank (2024), adopting electric vehicles can reduce energy and maintenance costs by 69.87%

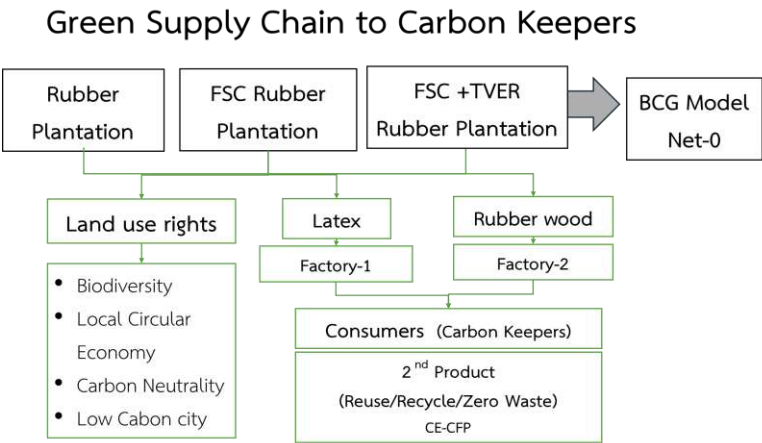


Figure 5 Land Use in Rubber and Rubberwood Green Supply chain

2.2.4 Advancement to Secondary Products and the Role of Consumers as Carbon Stewards

The development of primary products into secondary products, such as biofuels and recycled products (CE-CFP: Circular Economy–Carbon Footprint of Product), promotes circular economy principles and

reduces waste generation. Utilizing production residues or by-products for biofuel production or recycling represents an important approach to improving resource efficiency, minimizing industrial waste, and adding value to leftover materials within the rubber industry system.

At the same time, communicating and raising consumer awareness about the role of

rubber products in carbon sequestration, along with promoting environmentally friendly consumption, can enhance consumer participation in the green supply chain. Consumers can thus play a role as “carbon stewards” by supporting sustainable products and contributing to a more environmentally responsible supply chain.

2.2.5 Barriers and Practical Challenges

The implementation of EUDR and FSC measures in supply chain management requires significant business adaptation, while also creating new opportunities for organizations. On the opportunity side, these measures enhance product credibility, particularly in European markets where environmental concerns are taken seriously. Products that can demonstrate they are not associated with deforestation [17] or that have verifiable and compliant sourcing are more likely to gain market access. They can also command higher value, as many consumers are willing to pay a premium for environmentally friendly products. In addition, compliance with these standards improves traceability systems, enabling organizations to clearly identify the origin of raw materials. This reduces legal risks and increases transparency in management, while also strengthening the organization's image as a responsible and forward-looking business aligned with global trends.

However, several challenges arise in implementing these measures. One of the main issues is increased costs, including FSC certification fees, investments in traceability systems, and adjustments to production processes to comply with EUDR requirements. These costs can be particularly burdensome for small and medium-sized enterprises. Furthermore, EUDR imposes strict requirements, such as detailed identification of raw material sources, including geographic coordinates, making data collection and verification more complex. Supplier-related issues also present significant challenges [18], as organizations may need to change suppliers or invest in supplier development if partners are unable to meet the required standards. This process requires additional time and resources. Moreover, the level of understanding among

organizational personnel is critical; insufficient knowledge of these measures may lead to inefficiencies and difficulties in implementation.

Conclusions

The analysis of the supply chain for natural rubber and rubberwood products shows that it can be classified into three main stages: upstream, midstream, and downstream. Each stage involves different activities related to resource use and greenhouse gas emissions.

At the upstream level, rubber cultivation and plantation maintenance—through the use of chemical fertilizers, water, and agrochemicals—contribute significantly to greenhouse gas emissions. For example, emissions from the cultivation of *Hevea brasiliensis* can reach up to 6.4 tCO₂e, while the use of ammonium-based chemicals can generate approximately 35.90 kgCO₂e. However, the Green Supply Chain approach can mitigate these impacts by promoting the use of organic or bio-compost fertilizers, which can reduce nitrous oxide emissions by 30–50%. In addition, the use of biological products, such as microbial pest control agents, can reduce greenhouse gas emissions by 5–20%, or approximately 0.1–0.5 tCO₂e per rai per year.

At the midstream level, processing activities such as drying and thermal energy use are highly energy-intensive, generating emissions of approximately 80.92 tCO₂e. Fuel consumption in transportation and production processes averages about 0.033 gha per ton, while water usage is around 0.028 gha per ton. The Green Supply Chain approach emphasizes the adoption of clean and renewable energy sources, such as reducing reliance on coal-based electricity, which emits approximately 0.9 kgCO₂e per kWh. It also promotes the transition to electric vehicles for transportation, which can reduce energy and maintenance costs by up to 69.87%, as well as the use of sensor technologies and efficient water management planning, which can reduce water consumption by 20–40% and lower greenhouse gas emissions by approximately 0.2–0.7 tCO₂e per rai per year.

At the downstream level, electricity and fuel consumption in transportation and

distribution remain key sources of greenhouse gas emissions, with emissions from electricity use at approximately 51.82 kgCO₂e and from transportation at around 1.08 kgCO₂e. Nevertheless, the Green Supply Chain approach can reduce these impacts through the use of clean energy, improved logistics efficiency, and the promotion of electric vehicles.

Furthermore, the integration of circular economy concepts, including the development of primary products into secondary products such as biofuels and recycled materials, as well as the involvement of consumers as “carbon stewards” through the selection of environmentally friendly products, represents an important mechanism for reducing greenhouse gas emissions and promoting the long-term sustainability of the natural rubber supply chain.

Acknowledgements

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Enhancing Value of Natural Waste by Converting It into Air-Filtration Media

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Abstract

This study investigates the properties and optimal conditions of air filter sheets and evaluates the air filtration efficiency of filter media produced from waste pineapple and bamboo leaves. The air filter sheets are fabricated from natural agricultural waste materials, specifically pineapple leaf fibres and bamboo fibres. Fabrication involved fibre quantities of 100, 200, and 300 grams combined with binder concentrations ranging from 5% to 20% by weight. The physical properties of the air filter sheets demonstrated favourable surface characteristics, including smooth texture, uniform colouration, and structurally intact fibres without evidence of tearing. Morphological analysis showed that the fibres were longitudinally aligned, densely packed, and mechanically robust. Comparative physical assessments indicated that pineapple leaf fibre exhibited lower water absorption and moisture retention than bamboo fibre, contributing to a higher dust removal efficiency of up to 70%, compared to 50% for bamboo-based filters. Despite these advantages, long-term use revealed challenges, including increased moisture accumulation and increased susceptibility to microbial growth. These findings suggest that pineapple leaf fibre is a promising biodegradable material for air filtration applications; however, further optimisation is necessary to enhance moisture resistance and incorporate antimicrobial functionality for sustained performance.

Keywords : air filter; natural waste materials; particulate matter; pineapple leaf; bamboo leaf

Introduction

Indoor air pollution is a significant environmental and public health issue, as modern lifestyles result in individuals spending over 90% of their time in enclosed environments such as homes, schools, offices, hospitals, and other public buildings [1]. Exposure to indoor air pollutants including fine particulate matter (PM_{2.5} and PM₁₀), carbon monoxide (CO), ozone (O₃), black carbon

(BC), sulfur dioxide (SO₂), and nitrogen oxides (NO_x) is strongly associated with various health problems [2]. These include respiratory and cardiovascular diseases, as well as Sick Building Syndrome (SBS) and Building-Related Illnesses (BRI), which present with symptoms such as headaches, fatigue, nausea, and allergic reactions [2, 3]. Indoor air contaminants originate from both external and internal sources. Pollutants may enter buildings through ventilation systems or arise internally

due to poor air circulation, accumulation of dust mites, chemical emissions from furnishings and paint, excessive humidity, and microbial growth on damp surfaces [2, 3]. The increasing prevalence and persistence of these pollutants underscores the urgent need for effective air filtration technologies to maintain indoor air quality and reduce adverse health effects.

Air filtration systems are widely employed to control indoor air pollution. Air filters function primarily through two mechanisms: mechanical filtration, which uses fibrous porous media to physically capture particles as air passes through, and chemical filtration, which relies on adsorption and chemisorption to remove gaseous pollutants, typically at the submicron scale ($<0.01\ \mu\text{m}$). The efficiency of chemical filtration depends on factors such as air velocity (residence time), temperature, and humidity [2]. High-efficiency filtration systems, including High-Efficiency Particulate Air (HEPA) and Ultra-Low Penetration Air (ULPA) filters, are recognized for removing up to 99.97% of airborne particles. However, these systems predominantly use synthetic polymer-based materials, leading to high production costs and environmental concerns regarding disposal. As a result, there is increasing interest in developing sustainable, biodegradable alternatives for air filter fabrication [4].

Agricultural residues represent a promising and renewable resource for air filtration applications. In Thailand, the cultivation of export-oriented crops generates substantial volumes of underutilized biomass. For example, approximately 2.7 million tons of pineapple leaf waste are produced annually [5]. The commercial bamboo industry similarly yields over 3.4 million tons of harvested biomass each year, with processing waste comprising up to 50-60% of the total, resulting in significant quantities of discarded leaf residue [6]. These materials are often burned in open fields, which contributes to external $\text{PM}_{2.5}$ pollution, yet they possess favorable structural properties for filtration. Pineapple leaf fiber offers high tensile strength and a rich cellulose network [7, 8], while bamboo leaves provide biogenic silica and structural flexibility [9, 10].

Lignocellulosic biomass, including pineapple and bamboo leaves, has attracted considerable attention due to its high cellulose content, biodegradability, and advantageous structural properties. Pineapple leaf fibers exhibit high tensile strength and cellulose content, while bamboo-derived fibers provide flexibility, porosity, and mechanical robustness, making them suitable for filtration applications. These materials present a promising approach for developing eco-friendly filtration media with reduced environmental impact.

Recent advances in air filtration research have focused on cellulose-based and biopolymer materials, particularly nanocellulose, due to their high surface area, tunable porosity, and renewable characteristics. Nanocellulose-based aerogels and membranes have demonstrated excellent filtration performance for both particulate matter and gaseous pollutants, with studies indicating their potential to compete with synthetic nanofiber filters [11, 12]. Regenerated and nanostructured cellulose filters have been fabricated to achieve high filtration efficiency through hierarchical pore structures and optimized fiber networks [13]. Recent studies on nanocellulose-reinforced air filters have demonstrated enhanced mechanical strength and antibacterial efficiency of up to 99.9%, suggesting potential for multifunctional filtration systems [14]. Additionally, microfibrillated cellulose-based composite filters incorporating antimicrobial agents have achieved filtration efficiencies exceeding 99.99% while providing antibacterial functionality [15].

Despite these advancements, several critical limitations persist. Many cellulose-based filters are highly hydrophilic, resulting in moisture absorption, structural instability, and reduced filtration efficiency under humid conditions. This issue is especially pronounced in tropical climates, where high relative humidity accelerates material degradation and compromises filter performance. Recent research has sought to address this challenge by developing composite biodegradable filters with improved humidity resistance and extended service life; however, issues related to long-term durability and consistent performance remain [16].

Although some advanced filtration materials incorporate antimicrobial functionality, most conventional and bio-based filters do not effectively inhibit microbial growth, which can result in secondary contamination risks. Recent studies have explored multifunctional designs that integrate antibacterial nanoparticles and functional coatings; however, these approaches often require complex fabrication processes or compromise biodegradability [14, 15].

Recent studies from 2023 to 2025 have shown that natural cellulose and biopolymer networks can achieve particulate capture efficiencies comparable to those of synthetic media [17, 18]. However, a significant research gap remains in their practical application: conventional biodegradable filters are highly hydrophilic. In high-humidity environments, this characteristic leads to structural degradation, increased pressure drops, and substantial losses in filtration efficiency [19]. Additionally, retained moisture and trapped organic matter can promote bacterial and fungal growth, posing secondary health risks [20]. Addressing these limitations requires the development of biodegradable filters that are moisture-resistant and possess additional functional properties.

The present study focuses on the development and optimization of advanced air filter media derived from waste pineapple and bamboo leaves. The specific objectives are to (1) investigate the physical and structural properties of these combined natural fibers, (2) determine the optimal conditions for producing air filter sheets, including the selection and concentration of binders to impart moisture resistance, and (3) evaluate the filtration performance of the fabricated media.

