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Low-carbon municipal solid waste management using bio-based solutions and community participation: The case study of cultural tourism destination in Nan, Thailand

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ABSTRACT

Tourism expansion has led to increased municipal solid waste (MSW) generation, which can exacerbate environmental and societal problems if proper waste management systems are not implemented. The study develops a framework for implementing bio-based solutions (BbS) for MSW management in a cultural tourism destination, using the walking street in Nan, Thailand, as a case study. Four low-carbon waste management scenarios were assessed, including increasing recycling rates (RE), using food waste as animal feed (BbS1), using bagasse containers as a soil conditioner (BbS2), and substituting single-use plastics with bamboo products (BbS3). Results showed that the BbS1 scenario had the highest performance in greenhouse gas (GHG) mitigation, reducing 66.3 t CO_2e/year, followed by BbS2, RE, and BbS3 scenarios, which reduce GHG by about 12.3, 11, and 1 t CO_2e/year, respectively. However, the BbS2 scenario has an additional benefit in returning around 84 kg N/year to the soil. Implementing the combination of RE, BbS1, BbS2, and BbS3 reduced waste to landfills by about 25.5 t MSW/year and reduced GHG emissions by 90.3 t CO_2e/year. Enhancing residual waste management is recommended, which can lead to mitigation of about 164.3 t CO_2e/year, or 83 % GHG emissions reduction compared to the base case.

1. Introduction

Tourism is a crucial economic sector that offers several opportunities for cities and destinations, such as economic growth, income generation, and employment opportunities. Cultural tourism represents around 39 % of all tourism activities [1], which makes its promotion important for various cities, particularly those with rich cultural heritage for conservation purposes. Cultural tourism enables tourists to participate in local cultural activities, including culture and traditions, heritage, rituals, and lifestyles [2], fostering genuine cultural exchange with locals. This has significant economic and cultural benefits for destinations and supports local communities. Nonetheless, Leung et al. (2018) [3] have found that tourists and visitors pose a critical threat to over 60 % of World Heritage Sites. The rapid increase in the number of tourists visiting these destinations has raised concerns about environmental issues,

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particularly the generation of municipal solid waste (MSW) and the resulting increase in greenhouse gas (GHG) emissions caused by tourism activities. Given that the tourism sector is highly vulnerable to climate change, it is imperative that local governments in tourist cities encourage climate action in their destinations for the adaptation and resilience of the tourism sector. Numerous studies have analyzed the GHG emissions resulting from tourism activities. At the global level, the tourism sector has contributed around 5–8% of global emissions [4–6]. Considering the entire supply chain of the tourism industry, the carbon footprint of global tourism was estimated to be around 3.9–4.5 Gt CO_2e in 2013 [5]. Although transportation has been identified as the primary contributor to GHG emissions in the tourism sector, the increasing amount of MSW generated by tourism is also a crucial factor that can contribute to GHG emissions. In 2001, 4.8 Mt of solid waste were generated by the world's 692.5 million international tourists [7], a figure that is expected to increase by 251 % by 2050 [8]. MSW is a significant source of methane emissions from the anaerobic decomposition of waste in open dumps and landfill sites [9]. Even following the closure of the landfill, the MSW continues to release methane for years [9]. The decomposition of MSW has been estimated to be the third major anthropogenic source of methane by contributing around 11 % of the total anthropogenic methane emissions [10]. Therefore, in tourism destinations, appropriate and efficient solid waste management is essential for mitigating GHG emissions and sustainable development.

Improper MSW management can lead to ecosystem degradation, including the deterioration of land and surface water quality [11]. Inefficient MSW management can also result in high operating costs to address water contamination and decrease tourist numbers, adversely affecting tourist regions [12]. Thus, tourist destination cities face waste management challenges created by tourism activities and tourists as waste producers. Moreover, developing countries like Southeast Asia or small cities lacking policies and basic infrastructure for MSW management would face more severe impacts [13]. Therefore, cost-efficient and environmentally sound MSW management systems, including collection, transport, processing, and final disposal, are crucial for tourist cities [14].