Methodology

Air Filter Sheet Production Method

The process for producing air filter sheets from pineapple or bamboo leaf fiber involves the following steps as shown in **Figure 1**: (1) Preparation of Raw Material: Discarded pineapple (PN) or bamboo (BN) leaves obtained from agricultural waste are cut into small, uniformly sized pieces as required. (2) Alkaline Treatment: The leaves are boiled in 2.5 liters of water mixed with sodium

hydroxide at a ratio of 1:10 for 3 hours. (3) Oxidizing Treatment: The boiling process is repeated with 35% hydrogen peroxide solution (H_2O_2) for 1 hours to further bleach and refine the fibers. (4) Washing: The liquid is filtered out, and the fibers are thoroughly rinsed with clean water to remove any residual chemicals. (5) Blending with Binder: The fibers are mixed with a starch-based adhesive in varying proportions of 5%, 10%, 15%, and 20% relative to the dry weight of the fiber at 100, 200, and 300 grams, respectively. These formulation parameters were systematically investigated to evaluate their effects on the permeability characteristics. (6) Sheet Formation: The fiber pulp is evenly spread onto a mesh screen with size 20*30 cm. to form a uniform layer. (7) Drying and Finishing: The formed sheet is allowed to dry at 60°C for 12 hours before being carefully removed from the mesh screen.

The sheet-forming process was rigorously standardised to achieve uniformity, consistent quality, and reproducible thickness in the air filter media. Rather than relying solely on post-fabrication thickness measurements, quality control was implemented by regulating the screening depth. For each sample, a fixed volume and concentration of the fiber-binder suspension were applied to the forming mold. This approach ensured a uniform basis weight and consistent distribution of the fibrous network across all sheets.

Characteristics and performances

1. Physical Characterization: Water Absorption Capacity and Moisture Content Analysis were evaluated in accordance with ASTM D3285 standard [21] and ASTM D6304 standard [22], respectively.

2. Morphological and Functional Analysis: Morphological characterisation of fibres was conducted using scanning electron microscopy (SEM). Regarding Filtration Performance Evaluation, the filtration efficiency of the developed filter media was evaluated using a laboratory-scale air filtration test system under controlled environmental conditions as illustrated in **Figure 2**. Aerosol particles were

generated and introduced into a continuous airflow stream passing through the test filter media. Talc-based baby powder was used as the particulate matter source, with a typical particle size range of 1-10 μm , representing total particulate matter (PM_{10}) [23]. This size range is widely recognized as relevant for studies of indoor air quality, aerosol exposure, and filtration performance, as such particles can penetrate the human respiratory system and are commonly encountered in indoor environments [23]

Airborne particle concentration was determined following the NIOSH Method 0500 (Particulates Not Otherwise Regulated, Total) [24]. This gravimetric method provides a reliable measurement of total suspended particulate concentration and is widely used in occupational and environmental exposure assessments [24].

Upstream (C_{in}) and downstream (C_{out}) particle concentrations were measured to evaluate filtration performance. Filtration efficiency ($\eta\%$) was calculated using the following equation:

$$\eta\% = \left(\frac{C_{in} - C_{out}}{C_{in}} \right) \times 100$$

where:

C_{in} = upstream particle concentration (mg/m^3),

C_{out} = downstream particle concentration (mg/m^3).

3. Application Testing: Operational performance tests involved replacing the commercial air filter in an air purifier fan with the fabricated air filtration media. The device was operated for 8 hours per day at 25-32°C over 5 days to assess the usability and effectiveness of the developed air filter sheets.

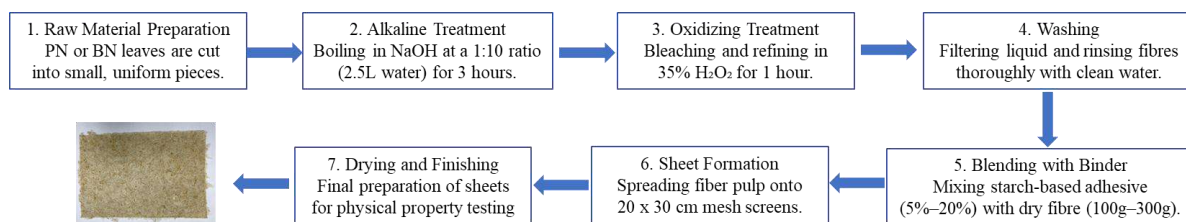


Figure 1 Schematic of the fabrication of air filter sheet process

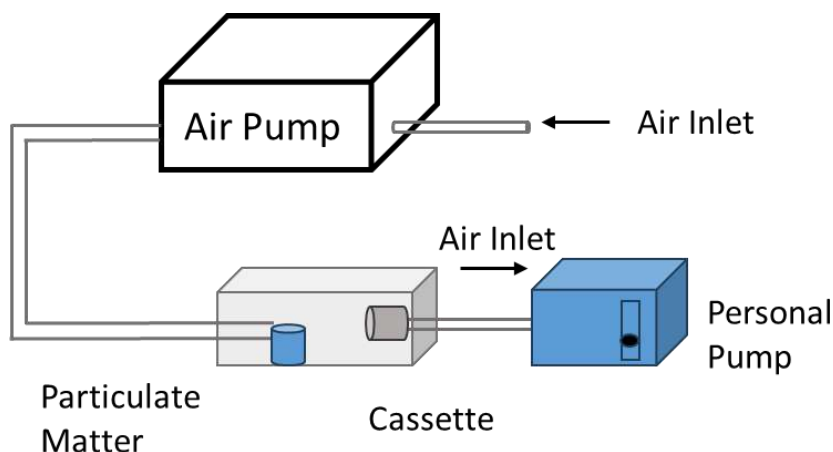


Figure 2 Schematic of Filtration Experimental

Results and Discussions

Morphological Characteristics of PN and BN Filter Media

The air filter sheet characteristic must demonstrate cohesive structure, resistance to tearing, and uniform thickness throughout. According to the specified criteria [25], the filter sheets should be free from perforations, tears, visible contaminants, or mold. Additionally, they must exhibit a clean and consistent surface, without smudging, peeling, flaking, or irregular coloration. As shown in Figure 3, the air filter sheets fabricated from pineapple and bamboo leaf fibers meet these quality standards. The surfaces were free of visible defects, including tears, contaminants, and discoloration. The sheets also demonstrated a smooth texture and consistent coloration, with no signs of surface irregularities. The results of this study demonstrate that natural fibers derived from agricultural waste, specifically those from pineapple and bamboo leaves, can be effectively utilized to produce air filter sheets that meet essential quality standards. The physical evaluation of the filter sheets revealed satisfactory performance across all samples, with particular attention to criteria such as surface cohesion, resistance to tearing, uniform thickness, and overall aesthetic integrity. These characteristics are critical for maintaining mechanical filtration efficiency and ensuring durability during use. Notably, the preparation method had a significant influence on the visual and structural properties of the filter sheets. This finding supports previous literature [2, 25, 26], which attributes such effects to the oxidative bleaching action of H_2O_2 on plant-based fibers. The bleaching not only improves the aesthetic quality of the material but may also enhance fiber porosity and cleanliness, which are favorable attributes in air filtration applications.

Furthermore, the physical appearance of the filter sheets remained consistent or improved with increasing fiber content. Samples prepared with 200 and 300 g of fiber exhibited consistently high overall quality, indicating that higher fiber loading did not adversely affect structural integrity. The evaluation was conducted according to community product standard criteria for air filter sheets [25], in which qualitative ratings such as “good” and “fair” are assigned based on visual and structural attributes,

including surface uniformity, fiber distribution, bonding integrity, and pattern consistency. A “good” rating generally reflects a uniform surface with well-distributed fibers, minimal defects, and satisfactory structural cohesion, whereas a “fair” rating indicates moderate uniformity with some irregularities in fiber arrangement, visible defects, or less consistent pattern formation.

These findings suggest that the manufacturing process is robust and scalable for producing thicker or denser filter media suitable for higher filtration demands. However, although the PN sample at 100 g was rated as “good” in overall appearance, it received only a “fair” rating in pattern quality. This discrepancy implies that lower fiber content may limit the formation of a well-defined and homogeneous fibrous network during sheet formation, resulting in uneven pore distribution. Such structural inconsistency could negatively affect filtration performance by creating preferential flow paths. Therefore, optimizing fiber concentration is critical not only for maintaining mechanical integrity but also for achieving uniform pattern formation and consistent pore structure, which are essential for effective filtration.

Air filter sheets fabricated using the PN method with 5% binder and varying fibre content exhibited continuous, elongated, and rounded fibres. These fibres were unfragmented and formed overlapping clusters, with binder distributed between them. When fibre content was held constant, and binder ratios varied, the fibres consistently formed overlapping clusters with a continuous and rounded structure, and the binder remained present between fibres [2]. The macroscopic appearance of bamboo leaf (BN) filter sheets remained highly uniform and consistent across all tested binder concentrations (5–20 wt%). This visual stability is attributed to the geometric and structural properties of the processed bamboo biomass. Milling and blending bamboo leaves into short, micro-fibre particles resulted in a highly homogeneous dispersion within the aqueous suspension. In contrast to long, flexible fibres that tend to entangle and form visible macroscopic clumps at higher binder concentrations, the short and relatively rigid bamboo fibres maintained an even distribution. As a result, the binder uniformly coated the pre-dispersed fibre matrix without causing large-scale

structural deformation. Although increasing the binder content significantly altered the internal micro-porosity and airflow resistance, the external macroscopic uniformity of the BN sheets was preserved.

Scanning electron microscopy (SEM) is frequently employed to examine fibre surface morphology, as shown in Figures 4-6. Figure 4 presents the morphology of air filter sheets fabricated with 300 grams of fibre at 500x magnification. Both fibre types exhibited continuous, elongated, and rounded structures

without signs of fragmentation, forming overlapping clusters with binder distributed throughout the fibre network [9, 27]. Notably, BN fibres appeared more densely packed than those produced by the PN method. Pineapple leaf fibers exhibited a long and slender morphology, as seen in **Figure 5**. The fiber morphology remained consistent regardless of the extraction method. At a magnification of 2,500× (**Figure 5**), the surface texture appeared distinctly rough and irregular. Densely packed fibrils were visible compared to those in **Figure 6**.

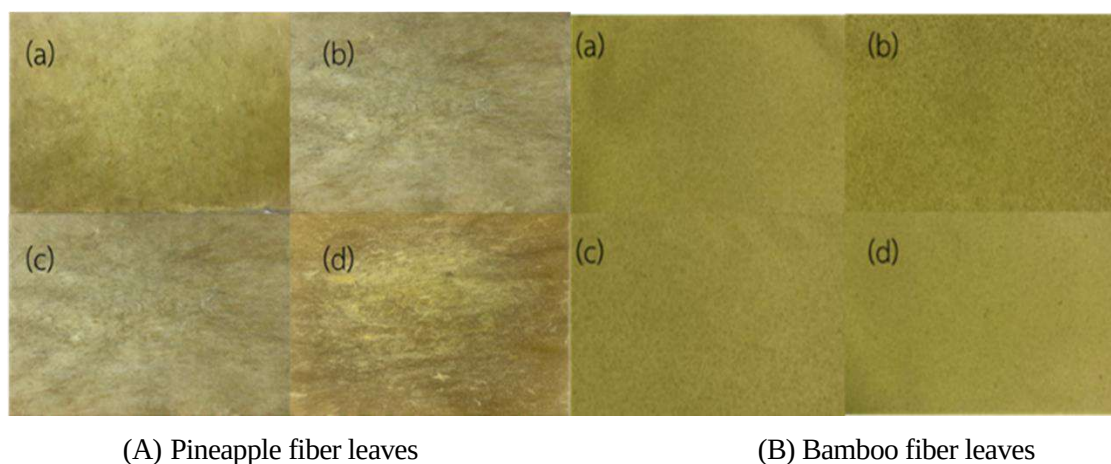


Figure 3 The surface characteristic of air filters fabricated from 300 g of (A) Pineapple and (B) Bamboo leaves at a function of binder concentration of (a) 5%, (b) 10%, (c) 15% and (d) 20%

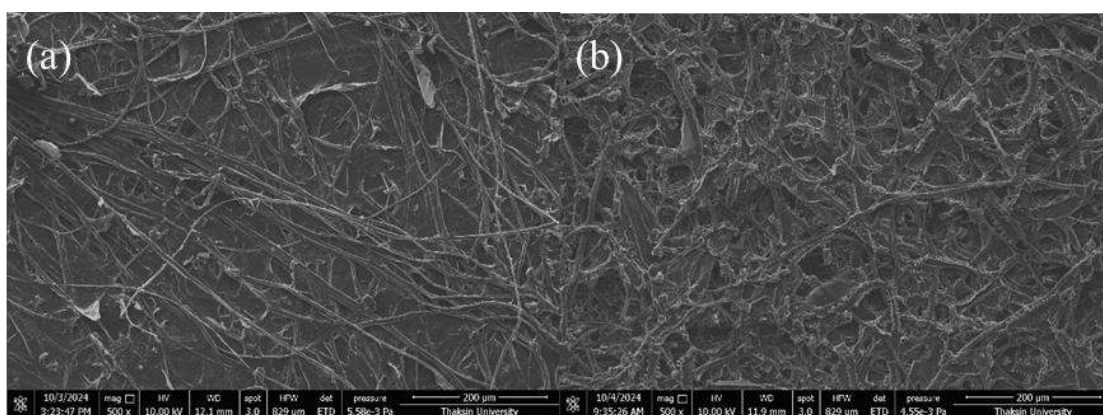


Figure 4 SEM image of the surface of air filter sheets fabricated from 300 g mixed with 20% binder at magnification of 500x of (a) Pineapple fiber and (b) Bamboo fiber

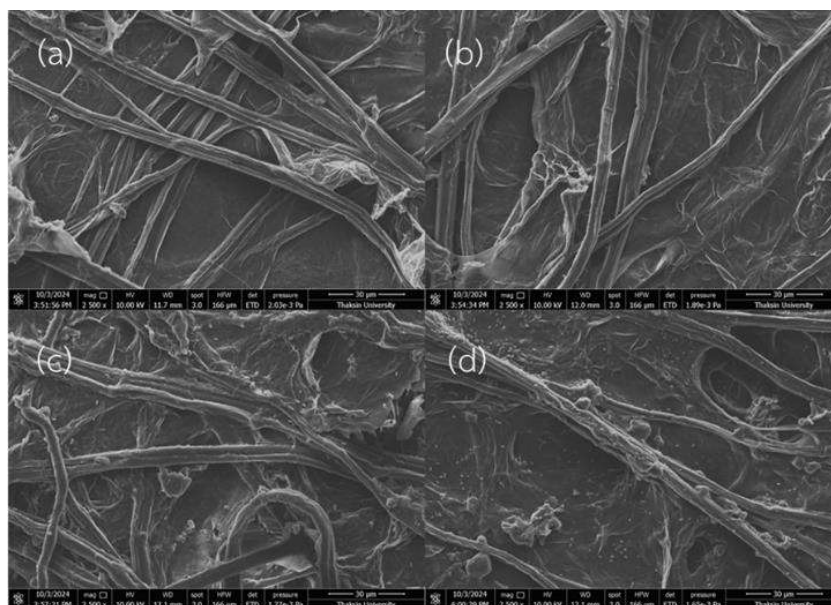


Figure 5 SEM image at magnification of 2,500x of the surface of Pineapple air filter sheets fabricated from 300 g at a function of binder concentration of (a) 5%, (b) 10%, (c) 15% and (d) 20%

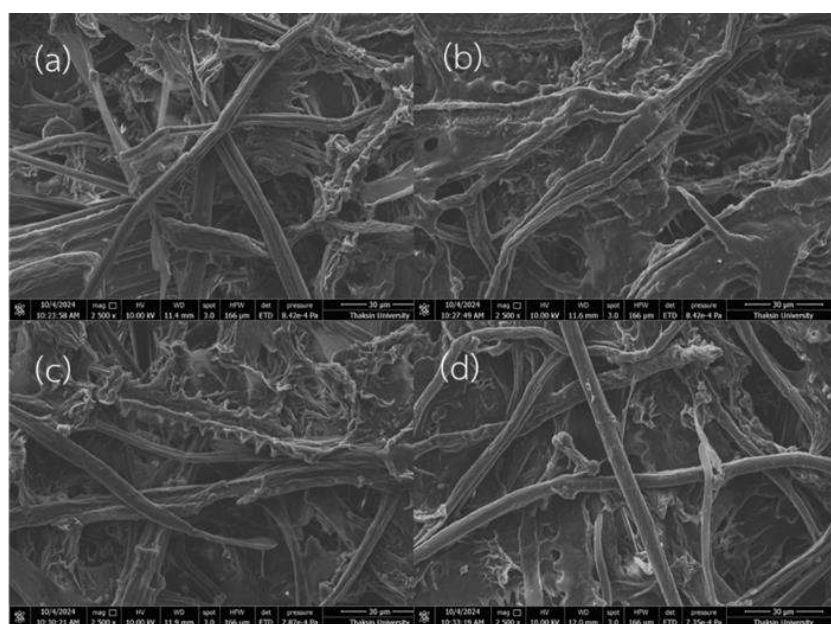


Figure 6 SEM image at magnification of 2,500x of the surface of Bamboo air filter sheets fabricated from 300 g at a function of binder concentration of (a) 5%, (b) 10%, (c) 15% and (d) 20%

Scanning electron microscopy (SEM) observations of pineapple leaf (PN) and bamboo leaf (BN) waste fibres indicate that binder concentration (5-20 wt%) controls the development of fibre network architecture, which in turn determines bulk properties and filtration performance. At a low binder content of 5%, the loosely arranged fibrous network with large inter-

fibre voids results in high porosity and airflow permeability. However, limited fibre contact at this level reduces mechanical integrity and increases moisture uptake through open, hydrophilic pathways [28]. Increasing the binder concentration to 10-15% promotes the formation of bridging structures and thin film-like coatings, which enhance inter-fibre adhesion and create

a more integrated network. This modification reduces pore size while maintaining sufficient connectivity for airflow. The resulting intermediate structure achieves an optimal balance between permeability and particle capture, as rough fibre surfaces, particularly the more fibrillated PN fibres, improve mechanical interception, diffusion, and adhesion mechanisms. At 20% binder, excessive coating and pore filling produce a dense, compact matrix with restricted pore connectivity, which reduces permeability and increases pressure drop, despite potentially higher particle retention [29]. Compared to PN fibres, BN fibres form a more densely packed, channel-like structure due to their rigid morphology, resulting in more stable airflow pathways and enhanced mechanical strength. In contrast, PN fibres are more sensitive to binder-induced densification, leading to greater reductions in porosity and water absorption. These structure–property–performance relationships are consistent with recent studies that emphasize the importance of binder-induced pore evolution and surface modification in natural fibre-based filtration media. Optimal performance is achieved by balancing pore accessibility, surface functionality, and network integrity [28–31].

With respect to water absorption according to binder ratios, the structural evolution observed via SEM directly explains the experimentally observed decline in water absorption with increasing binder ratios. Fundamentally, the high moisture uptake at lower binder concentrations (5 wt%) is driven by the inherent biochemical structure of the lignocellulosic fibers. Cellulose macromolecules possess abundant equatorial hydroxyl (-OH) groups, rendering the uncoated fiber surfaces highly hydrophilic and prone to hydrogen bonding with water molecules. As the binder concentration is incrementally increased to 20 wt%, the polymeric binder forms a continuous film that physically encapsulates the fiber network. This binder coverage acts via a dual mechanism: chemically, it masks the exposed hydrophilic hydroxyl sites on the cellulose surface, preventing direct moisture interactions; physically, it fills the inter-fiber voids, effectively blocking the capillary pathways that would otherwise facilitate bulk water ingress [28]. While fundamental micro-chemical analyses

(such as FTIR or contact-angle goniometry) are often used to quantify these specific surface energy changes, the macroscopic bulk water absorption data obtained in this study provides robust functional evidence of this encapsulation effect. The profound reduction in bulk water uptake at higher binder loadings confirms that the binder successfully neutralizes the inherent hydrophilicity of the cellulose network

Filtration Performance Evaluation

Figures 7 and 8 demonstrate the water absorption and moisture content of air filter sheets fabricated using the PN and BN methods with varying fibre quantities (100, 200, and 300 grams) and binder concentrations (5% to 20%). The results demonstrate a consistent decreasing trend in both water absorption and moisture content as binder concentration increased. Regarding air filter sheets produced using the PN method, initial water absorption levels at a 5% binder ratio were approximately 66.97%, 66.85%, and 62.40% for fiber weights of 100, 200, and 300 grams, respectively. As the binder ratio increased to 20%, water absorption correspondingly declined to 62.40%, 56.23%, and 44.75%. This reduction can be attributed to increased binder coating on fibre surfaces, which blocks hydrophilic sites and reduces pore accessibility, thereby decreasing the material's capacity to retain water, thereby limiting water penetration and retention. Similar trends have been reported in recent studies on natural fibre–biopolymer composites, where increased polymer or crosslinking density reduces porosity and restricts moisture uptake [14, 29, 31]. The denser fibre-binder matrix likely restricted the availability of hydrophilic sites on the fibres, thereby minimizing capillary action. This trend was similarly observed in sheets prepared with the BN method, although the overall water absorption levels were slightly higher than those of the PN samples across all binder ratios and fibre quantities.

The superior performance of PN filter sheets in terms of lower moisture retention can be explained by the intrinsic properties of pineapple leaf fibres. These fibres are less hygroscopic and possess a denser microstructure compared to bamboo fibres, which tend to exhibit higher porosity and greater moisture affinity [2, 8, 10].

This characteristic is crucial in air filtration applications, where excessive moisture can not only impair filtration efficiency but also facilitate the growth of microorganisms. The lowest water absorption and moisture content were observed in the PN300/20% sample. This suggests that this formulation is optimal for minimizing water retention. Minimizing water retention benefits filter durability and performance. High moisture content can reduce airflow, promote clogging, and degrade filter materials over time.

Particulate Matter Removal Efficiency

Figure 9 illustrates that particulate matter (PM) removal efficiency positively correlates with binder concentration for both PN and BN filter media. PN filters consistently demonstrated superior filtration performance, increasing from approximately 60% at 5 wt% binder to a peak of 70% at 20 wt%. However, BN filters exhibited significantly lower capture efficiencies, ranging from 42% to 52% across the same binder loadings.

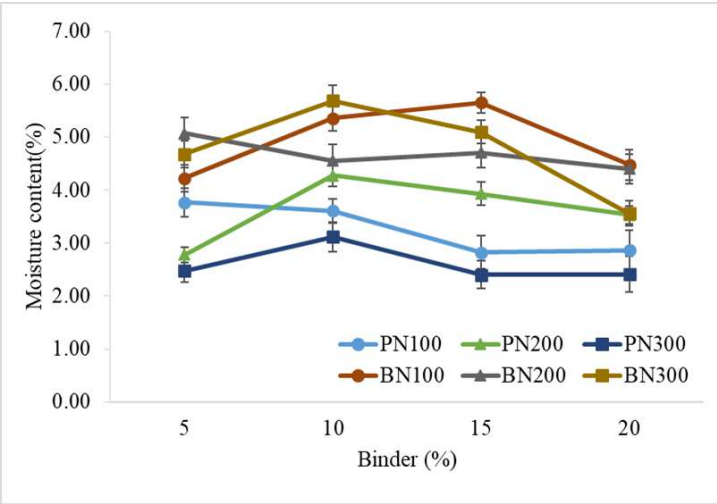


Figure 7 The water absorption of PN and BN air filter as a function binder concentration

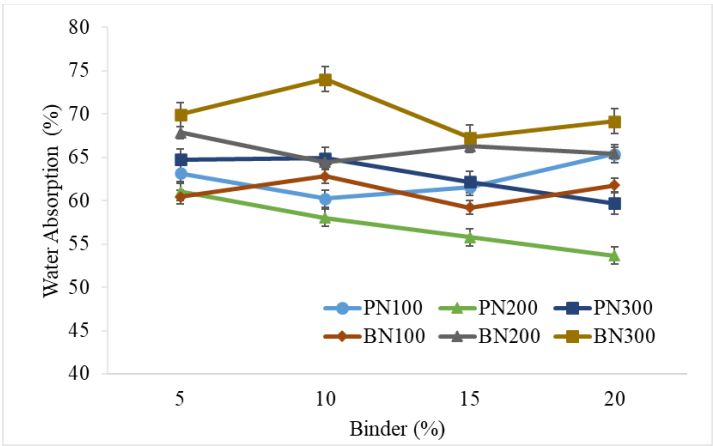


Figure 8 The moisture content of air filter sheets from PN and BN as a function binder concentration

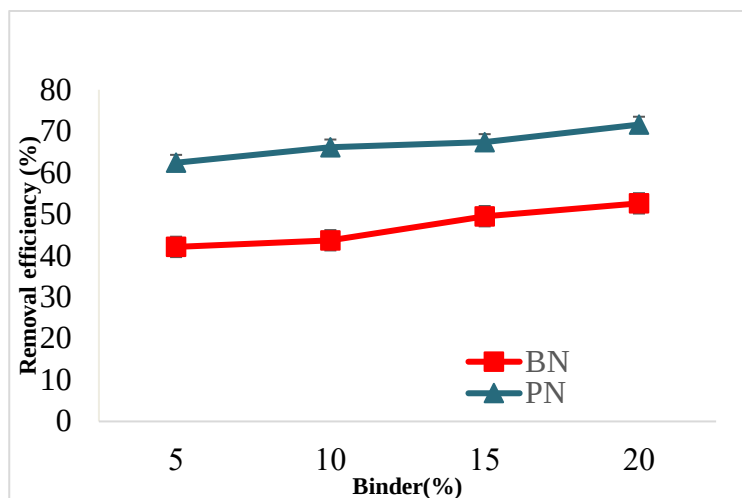


Figure 9 The particulate matter removal efficiency of air filters fabricated using 300 gram of Pineapple fiber and Bamboo fiber

The progressive improvement in efficiency at higher binder concentrations is attributed to microstructural densification. As the binder bridges inter-fibre gaps, effective pore diameters decrease, thereby enhancing PM capture via mechanical interception and inertial impaction [29]. Furthermore, the marked performance disparity between the two materials stems from their inherent fibre morphologies. The highly fibrillated, flexible nature of PN creates a dense, tortuous network that maximizes surface area and effectively traps fine particulates [14]. Conversely, the inherently rigid, tubular structure of BN forms a more ordered, channel-like architecture [30]. While this ordered structure likely improves airflow permeability, it provides fewer physical obstacles for traversing particles, resulting in higher aerosol bypass and lower overall capture efficiency.