In recent years, there has been an increased global focus on finding sustainable waste management solutions to mitigate the impacts of climate change in the tourism sector [15]. Various approaches have been suggested for municipal solid waste prevention and treatment in tourism, such as conducting a solid waste audit to understand the waste characteristics and the nature of problems in the study area. Two approaches have been used for tourist waste generation assessment: bottom-up and top-down [16,17]. Both methods have produced similar results, with around 1.1–1.67 kg of waste generated per tourist per day [16,18]. Gidarakos et al. (2006) [19] estimated that tourists in the Mediterranean island of Crete, Greece, generate around 1.2 kg of MSW per tourist per day. Similarly, Mateu-Sbert et al. (2013) [20] found that an increase in the tourist population of Menorca Island, Spain, led to an overall increase in MSW of 0.28 % or equivalent to about 1.31 kg of waste per tourist per day. In developing countries in Asia, MSW consists of about 56 % biodegradable waste, 16 % recyclable waste, and 28 % non-recyclable waste [21]. In Thailand, for example, MSW composition is about 57 % biodegradable waste, 9 % recyclable waste, and 34 % non-recyclable waste [22,23], with food waste being the main proportion of biodegradable waste [24]. The annual carbon footprint from food waste is estimated to be 3.3 billion tonnes CO_2e, which accounts for approximately 8 % of global greenhouse gas emissions, according to the FAO (2013) [25]. However, the waste composition can vary depending on the activities in a tourism destination. The lack of appropriate MSW management, particularly the source-sorting of food waste and the separation of recyclable wastes for recycling, has led to a high amount of residual MSW that must be sent to landfill and incineration [26].

Various strategies for solid waste management have been implemented, including source reduction, green purchasing, reuse and recycling, waste recovery, and waste disposal [27,28]. Studies have investigated three major strategies for their potential to reduce GHG emissions from MSW: food waste prevention, reductions in single-use plastic, and increased separate collection and recycling of waste [18]. Recently, the circular economy has been emphasized as a waste prevention strategy [29] aimed at changing the production and consumption model to limit waste and protect natural resources, biodiversity, and the climate. Implementation areas include avoiding disposable plastic, preventing waste, and promoting cooperative reuse and recycling [29]. However, waste management in many tourist destinations faces challenges, as tourists are often unaware of how waste management problems occur in a particular region.

Additionally, tourists may inefficiently separate different fractions of solid waste, increasing the amount of mixed MSW that cannot be effectively managed and must be disposed of as residual MSW [30]. Therefore, in addition to appropriate management of existing MSW, solid waste minimization in tourist activities should be promoted to reduce downstream waste management costs, such as waste collection, transport, and disposal [12]. Reducing greenhouse gas emissions has become increasingly important, and innovative approaches are being sought.

Nature-based solutions (NbS) have been gaining attention as a sustainable way to address the climate challenge while enhancing livability and improving the quality of life in cities. The concept of NbS was developed by the International Union for Conservation (IUCN) to emphasize the importance of biodiversity conservation along with climate change mitigation and adaptation [31]. NbS approaches are particularly relevant to tourism when natural, cultural, and heritage resources have been affected [32]. Various studies have explored NbS approaches for tourism in protected areas, including the provision of ecotourism services, management of heritage sites, and mitigation of tourism impacts [33–35]. NbS involves innovative use of natural systems, such as forests, wetlands, and coastal ecosystems, to provide services that simultaneously benefit people and the environment. A range of NbS has been proposed, including green roofs, green infrastructure, the creation of green spaces, and urban agriculture, which can bring benefits to human society. NbS, therefore, has been promoted as a tool for solving diverse environmental and societal problems using the inherent qualities of ecosystems and nature. However, to handle the solid waste problem, the study aims to focus on using Bio-based solutions (BbS), which focus specifically on utilizing biological resources to develop sustainable options for managing the solid waste problem caused by tourism. For example, bio-based products derived from biomass and bioplastics have been introduced as alternatives to single-use plastics in various studies aimed at mitigating the solid waste problem [18,36–38]. The advantage of using bio-based products is that they primarily use renewable materials. However, at their end-of-life, these products become post-consumer waste that needs to be assessed for environmental sustainability in different waste management scenarios [38]. Life cycle assessment has been recognized as an appropriate approach to determine the environmental sustainability of an MSW management system [39]. This method has been commonly used to compare the GHG emissions performance between existing and new MSW management options [18,24,40]. Researchers have also quantified the carbon footprint of beverage packaging used by tourists to identify suitable strategies for reducing GHG emissions and waste generated by passengers [41].