To elucidate the observed filtration performance, a simplified mechanism is proposed that considers the combined effects of mechanical sieving, interception, and adhesion within the fibrous matrix. At low binder content (5%), the filter exhibits large pore sizes and weak fibre–fibre interactions, allowing fine particles to traverse the open network and diminishing the efficacy of mechanical sieving. As binder content increases to 10-15%, enhanced fibre cohesion leads to smaller pores and a more interconnected

network, thereby improving particle capture through interception as particles following airflow trajectories encounter fibre surfaces. The intrinsic surface roughness and molecular structure of lignocellulosic fibres further facilitate adhesion, enabling particles to attach via van der Waals forces. The binder amplifies this effect by increasing the number of fibre contact points and stabilising the overall structure. At high binder content (20%), excessive densification and pore blockage enhance particle capture by sieving, but also restrict airflow and elevate pressure drop. Thus, filtration performance is determined by the interplay between structural characteristics and capture mechanisms, with optimal results achieved at intermediate binder levels where a balance between pore structure and fibre bonding is maintained. These findings align with recent studies emphasising the significance of microstructure and surface properties in natural fibre-based filtration systems [30-31].

Application of air filter media

In the long-term application test, microbial growth was observed on the surface of the filter media after extended use, highlighting a potential limitation for practical deployment. The exposure conditions during this test were typical of a tropical environment, with ambient temperatures of approximately 25-32 °C and relative humidity in the range of 70-85%, under natural airflow

without controlled ventilation. Post-exposure evaluations revealed an increase in moisture content relative to the initial state. The presence of microbial contamination was identified through visual observations, including surface discoloration, spot formation, and localized colony-like growth on the filter sheets. Although specific microbial species were not characterized in this study, these findings suggest that the lignocellulosic nature of the fibers, combined with high humidity conditions, can promote microbial colonization over time [28, 31]. To enhance the durability and hygienic performance of the developed filter media, the incorporation of antimicrobial agents such as chitosan, silver nanoparticles, or plant-derived essential oils is recommended. These additives have been widely reported to inhibit microbial growth and improve the functional performance of natural fiber-based materials [14, 29].

These findings highlight the potential of pineapple leaf fiber as a promising candidate for sustainable air filter production, particularly when paired with optimized binder concentrations. However, improvements in moisture resistance and the incorporation of antimicrobial agents are recommended for enhancing long-term performance under ambient environmental conditions.

Conclusions

This study establishes the fundamental structure-property relationships of agricultural waste-derived lignocellulosic fibers for use in sustainable air filtration media. By shifting away from synthetic polymers, we demonstrated that the intrinsic morphological and chemical properties of natural fibers dictate their functional aerodynamic performance. Specifically, pineapple leaf (PN) fiber demonstrated superior mechanical integrity and particulate filtration performance, a result directly driven by its highly fibrillated, denser network architecture and inherently lower hygroscopicity. Conversely, while bamboo leaf (BN) fiber exhibited higher structural flexibility and uniform binder dispersion, its greater moisture sensitivity and rigid, tubular morphology limited its overall filtration efficacy. Despite these promising structural capabilities, extended operational evaluations

highlighted the inherent vulnerabilities of untreated cellulosic matrices, namely moisture accumulation and subsequent microbial proliferation. Therefore, while this study validates the strong baseline potential of pineapple leaf fibers, future development must address these biological and environmental limitations prior to real-world deployment. Subsequent research directions should focus on engineering hybrid fiber composites to balance permeability and strength, as well as integrating targeted surface hydrophobization and active antimicrobial modifications to ensure long-term operational durability and safety.

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Systemic Value of Functional Based Clusters and Strategic Environmental Assessment Framework in Integrated River Basin Master Planning

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Abstract

This article explores the systemic value of integrating the Function-Based Clusters (FBCs) and Strategic Environmental Assessment (SEA) framework into Thailand's river basin master planning. The FBC–SEA approach combines functional zoning (F1–F6 with sub-zoning) with strategic assessment processes, thereby linking spatial logic with systemic analysis. The study highlights five key dimensions of water management: domestic water supply, productive and economic uses, water-related disasters, water quality and environment, and governance and management. Drawing from empirical studies on risk mapping, SEA implementation, and participatory water governance, the analysis demonstrates that FBC–SEA enhances upstream–downstream causal reasoning, strengthens participatory governance through functional-zone forums, improves climate resilience by facilitating scenario development, and provides measurable outputs such as policy maps, indicators, and dashboards. Furthermore, risk maps superimposed on FBC zones identify vulnerable areas and enable spatial prioritization to achieve equity across urban, agricultural, and marginalized communities. In contrast, conventional SEA applied without spatial-functional integration tends to remain fragmented and less effective in capturing systemic relationships and more oriented toward short-term measures. The study concludes that adopting the FBC–SEA framework in full can transform river basin master plans into *living plans* that are transparent, adaptive, and aligned with global agendas such as the Sustainable Development Goals (SDGs) and the Paris Agreement.

Keywords : FBC–SEA; River Basin Master Plan; Risk Map; Governance; Climate Resilience; Sustainable Development Goals

Introduction

River basin management in Thailand has long been framed through the lens of Integrated Water Resources Management (IWRM), which emphasizes efficiency, equity, and sustainability [1]. Yet, challenges remain acute: rural households still lack reliable access to safe drinking water, conflicts over irrigation water allocations are intensifying, urban floods continue to paralyze major cities, and water quality degradation persists. These challenges highlight the inadequacies of fragmented governance and conventional problem-based planning.

Theoretical debates on the structure–function relationship of river basins provide a critical foundation for rethinking master planning. Watershed systems can be understood as an integrated assemblage of geomorphology, forest cover, and human settlement patterns, which fundamentally determine hydrological and ecological functions such as runoff regulation, groundwater recharge, and ecosystem service provision. The River Continuum Concept [2] describes how structural gradients from headwaters to large rivers condition ecological functions. Allan [3] emphasized the socio-ecological functions of river basins in linking ecosystems to livelihoods. Postel and Richter [4]

further linked water structure–function dynamics to sustainable water use.

Strategic Environmental Assessment (SEA) has been formally guided in Thailand by the National Economic and Social Development Council (NESDC), which defines SEA as a flexible and long-term strategic process supporting decision-making through balanced consideration of economic, social, and environmental dimensions, with strong emphasis on stakeholder participation and sustainability. The Function-Based Clusters (FBCs) and Strategic Environmental Assessment (FBC–SEA) framework proposed in this study does not replace or challenge the NESDC SEA process. Rather, it complements existing SEA practice by embedding SEA procedural steps within a spatially explicit functional zoning structure, thereby enhancing operational clarity, spatial prioritization, and replicability across river basins.

Within this conceptual frame, the FBC–SEA framework builds on both Thai and international traditions. By clustering river basin functions into six categories (F1 headwaters, F2 storage, F3 conveyance, F4 urban/economic zones, F5 agriculture, and F6 vulnerable areas) and embedding these clusters into SEA processes, FBC–SEA operationalizes the structure–function paradigm into practical planning.

This study contributes to Strategic Environmental Assessment and river basin planning literature by providing a spatially replicable operational framework that

systematically embeds SEA procedural steps within Function-Based Clusters, thereby bridging the gap between strategic assessment and spatial implementation in integrated river basin master planning.

Conceptual Background: IWRM, SEA, and FBC

Integrated Water Resources Management (IWRM) has served as a guiding principle in global and Thai water policy. Its integration framework seeks efficiency, equity, and sustainability, but its application has often been criticized as overly abstract. FBC–SEA can be seen as an operationalization of IWRM, turning general principles into spatially explicit and policy-relevant processes.

Strategic Environmental Assessment (SEA) is central to this process. SEA traditionally follows a cycle of scoping, scenario and impact analysis, trade-off evaluation, and mitigation design. However, without spatial functional clusters, SEA risks being reactive and fragmented.

Function-Based Clusters (FBCs) bring spatial clarity. By categorizing zones based on their systemic roles, FBCs provide an entry point for linking upstream–downstream causality with social and economic considerations. Sub-zoning allows further granularity, for example distinguishing peri-urban industrial clusters (F4B) from central business districts (F4A).

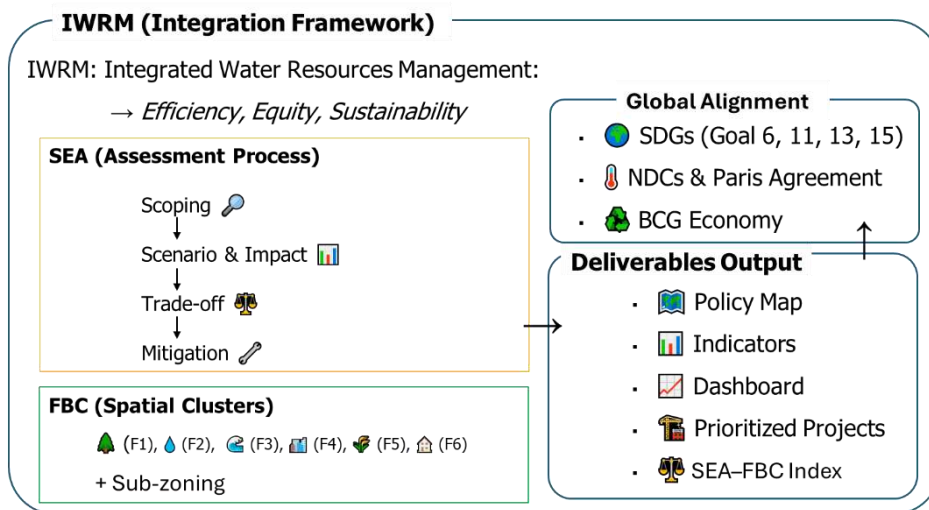


Figure 1 IWRM Integration Framework including SEA processes, FBC zones, global alignment, and deliverables

Methodology

This article applies a qualitative comparative analysis supported by literature review and empirical evidence. The methodology involves three steps:

First, theoretical perspectives on structure–function relationships were reviewed from Thai and international sources.

Second, a comparative framework was developed to contrast SEA-only approaches

with SEA combined with FBCs across the five water management dimensions: domestic supply, economic uses, disasters, water quality, and governance.

The analytical structure of this comparison is summarized in **Table 1**, which outlines how conventional SEA and FBC–SEA differ in addressing systemic relationships, spatial prioritization, and governance mechanisms across the five dimensions.

Table 1 Comparative Analytical Framework comparing Conventional SEA and FBC+SEA across five dimensions

Water Dimension	Conventional SEA (Non-spatial Integration)	SEA+FBC (Spatially Functional Integration)
Domestic Water Supply	Focuses on shortage areas only	Links upstream forest (F1) and storage (F2) to household water access
Productive & Economic Uses	Considers irrigation demand conflicts	Connects F5 agriculture & F4 urban zones to systemic allocation mechanisms
Water-related Disasters	Identifies flood/drought hotspots	Uses F1–F3 causal chains to design mitigation and adaptive scenarios
Water Quality & Environment	Monitors pollution in critical rivers	Integrates F6 vulnerable zones and ecological services into SEA
Governance & Management	Ad hoc participation; fragmented institutions	Functional participatory forums per FBC; systemic monitoring dashboards

Third, empirical cases were synthesized, including flood hazard mapping in Nakhon Ratchasima [5], participatory water governance in Southern Thailand [6], and urban water dashboards in Lamphun [7]. This procedural framework is designed to be transferable and replicable across river basins with comparable spatial datasets and planning contexts.

The procedural integration is further detailed in Box 1.

Box 1. Replicable Procedural Steps of the FBC–SEA Framework

Step 1: Basin Delineation and Spatial Data Assembly

River basin boundaries are delineated using GIS integrating topography, hydrology, land use, forest cover, settlements, and socio-economic indicators.

Step 2: Functional Classification into FBC Zones (F1–F6)

Spatial units are classified into six clusters reflecting structure–function relationships.

Step 3: SEA Screening and Scoping by Functional Zone

Strategic issues and sustainability indicators are identified per zone following NESDC SEA guidelines.

Step 4: Scenario and Alternative Development

Alternatives are formulated using upstream–downstream causal logic.

Step 5: Strategic Assessment and Sustainability Measures

Options are evaluated across economic, social, and environmental dimensions.

Step 6: Participatory Validation and Decision-making

Functional forums validate alternatives and support planning consensus.

Step 7: Outputs, Monitoring, and Replication

Policy maps, indicators, and dashboards are generated for basin-wide monitoring.

This framework operationalizes SEA within a spatial-functional architecture, ensuring replicability and policy relevance.

Results and Discussions

Structure–Function Logic

The structure–function paradigm is evident in the FBC design. F1–F2 clusters reflect natural structures regulating water quantity, while F4–F5 clusters highlight socio-economic structures. F6 clusters capture vulnerable communities structurally exposed

to risk. By aligning SEA assessments with these clusters, causal chains from upstream forest loss to downstream flood vulnerability become clear. These findings indicate that integrating FBC with SEA enhances the ability of strategic planning to capture upstream–downstream causality, spatial differentiation, and governance coherence compared to conventional SEA approaches.

Function Based Cluster	STRUCTURE	FUNCTION
 F1 headwaters	Forest / Headwaters 	Infiltration, baseflow, ecosystem services
 F2 reservoirs and wetlands	Storage 	Seasonal regulation, drought buffering
 F3 rivers and floodways	Conveyance 	Flow transport, sediment balance, flood pathways
 F4 urban/economic zones	Urban / Economic Zones 	Water demand, pollution, governance pressure
 F5 agricultural lands	Agriculture 	Irrigation use, food security, rural livelihoods
 F6 vulnerable areas	Vulnerable Areas 	High exposure to floods/droughts, equity, adaptive capacity

Figure 2 Conceptual diagram mapping FBCs to structure–function relationships

Empirical Evidence: Risk Mapping

Flood hazard maps and risk assessments in Thailand illustrate the systemic value of FBCs. For example, risk maps of the Mun River Basin combine hydrological and socio-economic layers, identifying high-risk agricultural zones. Bangkok flood risk studies [8] reveal inequities in exposure across districts. Integrating these risk maps into FBC zones enables prioritization of interventions.

Governance and Participation

FBCs create platforms for inclusive participation. Farmers in F5 zones, urban residents in F4 zones, and marginalized groups in F6 zones can each engage in governance forums tailored to their realities. Empirical research in Southern Thailand shows that participatory forums improve trust and reduce conflict [6]. The Bangkachao case demonstrates how

peri-urban community voices strengthen environmental governance [9].

Climate Resilience and Scenarios

Scenario analysis is strengthened by FBC–SEA. For example, in the Chao Phraya Basin, studies highlight the need to combine diversion canals (grey infrastructure) with retention wetlands (NBS) for effective adaptation [10]. Economic assessments of NBS confirm cost-effectiveness in reducing flood risk [11].

Outputs and Monitoring

Deliverables of FBC–SEA go beyond project lists. Policy maps, indicators, and dashboards make systemic performance measurable. Case studies of Lamphun’s urban water dashboard [7] and Bangkok’s utility resilience [8] demonstrate practical monitoring applications.

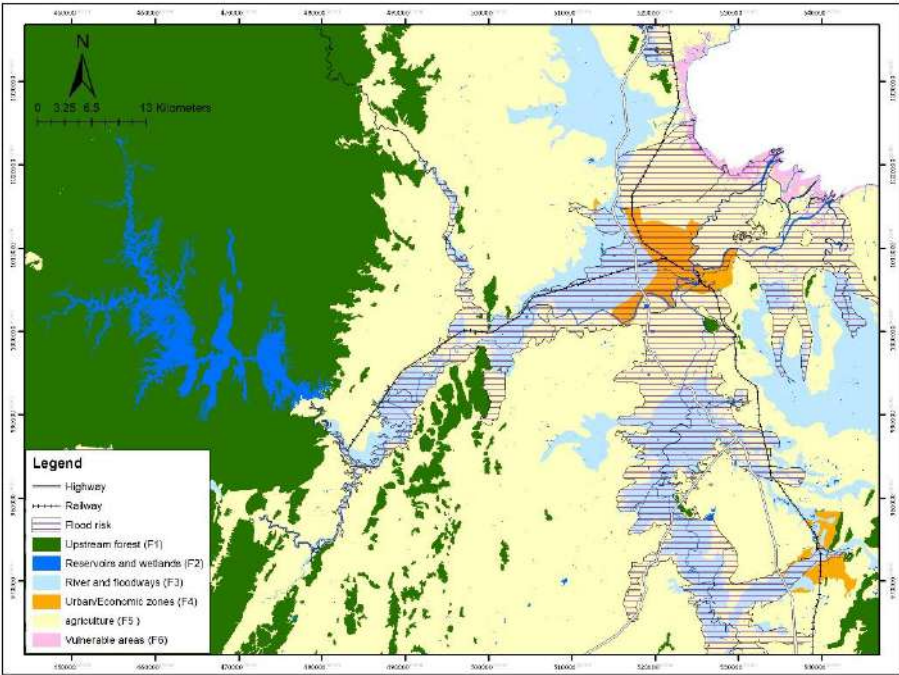


Figure 3 Sample risk map overlaid with FBC zones

Table 2 Scenario Comparison: Grey vs. Nature-Based vs. Integrated

Criteria	Grey Infrastructure	Nature-Based Solutions (NBS)	Integrated Approach (Grey + NBS + FBC–SEA)
Cost-effectiveness	High capital, high maintenance	Lower cost, co-benefits	Balanced cost with diversified benefits
Climate Resilience	Limited adaptability	High adaptability to variability	Highest resilience through redundancy
Social Acceptance	Moderate; often top-down	High; community-friendly	High; participatory and context-specific
Equity	Benefits urban/industrial zones	Benefits vulnerable & rural zones	Balanced across F1–F6
Policy Integration	Weak alignment with SDGs/Paris	Strong ecosystem alignment	Strongest alignment with SDGs, Paris, BCG



Figure 4 Example of dashboard concept aligned with FBC zones

Global Alignment

FBC–SEA outputs align with global agendas:

- SDG 6 on water, SDG 11 on resilient cities, SDG 13 on climate, and SDG 15 on ecosystems.
- NDCs and the Paris Agreement provide climate adaptation pathways

that can be operationalized through FBC–SEA.

- The Bio-Circular-Green (BCG) Economy strategy of Thailand resonates with FBC–SEA’s systemic and integrative approach.

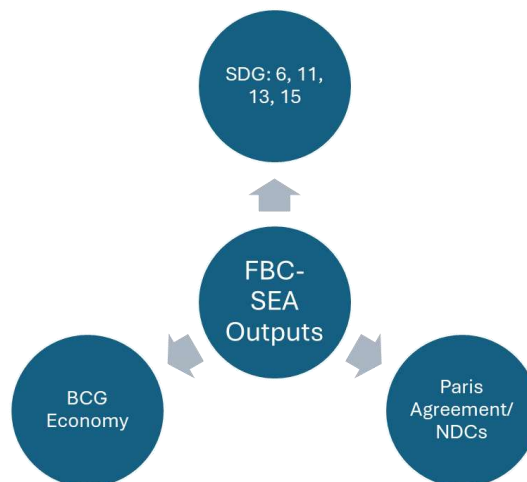


Figure 5 Alignment of FBC–SEA outputs with SDGs, Paris, BCG

Conclusions

Beyond conceptual integration, this study demonstrates how FBC–SEA translates SEA principles into actionable planning procedures, enabling functional prioritization, participatory decision-making, and measurable outputs such as policy maps and indicators. This positions SEA as an active planning engine rather than a compliance-oriented assessment tool.

SEA without FBCs can address immediate challenges but risks neglecting systemic upstream–downstream logic, equity, and resilience. In contrast, FBC–SEA integrates structure–function theory, risk-based evidence, participatory governance, scenario analysis, and measurable outputs. This transforms river basin master plans into *living plans*—transparent, adaptive, and globally aligned.

Policy Implications

1. Institutional adoption of FBC–SEA as a standard planning tool ensures systemic coherence in water management.
2. Integration of risk maps with functional zoning guides equitable spatial prioritization.
3. Development of indicators and dashboards makes basin performance measurable and transparent.
4. Creation of functional participatory forums ensures inclusiveness and reduces conflicts.
5. Linkage with global frameworks such as the SDGs, Paris Agreement, and BCG Economy elevates Thailand's credibility in international environmental governance.

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Does a Single-Use Leaf Bowl Enhance Well-Being and Reduce Carbon Footprint?

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Abstract

Carbon footprint (CF) became one of the valuable tools for assessment of greenhouse gas emission, resulting in global warming followed by the climate change, particularly in the food sector. The impact originated from food, food production, and packaging. Natural packaging was utilized for items such as wrappings, bowls, and bamboo tubes. These replaced modernized packages, including plastic bags and boxes as well as single-use polystyrene bowls. The latter significantly caused harm to both human health and the environment. These impacts led to the aims of this research, which were (1) to mold the leaf bowls from three types of leaves: *Licuala spinosa*, *Dipterocarpus alatus* Roxb. ex G.Don., and *Nelumbo nucifera* Gaertn followed by physical and biological testing; and (2) to assess the CF of each bowl compared to a polystyrene bowl. Molding factors were optimized using Minitab software. The optimized conditions were heating the leaves at 160 °C for 8 min, applying to all leaf types. The three different leaves were arranged parallel, perpendicular, and parallel to the vein, respectively. The leaf bowls from *Dipterocarpus alatus* Roxb. ex G.Don. provided an elegant look, high tensile stress resistance, and leak resistance; moreover, no microbial contamination was observed until the 30th day. CF was assessed from the optimized factors and calculated by emission factors (EF) from the Thailand Greenhouse Gas Management Organization (TGO). A total of 1.8055 kgCO₂eq of carbon dioxide was emitted per one leaf bowl under the optimum molding factors. The emission was approximately 60% less than polystyrene foam (2.985 kgCO₂eq per kg, excluding the molding process). The significant advantages of leaf bowls were (1) no emission from raw material, (2) no toxicity, and (3) no requirement for waste management.

Keywords : leaf bow; carbon footprint; Minitab software; tensile stress; microbial contamination

Introduction

Due to data from the United Nations, food production covered one-third of greenhouse gas (GHGs) emissions: CO₂ from agriculture and land use; CH₄ from livestock production; and N₂O from fertilizer and chemical use and energy use for the supply chain and waste [1]. Food waste was divided into food waste itself and its packaging. Uneaten

food decomposes and emits CO₂ and CH₄ while emissions from packaging depend on the kind of materials, such as chilled packages, bottles, and cans, which require specialized waste management. In contrast, the food packaging made of leaves can naturally decompose; no waste management is required. After use, food packaging directly decomposed but more than one third did not enter collection system [2]. Plant-based bioplastics; biodegradable (such as

poly-lactic acid (PLA), polyhydroxybutyrate (PHB), or biopolymer-based plastics) and non-degradable (biobased polyolefins: e.g., bio-PE, bio-PP, and bio-PET), and agro-materials were recently marketed to minimize impact from food packages [3].

Starting in the 1800s, naturally occurring materials such as gourds, shells, and leaves were used to hold food. Primitive materials, including pottery, paper, and glass were shaped into food containers. From 7000 B.C., the raw materials used to make glass—limestone, soda, sand, and silica remained the same until today with additives developed to provide color, shine glass and appropriate properties [4]. Following the discovery of tin plating in Bohemia in A.D. 1200, tin-coated iron cans were used for foods and drinks. Metal cans were initially manufactured for snuff since they provided an excellent barrier to prevent moisture, microbial contamination while protecting the flavor of the products. The latter was discovered by Nicholas Appert to be used in canning operations when challenged by the French Emperor Napoleon Bonaparte to develop a method to preserve food for his army. Appert used glass bottles with corks secured with wire as a closure to contain food while heating. The glass bottles were fragile and were soon replaced by metal cans. The cans allowed products to be heat-processed to extend their shelf-life and prevent spoilage. Paperboard was first used to manufacture folding cartons in the early 1800s. Today, corrugated boxes are widely used as shipping containers to hold several smaller packages. Plastics, including cellulose nitrate, styrene, and vinyl chloride, were discovered in the 1800s but were not used in packaging until the 20th century.