The study aims to develop a systematic approach for identifying and evaluating low-carbon MSW management scenarios in a tourist destination area, given the expectation of preserving the ecosystem and local natural resources and promoting cultural tourism. Bio-based solutions (BbS) have been focused on as the key scenarios for MSW management. The proposed bio-based approaches aim to minimize the use of non-renewable resources, increase the recovery and utilization of MSW nutrients, mitigate GHG emissions, and reduce solid waste to landfills in accordance with the circular economy promotion [42,43]. The IUCN Global Standard for NbS framework [44] has been referred to as the initial guideline to develop a novel framework for implementing bio-based solutions for MSW management. The selected study area is the walking street and night market, or so called *"Kad Khuang Muang,"* a well-known cultural tourism destination in Nan province. Nan is a province situated in Northern Thailand, sharing its border with Laos on the east. The reason for choosing Nan province is because it has gained popularity as a tourist destination for ecotourism and cultural tourism. The ASEAN Clean Tourist City Standard was awarded to the Nan town municipality in 2018 [45], further highlighting its appeal. In addition, the local government of Nan has established a Low-Carbon City Committee (LCCC) to oversee the implementation of low-carbon development strategies and track progress towards the province's climate change targets. However, the rapid expansion of tourism in Nan has raised concerns about solid waste management [40]. The walking street and night market have been selected to implement the waste management program because it could be further applied to other provinces nationwide. The study's novelty includes the development of a framework to identify and evaluate low-carbon MSW management scenarios focusing on bio-based options and the quantitative assessment by comparing the environmental performances of different MSW management scenarios.

2. Methods

A framework has been developed to identify and assess the potential bio-based solutions for waste management in the cultural tourism destination under study.

2.1. Conceptual framework

Fig. 1 depicts the framework developed for identifying, implementing, and assessing low-carbon waste management strategies, focusing on bio-based solutions and stakeholder engagement. The framework comprises four steps, as follows: (1) Identify the environmental and societal challenges associated with tourism and MSW management; (2) Identify the bio-based options for MSW management based on the local context; (3) Identify the required components and performance indicators to promote the bio-based solutions for waste management in the tourism destination; and (4) Implement and evaluate the environmental performance of the BbS for waste management.

Step 1. Identify environmental and societal challenges related to tourism and MSW management.

The aim of this stage is to establish the objectives and goals of implementing bio-based solutions for MSW management. The stakeholders associated with the studied tourism destination are classified into three groups, i.e., municipal officials, merchants, and

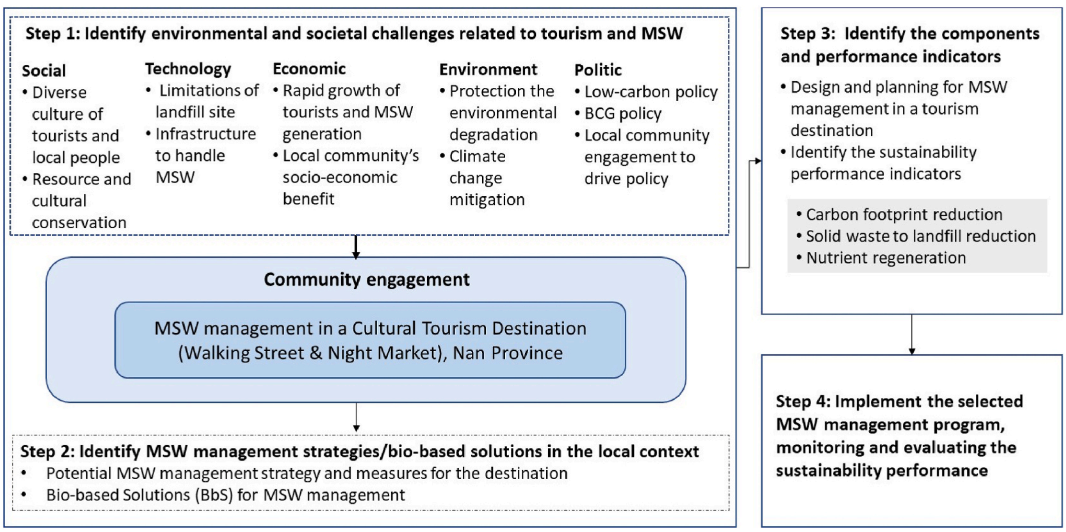

Fig. 1. Framework for implementing BbS for MSW management in the tourism destination.

tourists. Municipal officials refer to the persons assigned, appointed, and employed by the local government to organize activities and carry out various activities around the studied tourism destination. Merchants represent the entrepreneur or person who has permission to operate, trade, and carry out various activities around the study site. Tourists represent the tourists who visit and join the activities in the walking street and night market.

Nevertheless, in Step 1, the cooperation of stakeholders like the municipality officers and merchants in the local community should be involved right from the beginning, as it was identified as one of the key success factors for NBS implementation [46]. Those two stakeholders are focused because they are both directly associated with the implementation of a waste management program at the study site. Purposive sampling has been used to select the municipality officers and merchants for interviews. Face-to-face interviews have been conducted for the samples of 10 municipality offices and 30 merchants. Semi-structured protocol interviews have been done to identify the key factors influencing the selection of waste management options in the study area. The STEEP analysis has been applied to help community stakeholders identify the key drivers influencing the focal issue, i.e., promoting cultural tourism and sustainable MSW management in Nan. STEEP analysis is a tool used to identify external factors that can significantly impact an organization [47]. STEEP represents Social, Technological, Economic, Environmental, and Political. The critical social issues identified included the diverse culture of tourists and locals, which could impact their ability to adopt good practices for MSW management.

Regarding technology issues, the rapidly growing number of visitors led to an increasing amount of MSW, while the lack of infrastructure for handling MSW remains a concern. Landfills are still the conventional practice for MSW disposal in rural communities of Thailand, and many landfill sites cannot accommodate the increasing amount of MSW generated in the future. Economic driving forces for sustainable MSW management included the potential boost to Nan's economy through tourism and an increased amount of MSW generation. Additionally, a sustainable MSW management program could benefit the local community by reducing plastic waste, conserving culture, and creating income opportunities.

Regarding environmental concerns, the community is focused on climate change mitigation and the prevention of environmental degradation. On the political front, the central government's external driving forces regarding low-carbon policy and the Bio-Circular-Green economy policy encourage the municipality to work on low-carbon MSW management. However, political uncertainty can also directly affect the policy, necessitating local community engagement to drive the policy on MSW management. The involvement of local stakeholders is crucial to identify areas requiring improvement and enhancing the creation of a low-carbon waste management strategy, while expert knowledge can complement in terms of explaining the causal relationships between bio-based solutions and the community's challenges [48–50]. The key driving forces for selecting MSW management solutions are summarized in Fig. 1.

Step 2. Identify MSW management strategies/bio-based solutions in the local context.

At this step, potential MSW management strategies and bio-based solutions have been identified through discussions with stakeholders via interpersonal communication. The focus was on characterizing the location, culture, local infrastructure, and availability of natural resources to select an appropriate MSW program for implementation in the tourism destination. The key stakeholders for this step are the municipality officials and the merchants. The interviews have been done interpersonally with the same interviewees of Step 1. The description of the bio-based waste management concept has been explained to the stakeholders. Potential measures for solid waste management from the stakeholders have been collected in this stage.

Step 3. Identify the components and performance indicators.

This step aims to identify the necessary components for implementing the MSW program and sustainability performance indicators for evaluating the bio-based solutions for waste management in the tourism destination. The output of this step is the design and planning for implementing MSW management in a tourism destination. For example, the study developed a conceptual site map of "Kad Khuang Muang," which includes the walking street and night market, to select the locations for waste separation bins for MSW segregation at the source. Environmental sustainability indicators, including carbon footprint reduction (CFR), solid waste to landfill reduction (SWR), and nutrient regeneration (NR), were used to evaluate the waste management program and BbS's performance. The CFR is used to indicate the performance of GHG emissions reduction from BbS options by comparing before and after implantation. SWR and NR are used to show the performance in the reduction of the final amount of MSW sent to the landfill and the amount of nutrients that can be recovered from the food waste via soil conditioner production. A data collection plan was developed and communicated to municipality officers and merchants.

Step 4. Implement the selected MSW management program, monitoring, and evaluation.

At this step, the waste management program and BbS for waste management have been implemented. The low-carbon walking street and night market campaign have been promoted to municipality officers, merchants, and tourists through public advertisements in April 2022. The conceptual site map of the walking street and night market and the designated locations for separating MSW at the source are prepared. Descriptions of each waste management scenario have been described in Section 2.3.

The baseline data of waste generation was collected from January 2021 – January 2022. The evaluation of the impacts, including the stakeholder perception survey, has been conducted in April 2022. To assess the impacts of the waste management program, field data regarding the amount of waste generation and composition of waste were primarily collected. There were nine sorting bins set in the tourism destination, which could be classified into nine types, i.e., general waste (mixed waste), food waste, bagasse dish/container, plastic bottle, wood stick, plastic glass, single-use cutlery, plastic bag, and plastic straw. There were assistant staff to help explain the waste bins to the people so that the waste could be correctly separated to estimate the waste composition. The analysis has been done to compare the environmental performance of the waste management program before and after implementation.