By the 19th century, natural food containers and metal cans were replaced with plastic bags and boxes, or wraps for food packaging. The distillation of styrene from a balsam tree was first discovered in 1831, but the products were brittle and easily shattered. Styrene foam (boxes, cups, and trays) became available worldwide from refinery processes by the 1950s due to its insulation and cushioning properties. In 1977, polyethylene terephthalate (PETE) containers became available for beverages. By 1980, foods and other hot-filled

products, such as jams, could also be packaged in PETE [5].

Located in an advantageous geographical area, Thailand has a tropical climate resulting in various kinds of plants. Besides the main function in photosynthesis, the sizes, textures, shapes, and patterns of leaves in tropical areas are different from those in temperate areas. The big leaves of teak (*Tectona grandis*) and lotus (*Nelumbo nucifera* Gaertn) enhance the absorption of solar energy for synthesizing glucose from carbon dioxide and water. In Oriental culture, including Thai, Lao, Myanmar, various big leaves and special types of foliage, such as banana (*Musaparakadiaca*), coconut (*Cocos nucifera* (L.) nypa palm (*Nypa fruticans*), and mangrove fan palm (*Licuala spinosa*) have been used as natural food packaging (food wraps and food baskets). These board leaves provide benefits including thick, waxy coated, palmately netted venation-convergence, pinnately paralleled venation, and palmately paralleled venation-divergence [6] for food containers.

Drawing from the knowledge and experience of using several types of leaves such as for wrappings, food bowls, bamboo tube applications, modern method can create a ready-to-use containers that are pleasing, have long shelf-life, and are free from microbial contamination. As a result, the aims of this research were (1) to mold the leaf bowls from three types of leaves: *Licuala spinosa*, *Dipterocarpus alatus* Roxb. ex G.Don., and *Nelumbo nucifera* Gaertn for physical and biological testing and (2) to assess the Carbon Footprint (CF) of each bowl compared to a polystyrene bowl. The success of this research lies in the optimized factors being applicable to all kinds of leaves. Moreover, it is safe to use these single-use leaf bowls after molding and proper storage.

Materials and Methods

Pneumatic molding machines were developed in-house by the Applied Mechanics and Product Design Research Group, Faculty of Engineering at Sriracha, Kasetsart University. The electrical heating system was applied only to the upper mold, which was then pressed

down onto the leaves by the pneumatic system. A constant pressure of 6 bars was applied, replacing the downward heater. The square mold ($16 \times 15 \times 2 \text{ cm}^3$) was made of high-quality iron because its thermal conductivity (79.5 W/m K) is higher than that of steel (50.2 W/m K) [7]. Moreover, iron is soft and easily shaped with a lathe [8]. Since iron is very reactive, it must be kept under a film of cooking oil to prevent rust caused by oxidation.

Collection and preparation of leaves

Leaves were selected based on four criteria: (1) typically and locally used as food wraps or containers; (2) not toxic and (3) soft, tough, and flexible; (4) easy to find and inexpensive. The selected leaves were as follows:

1. *Licuala spinosa* (mangrove fan palm). It grows in clumps in fresh or salt water. They are 2-7 meters high with a stalk of 4-7 cm [9]. Along with palmately paralleled venation-divergence of the fan-shaped leaves with 40-60 cm-long. They are used to wrap food, particularly in the eastern area of Thailand.

2. *Dipterocarpus alatus* Roxb. ex G.Don. This is a big evergreen tree with 30-60 meters tall which grows in tropical rain forests [10]. The big leaves are thick and tough. The 3rd - 5th leaves from each treetop were collected at Kasetsart University, Sriracha, Chonburi.

3. *Nelumbo nucifera* Gaertn known as sacred lotus is the aquatic plant that grows in flood plains of slow-moving streams [11]. The large, round-shaped leaves have the ability to repel water and dirt due to their hydrophobic surface structure.

The mangrove fan palm and lotus leaves were collected from Wat Bunnak Community, Klaeng District, Rayong Province. Three consecutive steps of cleaning were applied to all types of leaves: (1) mildly scrub the leaves with a soft brush to remove muddy particulates; (2) wash them again with clean water. In steps 1 and 2, each type of leaf was dipped one by one into a water tank (0.08 m^3). The fresh leaves were shaken to remove water before being wiped dry in the final step (step 3). All leaves were left in ambient air for partial dehydration to increase softness and toughness which

prevent them from becoming brittle during the molding process.

Optimized factors for molding containers

The optimized molding factors were obtained from *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G. Don. for appropriate conditions. The factors were then applied to *Nelumbo nucifera* Gaertn because of their morphological difference. The water content in *Nelumbo nucifera* Gaertn leaves is higher than in the other two terrestrial plants (observed from water released during molding). The factors affected by molding included leaf arrangement, temperature, and time. The tapioca paste (50 g of food grade tapioca flour in 100 ml of water followed by 200 ml of boiling water with vigorous stirring) was used as an adhesive, if necessary.

For *Licuala spinosa*, the dimensions of the leaves were 5-6 cm in width and approximately 55 cm in length, but they were tough in parallel with the vein direction. A total of 6-8 leaves were arranged in two directions: the same direction and the opposite direction of their veins. Before molding, the leaves were stuck together with adhesive. The molding temperature was varied from 100-150 °C with time intervals from 5 to 15 min.

For *Dipterocarpus alatus* Roxb. ex G.Don., the two layers of thick and tough leaves were arranged in two directions: parallel and opposite to the vein and stuck with adhesive. The heating temperatures varied from 110-180 °C and the heating time varied from 3-15 min.

The experimental design for molding *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G.Don from all parameters was considered from the resistance to tensile stress. Three factors were examined: each parameter consisted of two levels and two replications. The number of experiments can be calculated in Eq. (1).

$$\text{No. of experiment} = \text{No. of level}^{\text{No. of}} \\ \text{parameters} \times \text{No. of replication} \quad 1$$

The parameters were calculated from 16 experiments. The controllable factors were molding size, constant pressure at 6 bars, and quantity of adhesive. The uncontrollable parameters were characteristics of the leaf and

moisture content in the leaf. The experimental design for the highest resistance to tensile stress of *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G.Don. is presented in **Figure 1(a) and 1(b)**. The molding process was performed in a clean area, particularly the molding site of the machine. The mold was wiped with aqueous ethanolic solution (70%) to remove vegetable oil coated at the mold surface and for disinfection. The heater was warmed, and the pump was set at 6 bars. The temperature was set as a result of the experimental design while the leaf arrangement and time intervals were set as a result of the optimization factors.

The molding conditions were evaluated to produce durable leaf bowls based on their highest tensile stress. The Minitab software (License) was applied to analyze various factors, including leaf arrangement patterns, temperature, and time. Finally, the design was assigned at a significance level (α) of 0.05 and a confidence level of 95% for adequate accuracy {the probability of 5% was enough for rejecting the null hypothesis (H_0)}. Two basic hypotheses were as follows:

- H_0 = Leaf arrangement pattern, temperature, and time do not affect the tensile stress of leaf bowls.
- H_1 = Leaf arrangement pattern, temperature, and time affect the tensile stress of leaf bowls.

The experimental design was described using constant population characteristics that were statistically evaluated from the total population. Hypothesis testing and the p -value were applied to optimize the experimental conditions on a statistical basis, resulting in the effective use of resources such as raw materials, energy, budget, and time. Two hypotheses consisted of a null hypothesis (H_0) and an alternative hypothesis (H_1). The p -value was calculated to confirm the hypothesis by fixing the α value at a significance level. The p -value is the probability that the tested values equal the observed values. If the null hypothesis is true, the p -value is defined as the lowest value at the fixed significance level, leading to the rejection of the null hypothesis (p value $< \alpha$). The statistical symbols were represented as follows: population mean (μ), standard deviation (σ), correlation coefficient of the population (ρ), and total population (τ). The steps for experimental parameters were consecutively designed starting from defined problems to be solved and objectives to setting variables, the number of experiments at a statistical level, and final output settings. The results from the Minitab software are presented in the Pareto Chart and factorial design that were investigated to evaluate the factors related to tensile stress.

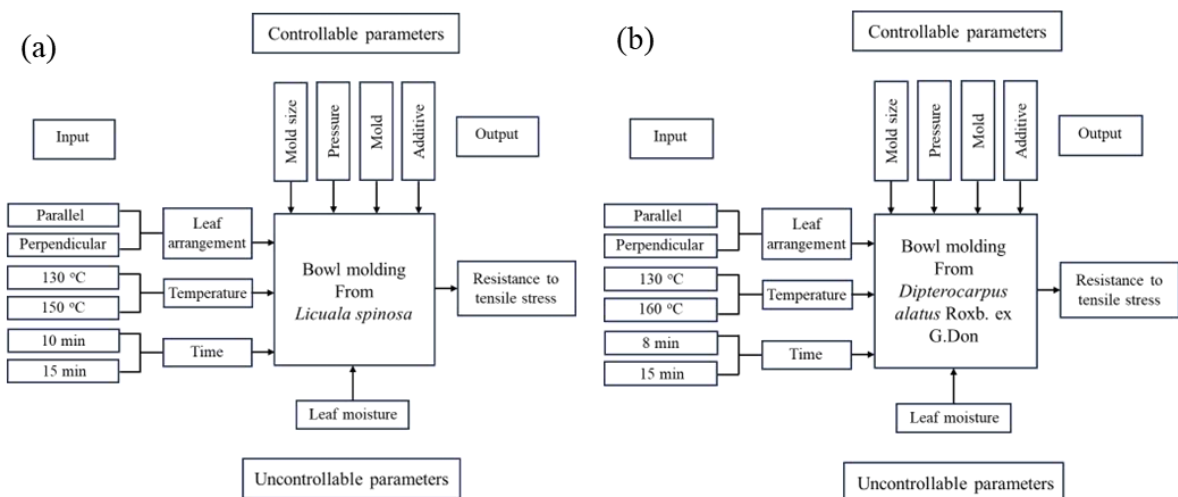


Figure 1 Experimental design for molding the leaf bowl, representing the highest resistance to tensile stress: (a) *Licuala spinosa* and (b) *Dipterocarpus alatus* Roxb. ex G.Don.

Test for physical properties of leaf bowls

There are no direct standards to qualify the physical properties of leaf bowls; they may be qualified by comparison with various paper packages seen in **Table 1**.

Microbial contaminations of leaf bowls

Tests for microbial growth were necessary for controlling pathogenic microorganism contamination and setting the shelf-life. After molding, the leaf bowl was still wet because the water inside the fresh leaves remained at the bowl surface. Before microbial testing, the leaf bowls must be dried at 40 °C for 2 h or until there is no weight change of the bowl. Swab both sides of the bowl surface with a sterile swab stick. Streak the swab stick on the nutrient agar (NA) surface in three Petri dishes. Incubate all Petri dishes at 37 °C for 24 h. Record the time interval when a colony of microorganisms is first observed.

Assessment of carbon footprint of leaf bowls

To quantify the carbon footprint, the cradle-to-gate boundary included transportation, washing, and molding. The functional unit of one leaf bowl without microbial contamination was applied. CF was accounted for from leaves to the finished leaf bowls. *Licuala spinosa* was naturally growing in community forests while *Dipterocarpus alatus* Roxb. ex G.Don. was from an almost 30-year planting at Kasetsart University, Sriracha Campus. The two types of plants can be considered as sources of green carbon sequestration. *Nelumbo nucifera* Gaertn is

an aquatic plant that is naturally grown in water resources. Each individual process and emission inventory was not shown. Each experimental step, including materials and chemicals, as well as electricity and carbon dioxide emissions was quantified. Due to the cradle-to-gate boundary, the waste disposal for used leaf bowls was not included. Furthermore, the average age of leaves in tropical areas ranged from six months to one year [13]; consequently, they naturally decay and decompose.

For the calculation of electrical consumption for heater [14], since the molding machine was assembled in-house, the electrical consumption was not directly measured. However, it was estimated using available conversion factors. A temperature increase of 1 °C was converted to 0.00052752791666667 kWh.

For the calculation of electrical consumption for pneumatic systems (Rapid Table, n.d.), the systems were used for individual machines. The consumption was calculated step by step using available conversion factors, as follows:

Step 1 Conversion of bar into pascal.

1 bar is converted to 100,000 Pa; then, 6 bars equal 600,000 Pa.

Step 2 Conversion of pressure (Pa) into energy (Joules).

$1 \text{ Pa} \times 1 \text{ m}^3 = 1 \text{ Joule of energy};$

Step 3 Conversion of thermal energy into electrical consumption.