A questionnaire survey was used to understand stakeholders' perceptions and opinions regarding the execution of the "Low carbon walking street and night market" campaign for MSW separation and management. The questionnaire survey was conducted in April 2022 for samples of about 330 samples, including 10 municipality officers, 40 merchants, and 280 tourists in the walking street and night market. Five research assistants who were trained in the sampling technique were recruited to conduct the questionnaire survey. The purposive sampling technique is used for the groups of municipality officers and merchants to cover various activities occurring in the walking street and night market, such as food sellers, cloth sellers, groceries, waste collectors, and walking street and market cleaners. The random sampling method is used for the perception survey of tourists. The questionnaire comprised two close-ended questions and one open-ended question. The close-ended questions were asked about (1) Whether the stakeholders agree that tourism waste is one of the contributors to GHG emissions and can affect the image of tourism destination? and (2) Which level of the stakeholders are satisfactory with the efficiency of MSW separation and waste sorting points following the waste management campaign? An open question was about the opinions regarding the problems of the ongoing waste management campaign and the suggestions for improving the existing MSW management measures toward low-carbon tourism.

The results were then shared with municipality officials and merchants to identify opportunities for developing sustainable BbS for waste management in the long term. This step also involves monitoring and evaluating the program's performance using the sustainability indicators identified in the previous step. Based on the findings, potential improvements and adjustments to the waste management program can be identified and implemented to enhance its effectiveness and sustainability. The feedback loop between merchants, tourists, and waste management program implementers (municipality staff) is crucial to ensure the long-term success of the program and the development of sustainable BbS for waste management in the tourism destination.

2.2. Study area (Nan Province, Thailand)

Nan Province covers an area of approximately 11,472 square kilometers and had a population of approximately 470,000 in 2019 [51]. The province has been experiencing steady economic growth and increased tourism in recent years. The Office of National Economic and Social Development Council (NESDC) reports that in 2020, Nan Province's Gross Provincial Product (GPP) increased by 1.8 % compared to the previous year [52]. The main industries driving the province's economy are agriculture, forestry, fishing, and tourism, particularly ecotourism and cultural tourism destinations. As shown in Fig. 2, the number of domestic and international visitors in Nan Province has consistently increased from 293,976 in 2011 to nearly one million in 2019 [53]. In 2019, visitors to Nan Province generated approximately 4.4 billion Thai Baht (THB) in revenue [54] - approximately 13 % of the total GPP of Nan Province in 2019, which was approximately 34.4 billion THB. However, the COVID-19 pandemic led to a decrease in visitors between 2020 and 2022, significantly impacting tourism and economic growth worldwide, including in Thailand. Although Nan Province offers various attractions, including cultural heritage sites and national parks, "Kad Khuang Muang" is a popular destination. Organized by the local government during weekends, the walking street spans about 500 m and passes through significant cultural heritage spots in Nan Town. The market offers a variety of products, including authentic Thai food, fruits and vegetables, natural garments, and souvenirs, mainly sourced from natural products. Visitors can also dine in groups on the floor with traditional Thai bamboo tables in a central area. Bamboo is one of the critical natural resources in Nan, and its forest resource management is therefore vital for the ecosystem and the community [55].

2.3. Low carbon waste management scenarios

Fig. 3 illustrates the conceptual site map of the walking street and night market and the designated locations for separating MSW at the source. The low-carbon walking street and night market campaign has been promoted from March to April 2022. The average number of daily visitors to the walking street and night market was approximately 1165 persons, and the average waste generation was around 0.4 t/day. The walking street activity operates only three days a week, resulting in approximately 156 days/year, from which

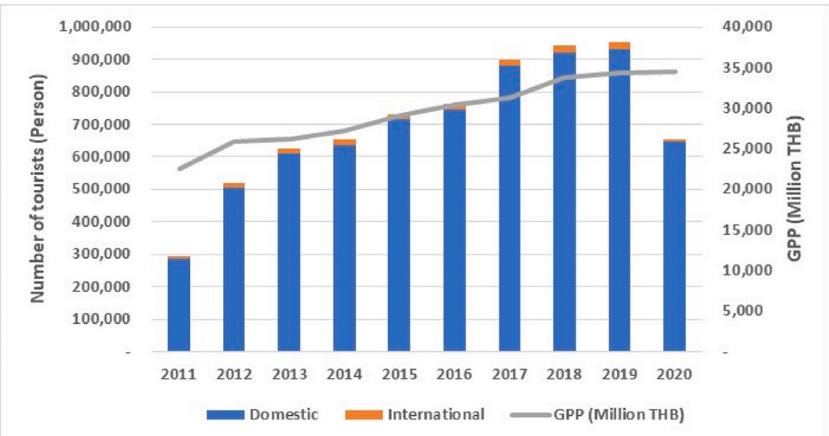

Fig. 2. Numbers of tourists in Nan Province from the year 2011–2020 and Gross Domestic Product (GDP).