$1 \text{ Joule} = 0.0000002778 \text{ kWh}$

Table 1 Test methods to indicate the physical properties of leaf bowls

Physical properties	Test methods
Tensile strength and elongation	Place the leaf bowl between two grips which clamp the bowl. Increase weight to the material gripped at one end while the other end is fixed. Measure the change in length of the bowl [12].
Leakage of leaf bowl	Place the dried-weighted blotting paper over each leaf bowl filled with water. Leave the bowl for periods of 0, 30, 60, 90, 120, and 150 min. Observe the leakage of the bowl from the weight increase at the first-time interval.

Results and Discussions

Characteristics of natural leaf bowls.
The size of the leaf bowl was 16 x 16 cm². The fresh green color was different for each individual leaf (**Fig. 2**). Moreover, all types of leaf bowls offer a pleasant aroma like burnt leaves. Both color and smell can enhance food appetite. Higher temperatures and longer times increased the dark shade of the green color. The leaf bowl molded from the parallel arrangement of *Licuala spinosa* provided higher resistance to tensile stress than the perpendicular arrangement at both heating temperatures (130 °C and 150 °C). The bowl was robust and retained its shape. This arrangement can be applied to molding from parallel venation leaves, such as banana, coconut, nipa palm, and sugar palm leaves. Furthermore, the complete overlapping of zig-zag leaves resulted in higher strength than the opposite direction. For *Dipterocarpus alatus* Roxb. ex G.Don., the leaf arrangement affected the performance at both temperatures.

Experimental design for molding conditions of leaf bowls. The results from the Minitab software are presented in **Fig. 3**. The other two types were examined in the same manner.

According to the Pareto chart of standardized effects (Fig. 3a), the three factors (three-way interactions) significantly affected the resistance to tensile stress (standardized effect was greater than 2.31, as calculated by Minitab software). The resistance to tensile stress was affected by leaf arrangement (A), molding temperature (B), and molding time (C). The calculated values (Fig. 3b and 3c) indicated a *p*-value less than 0.05; thus, the integrated factors (A, B, and C) led to the rejection of the null hypothesis *H*₀. It can be concluded that factor AB (parallel arrangement of leaves and molding temperature at 150 °C) was considered as the dominant factor, followed by molding time at 10 min. The optimized conditions in Table 2 presented the highest resistance to tensile stress at 0.0003142 ± 0.0000076 N/mm²).



Figure 2 Characteristics of the three types of leaves, experimental conditions, and color of each leaf bowl

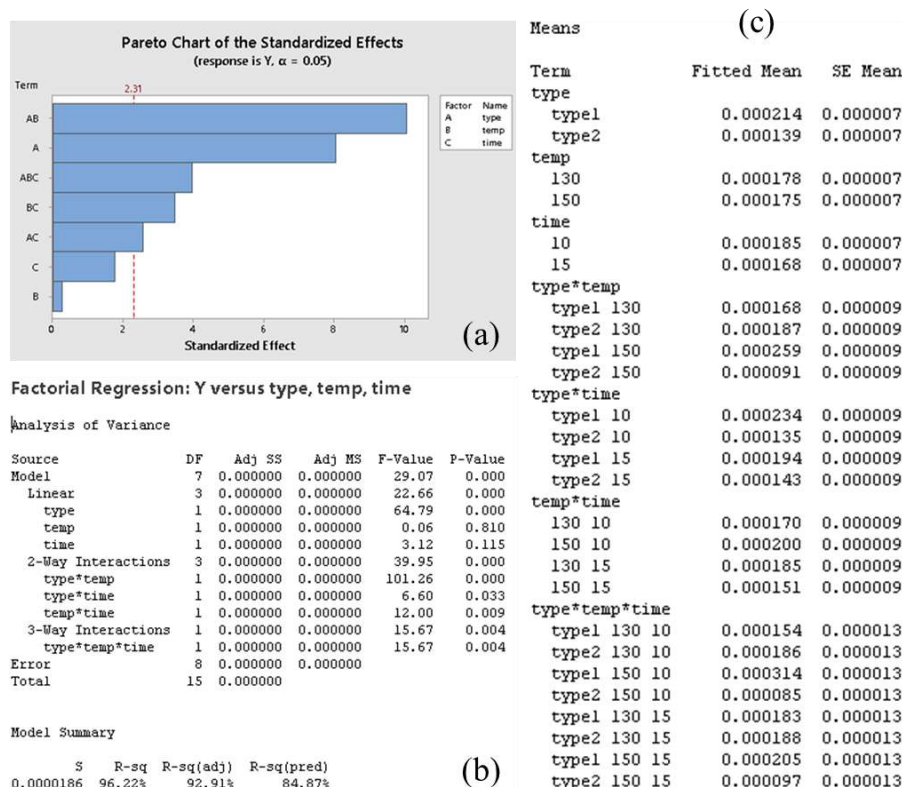


Figure 3 Optimized parameters of leaf bowl molding related to leaf arrangement patterns, temperatures, and time from *Licuala spinosa* (a) Pareto Chart, (b) Factorial regression, and (c) the average data values for resistance to tensile stress

Unlike *Licuala spinosa*, the Pareto chart of standardized effects indicated that the individual factors (A and B) significantly affected the highest resistance to tensile stress for *Dipterocarpus alatus* Roxb. ex G.Don. The p -values of three-way and two-way interactions were greater than α (0.05); therefore, they corresponded to the null hypothesis (H_0) (Fig. 4b). The results showed that leaf arrangement (p -value 0.039) and temperature (p -value 0.023) were significant; this indicates that only these two factors affect the resistance to tensile stress. The molding time did not significantly affect the resistance to the tensile stress, as its p -value (0.154) was higher than 0.05. It could be concluded that factor AB involved perpendicular leaf arrangement and a molding temperature of 160 °C. The molding time of 8 min was selected since there was no statistical effect (Fig. 4c), and avoiding the excess 7 mins reduced the CF from electrical consumption. The additional 7 min was not reasonable for three reasons: (1) the resistance to tensile stress increased only 0.000245 ± 0.000768 N/mm²;

(2) the electrical consumption and carbon dioxide emissions were almost twice as high; and (3) the highest resistance to tensile stress (at 8 min of molding) reached its maximum comparing with the other two types of leaves (Table 2).

Average resistance to tensile stress from experimental design. The variation in the data from the experimental design was evaluated to confirm the durability of the leaf bowls. The average tensile stress calculated for the optimum factors is summarized in Table 2. For *Nelumbo nucifera*, the molding conditions were evaluated based on the optimized conditions of *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G.Don. *Nelumbo nucifera* is an aquatic succulent plant; its leaf is much different from the first two. It is round-shaped with a diameter of approximately 50 to 80 cm, possessing a hydrophobic and waxy surface. Higher resistance to tensile stress was observed when the leaves were molded at the area of the leaf petiole. Only two leaves were molded at 150 °C for 10 min to produce one bowl. The bowl possessed a resistance to tensile stress of

$0.002252 \pm 0.001343 \text{ N/mm}^2$ which was higher than *Licuala spinosa* but lower than *Dipterocarpus alatus* Roxb. ex G.Don. Due to its zig-zag morphology, the leaves could not

closely adhere to one another. The three types of leaf bowls molded under optimized conditions showed the best properties in terms of color, shape, and tensile stress (see Fig. 5).

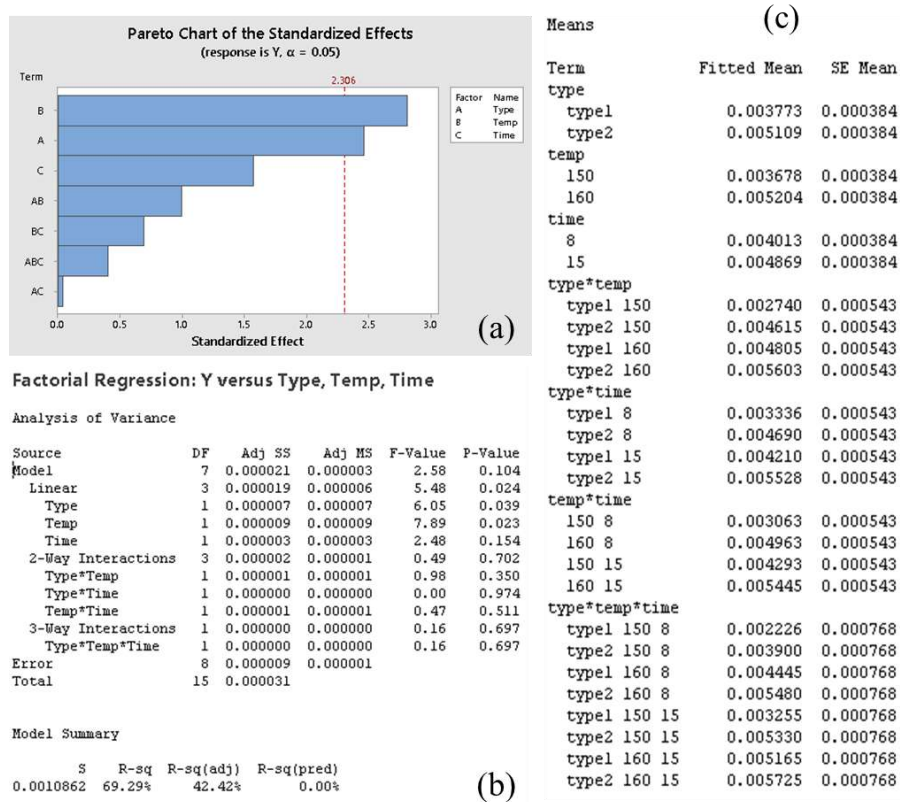


Figure 4 Optimized parameters of leaf bowl molding related to leaf arrangement patterns, temperatures, and time from *Dipterocarpus alatus* Roxb. ex G.Don (a) Pareto Chart (b) Factorial regression, and (c) average data values for resistance to tensile stress

Table 2 Summary of optimized conditions for molding the leaf bowls from three types of leaves

Leaves	Factors	Experimental conditions	Average resistance to tensile stress (N/mm ²)*
<i>Licuala spinosa</i>	Leaf arrangement	Parallel	0.0003142 ± 0.0000076
	Molding temperature (°C)	150	
	Molding time (min)	10	
<i>Dipterocarpus alatus</i> Roxb. ex G.Don	Leaf arrangement	Perpendicular	0.005480 ± 0.0005940
	Molding temperature (°C)	160	
	Molding time (min)	8	
<i>Nelumbo nucifera</i>	Leaf arrangement	Parallel (3 cm from the stalk)	0.0024173 ± 0.0006883
	Molding temperature (°C)	150	
	Molding time (min)	10	

*n = 2



Figure 5 Three leaf bowls from *Licuala spinosa*, *Dipterocarpus alatus* Roxb. ex G.Don., and *Nelumbo nucifera* at optimized conditions from Table 2

The experimental factors calculated from Minitab software were successfully applied to *Nelumbo nucifera*. The molding temperatures and time were almost in the same range except the arrangement patterns which depended on various factors such as the types of leaves, leaf vane, size, and nature of leaves. The two types of leaves were selected as samples to determine the experimental factors that could be applied to any leaf type. *Nelumbo nucifera* leaves were an example of these assumptions.

The color of the leaf bowl made from *Dipterocarpus alatus* Roxb. ex G.Don. was more uniform than *Licuala spinosa*. The leaf turned a darker color after heating because of moisture loss and tissue damage. The heat from a heater caused cell death at the leaf edges, leading to a dry, crispy brown or black color called necrosis [15]. The perpendicular arrangement resulted in higher resistance to tensile stress than the parallel arrangement because the pinnate parallel venation of the leaves in different directions made them overlap like a net. A smooth surface was observed on both sides at two different temperatures (130 °C and 150 °C), as seen in **Table 2**. At a lower temperature (less than 130 °C), the two layers of leaves could not blend into one layer, and the tapioca paste remained wet, resulting in an unstable shape. Unlike the other two types, only two large leaves of *Nelumbo nucifera* were molded in a parallel direction. They were placed close to their stalks because of their thickness. The excess water was released after molding. These bowls presented a fresher color than the other two. In addition to their naturally waxy-coated leaves, the bowls from these leaves displayed a slightly shiny surface. The aesthetic appearance of these bowls could enhance the food appetite. Since the molding process involved heat, the

smell of the leaf bowl was like roasted or baked leaves which was better than the smell of plastic.