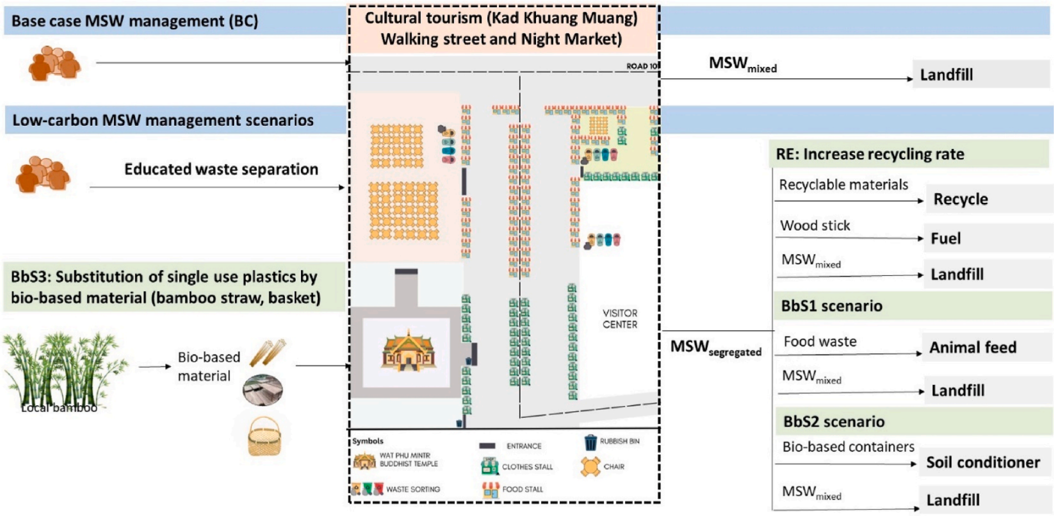

Fig. 3. Conceptual site map of "Kad Khuang Muang", designed garbage location for MSW separation and waste management scenarios.

waste generation from this tourist destination is estimated. The total number of annual tourists and visitors to the walking street and night markets is estimated to be around 181,740 persons. The assessment indicates that about 61.9 tons of solid waste would be generated annually.

A range of municipal solid waste (MSW) management systems have been established, including waste separation at source, waste recycling, and bio-based solutions for reducing single-use plastic waste and utilizing food waste through bio-based processes. These waste management scenarios have been developed based on the current solid waste issue, potential bio-based options, ease of implementation, and stakeholder feedback. The descriptions for the base case, which involves mixed waste collection and landfill, as well as the five alternative waste management and bio-based solutions scenarios, are provided as follows.

1. *Increased Recycling Rate of Waste Materials (RE):* Recyclable materials such as plastic bottles, bags, glasses, and single-use cutlery plastics are separated at the source for recycling. The remaining mixed waste is sent to the landfill. Wooden sticks are separated and used as biomass fuel. This reduces the amount of recyclable waste materials sent to landfills.
2. *Bio-based Solution Scenario 1 (BbS1):* Food waste is separated at the source and used as animal feed. The community has arranged a food waste separation facility, which means the amount of food waste sent to landfills is zero. The remaining waste is sent to the dump.
3. *Bio-based Solution Scenario 2 (BbS2):* Bagasse-based dishes and containers are separated at the source and mixed with soil to decompose. Bagasse contains approximately 2.7 % nitrogen. The resulting products are used as soil conditioners.
4. *Bio-based Solution Scenario 3 (BbS3):* Bio-based products are used as substitutes for single-use plastics. Bamboo straws are promoted as an alternative material to replace single-use plastics. A rental system is implemented to share bamboo baskets with tourists to avoid using single-use plastic bags. Based on field data, it is estimated that around 10 % of tourists have borrowed the baskets, which means that approximately 127 kg of high-density polyethylene (HDPE) plastic bag production would be avoided per year. The study does not consider the bamboo straw due to the initial stage of promotion and the lack of commercial users during the survey.
5. *Combined Management System Scenario (Combined RE + BbS1+BbS2+BbS3):* All waste management options, including RE, BbS1, BbS2, and BbS3, are combined to form an integrated waste management system. The remaining waste is sent to the landfill.

2.4. Environmental sustainability assessment of waste management scenarios

The study has identified various indicators to evaluate the environmental sustainability benefits of waste management and BbS scenarios, which are expected to have co-benefits for both human well-being and the ecosystem.

2.4.1. Carbon footprint reduction (CFR)

The study has employed the carbon footprint reduction (CFR) as an indicator to evaluate the greenhouse gas emission reduction resulting from the BbS scenarios. To assess the CFR, inventory data on material use, energy consumption, waste generation, and management for each BbS scenario were primarily collected from the study area. Equations (1) and (2) show the general equations used for carbon footprint assessment, which were used to compare the base case with the BbS scenarios. Equation (1) indicates the carbon footprint reduction, which is derived based on the comparison before and after implementation of the waste management program. Equation (2) is the general equation for estimating greenhouse gas emissions referred from IPCC (2006) [56]. Greenhouse gas emission factors were obtained from the Thailand Greenhouse Gas Management Office [57].

$$CFR = CF_{Basecase} - CF_{BbS-scenario} \quad \text{Eq. (1)}$$

$$CF = Activity\ data \times EF \quad \text{Eq. (2)}$$

The abbreviation CFR represents the potential reduction in carbon footprint (in kg CO_2e), while $CF_{Basecase}$ signifies the carbon footprint of the base case MSW management activity prior to modification by the BbS scenarios (in kg CO_2e). $CF_{BbS\text{-}scenario}$ denotes the carbon footprint of the waste management scenario proposed by BbS. Carbon footprint (CF) comprises the total greenhouse gas (GHG) emissions and removals in the system under study, expressed in CO_2e equivalents, and based on a life cycle assessment that employs the single impact category of climate change. Activity data encompasses all the quantities of materials, chemicals, and energy used in the system under investigation, while emission factors (EF) represent the GHG emission factors utilized to convert those quantities into GHG emissions (in kg CO_2e per unit of material/energy). Table 1 displays the EF values for various solid waste disposal activities by drawing upon the EF data obtained from TGO for carbon footprint assessment.

2.4.1.1. Solid waste to landfill reduction (SWR). It has been used as another indicator to evaluate the BbS scenarios to address the societal challenge regarding the limitation of sanitary landfills. The measurement is in the unit of about kilogram of solid waste to landfill. Eq. (3) shows the reduction of solid waste sent to landfills, which can be calculated by comparing the before and after implementation of the BbS scenarios.

$$SWR = SW_{Basecase} - SW_{BbS-scenario} \quad \text{Eq. (3)}$$

2.4.2. Nutrient regeneration potential (NR)

The indicator addresses the BbS scenario's potential for regenerating the soil's nutrient due to organic waste management (kg Nitrogen). Eq. (4) is derived based on mass calculation to estimate the amount of nutrients in the mass unit.

$$NR = Q_{soil,organic\ waste} \times \%Nutrient_{N,soil} \quad \text{Eq. (4)}$$

3. Results and discussions

3.1. Baseline MSW generation and GHG emission from the walking street and night market

Approximately 61.9 tonnes/year were estimated as the baseline solid waste generation from the walking street and night market. Table 2 presents the waste composition categorized into nine categories based on field data collection. The nine categories reflect the walking street activities, including food waste, bagasse dish/container, plastic bottles, wood sticks, plastic glass, single-use cutlery, plastic bags, plastic straw, and general waste (mixed waste that people did not separate). Plastic straws, with their lightweight, contributed only about 0.2 %. The mixed waste comprised food waste (21 %), garden and park waste (34 %), paper (8 %), wood (0.3 %), textiles (0.3 %), disposable diapers (1.3 %), rubber (1.6 %), plastics (21 %), metal (2.4 %), glass (9.4 %), and others (1 %) [59]. The waste was properly separated for each container due to the control of local staff and the poster indication. The nine containers used are case-specific for the studied tourism destination. The nine containers are designed based on two purposes, i.e. (1) to separate and estimate the amount of waste classified by type of waste that will be further recycled/reused and (2) to raise awareness among tourists on waste separation. In the base case, all waste generated from the walking street were sent to landfills, with an estimated carbon footprint of 197 t CO_2e/year for waste management and a zero-recycling rate. Fig. 4 shows the GHG emissions from the base case MSW management classified by waste type. It should be noted that general waste (mixed waste) management had the highest amount and GHG contribution due to its composition of organic wastes like garden and park waste and food waste that people in the walking street did not separate. The study found that some merchants had already used bagasse dishes/containers in the walking street to substitute single-use plastics. However, since all wastes will eventually be mixed and sent to landfills, there is scope for further improvement of

Table 1
Emission factors for solid waste management activities in Thailand.

Activity data	EF (kg CO_2e/kg)	Sources
Collection and unloading of municipal solid waste	0.0143	[57]
Municipal solid waste separation	0.0159	[57]
Landfill (open dump)	1.0388	[57]
Food waste landfill	2.53	[57]
Paper waste landfill	2.93	[57]
Leaves waste landfill	3.27	[57]
Wood branches landfill	3.33	[57]
Plastic waste recycling	0.4044	[57]
Food waste as animal feed	0	
Organic compost process	0.3326	[57]
Charcoal combustion	0.0023	[57]
Avoided plastics	−1.91	[58]
Avoided charcoal production	−1.0054	[57]
Avoided HDPE plastic bag	−6.7071	[57]

Table 2
Composition of waste based on on-site waste separation at the tourism destination.