Leakage of the leaf bowls was another important property for their application. Leakage was characterized by the time interval after putting liquid into the bowls. Leakage was observed within 30 min. Since two leaves of *Nelumbo nucifera* were used to mold the bowl, there was no leakage for up to 30 min. The parallel arrangement pattern of *Licuala spinosa* also provided less leakage than *Dipterocarpus alatus* Roxb. ex G.Don. The raw data for time intervals and volume of liquid leakage from the bowls are not shown. Due to the short time intervals before leakage, the leaf bowls are most suitable for dry foods such as fried food, grilled food, or salad. As a result, for dry food, the tapioca adhesive did not lead to leakage. During the molding process, the tapioca adhesive was dried; therefore, it did not leach or spoil the taste of the food. Using these for single-use purposes, such as a buffet or cocktail party, is more advantageous than using paper or single-use plastic bowls. They enhance food appetite and provide pleasant aroma, as well as lightening the washing load and reducing waste disposal.

Microbial contamination of leaf bowls was evaluated. These bowls must be free from contamination of pathogenic microorganism contamination for a specific period. This is the most important property of the bowls since they could not be cleaned after molding. It was considered that the bowls were sterilized by heat during the heating process. Unfortunately, the molding machine possessed only one front heater; thus, the excess water inside the leaves remained on the back side, enhancing microbial growth. Furthermore, the leaf bowls cannot be

washed with dishwashing liquid. The bowls molded from *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G.Don. were slightly contaminated after molding. Contamination was observed after 15 days, and the bowl surface was heavily contaminated within 30 days. While microorganisms on the leaf surface were sanitized by heat (150 °C) during the molding process. The zig-zag morphology and deep leaf grooves of *Licuala spinosa* leaves protected microorganisms within the serrations, where the temperature was not high enough to kill them (Fig. 6).

For *Dipterocarpus alatus* Roxb. ex G.Don., the microbial contamination was slight on the 15th day and almost disappeared by the 30th day. The naturally dried leaves and waxy smooth surface of the leaves left no space between the layers of the leaves. The drying process (40 °C for one h) resulted in the removal of water accumulation between the leaf layers. Microbial growth was inhibited by reducing the amount of water; thus, no microbial contamination was observed after 30 days. In contrast to the other two types of leaves, microbial contamination did not appear in the bowls molded from *Nelumbo nucifera*. Only two

leaves were molded, so there was no overlap between the leaves. The leaves were also sterilized via the molding process (150 °C for 10 min). Moreover, the removal of water occurred during both the molding and drying processes (40 °C for one h). However, the shelf-life of the natural leaf bowl was short compared to paper or single-use plastic bowls; it became crispy and broke after almost one month. Bowls molded from dried leaves, including banana leaves, coconut leaves, or betel palm sheaths, might be selected to extend the shelf-life.

Carbon dioxide emissions from a single leaf bowl. To assess the quantities of carbon dioxide emitted from molding one leaf bowl, the study was divided into direct data collection and calculations from available reference data. The inventory data for the molding process is presented in Table 3. The carbon footprint of the product was evaluated specifically for the molding process. Regarding characterization, the carbon footprint was mostly similar for each batch of molding. The most important procedure was sampling each to ensure reproducibility. The inventory data for leakage and microbial contamination is presented in Table 4.

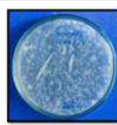
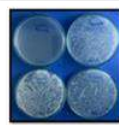
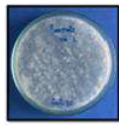
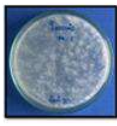
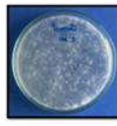
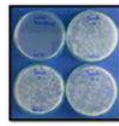
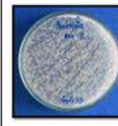
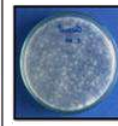
Test period (day)	Front sides of the leaf bowls				Back sides of the leaf bowls			
0								
15								
30								

Figure 6 Microbial contamination on the surface of leaf bowls molding from *Licuala spinosa*.

Note Data not shown for *Dipterocarpus alatus* Roxb. ex G.Don and *Nelumbo nucifera*

Table 3 Inventory data and emission factors (EF) of raw materials for molding leaf bowls

Inputs	Unit	Quantities	EF ² (kg CO ₂ eq)
Collection of <i>Licuala spinosa</i> and <i>Nelumbo nucifera</i>			
Diesel oil for van from KU Sriracha Campus) to Glang District, Rayong Province	km	110 *2	0.3522
Cleaning of leaves ¹			
Tap water	kg	80*2	0.5410
Molding Process			
Electricity for heating ³	kWh	0.0844	0.5986
Electricity for pneumatic ⁴			
<i>Licuala spinosa</i>	kWh	0.17	0.5986
<i>Dipterocarpus alatus</i> Roxb. ex G.Don.	kWh	0.14	0.5986
<i>Nelumbo nucifera</i>	kWh	0.17	0.5986

¹For each 50 bowls: *Licuala spinosa* 100 leaves, *Dipterocarpus alatus* Roxb. ex G.Don 150 leaves; *Nelumbo nucifera* 100 leaves.

²Emission factors from Thailand Greenhouse Gas Management Organization (Public Organization) [16].

³The optimum temperature for all three leaf types, calculated using Minitab was 160 °C, which is equivalent to 0.0844044666666672 kWh.

⁴Calculation of electrical consumption for pneumatic systems:

For *Licuala spinosa* and *Nelumbo nucifera* (molding time 10 min)

$$600,000 \text{ Pa} \times (0.012 \text{ m}^3/\text{min}) \times 10 \text{ min} = 612,000 \text{ Joules}$$

For *Dipterocarpus alatus* Roxb. ex G.Don. (molding time 8 min)

$$600,000 \text{ Pa} \times (0.012 \text{ m}^3/\text{min}) \times 8 \text{ min} = 489,600 \text{ Joule}$$

Calculated thermal energy for *Licuala spinosa*, *Dipterocarpus alatus* Roxb. ex G.Don. and *Nelumbo nucifera* were 0.17, 0.14 and 0.17 kWh, respectively.

Table 4 Electrical consumption for microbial examination

Step	Processes	Units	Quantities	Electrical consumption (kWh)
1	Manually mixing of nutrient agar (NA) 0.115 g in .5 l of distilled water	-	-	-
2	Culture sterilization by autoclaving at 120 °C for 20 min	kWh	3.0	3.0 x 1/3 = 1.0
3	Dry the leaf bowls at 40 °C for 1 h	kWh	3.0	3.0 x 1 = 3.0
4	Swab the surface of leaf bowl followed by spread on the NA in Laminar air flow for 2 h)	kWh	3.4	3.4 x 2 = 6.8
5	Incubate at 37 °C for 24 h	kWh	1.8	1.8 x 24 = 43.2
6	Sterile the cultured NA plate by autoclaving at 120 °C for 20 min	kWh	3.0	3.0 x 1/3 = 1.0

The carbon footprint of each leaf bowl was basically calculated using carbon dioxide emission factors from TGO (2023). The quantities of carbon dioxide were 1.8055 kgCO₂eq per bowl, compared to 2.985 kgCO₂eq per kg of polystyrene [17], excluding the molding process (single-use container). Since the cleaning step was very important, the leaves must be cleaned to remove dust and other contaminants, its GHG emission reached the highest level (95.01%). In this study, tapioca paste used as an adhesive was excluded because the amount was negligible and did not critically affect to the leaf bowls [18]. Similarly, tap water also provided the highest GHG emission, followed by the electrical consumption for analytical weighing machines. In the microbial contamination test, the incubation step consumed large amounts of

electricity due to the long duration required for microbial growth. Among three individual processes, the calculated GHG emissions were 5.10%, 2.64%, and 92.15% for molding, leakage, and microbial contamination, respectively. The new model of molding machines includes heaters on both sides of the mold; thus, it can be operated on-site without a pneumatic pump and adhesive, lowering GHG emissions by removing the transportation step. The carbon footprint of microbial testing reached its highest point at 32.9322 kgCO₂eq per batch (Table 5). However, it is not necessary to test an individual batch. If the molding and storage conditions of each batch are consistent, they may remain free from microbial contamination, similar to the results of the leakage test.

Table 5 Greenhouse gas emissions for one leaf bowl

Process	Material	Quantities	EF	GHGs emission (kg CO ₂ eq)	Percentage of GHGs emission
Molding processes					
Transportation ¹	Diesel oil	18.7 kg	0.3522 kg CO ₂ eq/kg	0.0659	3.62
Cleaning ²	Tap water	160 l	0.5410 kg CO ₂ eq/l	1.7312	95.01
Molding	Heat ³		0.5986 kg CO ₂ eq/kW h	0.008421	0.46
	Pneumatic ⁴		0.5986 kg CO ₂ eq/kW h	0.01696	0.93
Total				1.822481	100
Leakage (CF for 15 tests/batch)					
	Tap water	1.2 l	0.5410 kg CO ₂ eq/l	0.6492	68.83
	Tissue paper	0.03697 kg	0.6677 kg CO ₂ eq/kg	0.024685	2.62
	Weighing	0.450 kWh	0.5986 kg CO ₂ eq/kW h	0.26937	28.59
Total				0.943255	100
Microbial examination (CF for 54 tests/batch)					
	Nutrient agar	0.115 kg	0.0800 kg CO ₂ eq/kg	0.0092	0.03
	Sterilization	1.0 kWh	0.5986 kg CO ₂ eq/kW h	0.5986	1.82
	Drying	3.0 kWh		1.7958	5.45
	Lamina flow	6.8 kWh		4.07048	12.36
	Incubation	43.2 kWh		25.85952	78.52
	Autoclaving for sterilization	1.0 kWh		0.5986	1.82
Total				32.9322	100

Calculation

¹Greenhouse gas emissions from diesel fuel

Distance from KU SRC to Klaeng District, Rayong Province = 110 x 2 = 220 km

Fuel consumption = 220 km / 10 km/l = 22 l = 22 l x 0.850 kg/l = 18.7 kg

Greenhouse gas emissions = 18.7 x 0.3522 / 100 bowls = 0.0659 kg CO₂ eq

²Greenhouse gas emission from tap water

Greenhouse gas emissions = 80 x 2 x 0.5410 / 50 bowls = 1.7312 kg CO₂ eq

³Greenhouse gas emission from heat

Greenhouse gas emissions = 0.0844 x 10/60 x 0.5986 = 0.008421 kg CO₂ eq

⁴Greenhouse gas emission from pneumatic

Greenhouse gas emissions = 0.17¹ x 10/60 x 0.5986 = 0.01696 kg CO₂ eq

¹The longest molding time was selected to calculate carbon footprint.

The most significant advantages of leaf bowls are: (1) naturally sourced the raw materials and (2) no required waste management; they decay naturally. Due to organic waste separation, leave bowls can be considered as organic waste, it can be managed similar to organic waste mostly composting. No special management, transportation or landfill may require. Although, carbon dioxide emissions of natural leaf bowls were slightly lower than polystyrene foam, the utilization of polystyrene bowls generated a variety of VOCs [19]. Polystyrene (petroleum-based plastic) was a household waste including human carcinogen and mutagen [20]. It was a persistent chemical after exposure and recovery; it enhanced reactive oxidative stress (ROS) to aquatic organisms such as diatoms [21]. Finally, biodegradation of polystyrene was over 500 years in landfills [22]. There were no real limitations from seasonal availability of leaves. It could be explained as follows: (1) *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G.Don are the evergreen trees in the tropical regions. The latter is slightly different due to shedding leaves occasionally; (2) the rhizome of *Nelumbo nucifera* is still alive beneath the clay while the leaves and stems decay during the short period of the cold season. The types of plants could be found all around the country [23]. Although the conventional package such as plastics, papers and polystyrene is more convenient than modernized packages but they are self-sufficient and sustainable from their natural origins.

Conclusions

Natural leaf bowls via heat and pneumatic molding of *Licuala spinosa*, *Dipterocarpus alatus* Roxb. ex G.Don, and *Nelumbo nucifera* leaves can replace paper or single-use plastic bowls. The highest resistance to tensile stress was observed at 0.005480 ± 0.0005940 N/mm² of leaf bowl molded from *Dipterocarpus alatus* Roxb. ex G.Don. The optimized factors for these three leaf types were situated within the same range; therefore, they could be applied to most other leaf types. Leaf bowl molding based on these experimental factors, combined with leakage and shelf-life evaluation data, may yield microbial contamination results similar to those presented in this research. The most significant advantages

of leaf bowls are that they replace single-use paper and plastic bowls, reduce carbon dioxide emissions, and require no waste management. In alignment with Thailand's tourism policies, the leaf bowls may enhance the value added of food, particularly street foods such as Pad Thai, fried chicken, and fried or toasted meatballs. Moreover, as Thailand is located in a tropical region, a variety of leaves are available for molding or wrapping. These leaf bowls should be promoted on a commercial scale or through SMEs at a low cost, as they will serve as a distinctive identity for Thai street food.

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