Description	
General waste (mixed waste)	59 %
Food waste	30 %
Bagasse dish/container	5 %
Plastic bottle	2 %
Wood stick	1 %
Plastic glass	1 %
Single-use cutlery	1 %
Plastic bag	0.8 %
Plastic straw	0.2 %

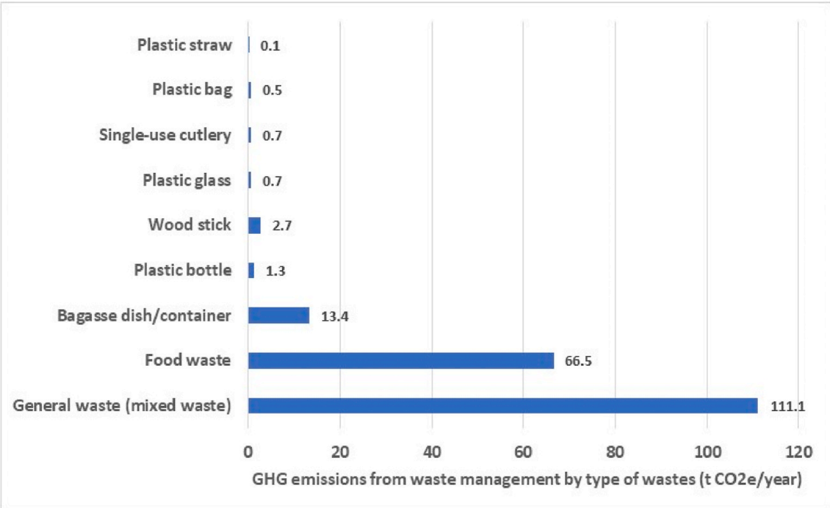

Fig. 4. GHG emissions for the existing MSW management system (Base case).

these bio-based materials to maximize the biomass benefits. It must be noted that, in practice, proper waste separation in a tourism destination is challenging and essential to the success of a waste recovery and management program. Therefore, encouraging and maintaining good waste separation requires several measures, especially not only the physical components like the separated containers. The interventions to raise awareness and motivation of tourists for waste separation, as well as the measures to increase engagement of local communities in waste separation efforts, are necessary [60,61]. The number of containers used should be designed with a clear purpose for further managing the separated waste. To address those challenges, tourism destinations must implement comprehensive waste management strategies involving education, infrastructure development, community engagement, and effective communication with tourists.

3.2. Environmental performances of MSW management and BbS scenarios

Table 3 displays the environmental performances of various waste management scenarios. The findings indicate that the BbS1 scenario, which results in a GHG reduction of 66.3 t CO_2e/year, has the highest performance, followed by the RE, BbS2, and BbS3 scenarios. The reduction in food waste in landfills, which amounts to 18.6 t/year and is the primary contributor to GHG emissions in the solid waste management system, is the main cause of the BbS1 scenario's significant GHG reduction. Using bagasse container waste to create soil amendments for agriculture can also help reduce GHG emissions (12.3 t CO_2e/year) and solid waste sent to landfills (3.1

Table 3
Waste management scenarios and their environmental performances.

Waste management scenarios	GHG reduction (CFR) (t CO_2e/year)	Solid waste to landfill reduction (SWR) (t SW/year)	Nutrient Regeneration (NR) (kg N/year)
RE: Increase recycling rate, i.e., plastics and wood sticks	11.0	3.7	–
BbS1: Food waste separation at source and used as animal feed	66.3	18.6	–
BbS2: Bagasse container is used to produce soil conditioner	12.3	3.1	84
BbS3: Substitution of single-use plastics by bamboo products	1.0	0.1	–

t/year), as well as return 84 kg of nitrogen to the soil, which aligns with the circular economy's biological materials concept. Bagasse soil amendments can also improve soil hydro and physical-chemical characteristics [62,63].

Increasing the recycling rate by segregating recyclable plastic waste and wood sticks (RE scenario) can reduce 11 t CO_2e/year. The net GHG reduction credits result from the tradeoff between the increase in GHG emissions from the plastic recycling process and the GHG reduction achieved by avoiding the production of virgin plastic. The BbS3 scenario demonstrates the sharing economy's benefits, which can help reduce waste generation at the source by avoiding the use of plastic bags.

Although the community is interested in promoting local bamboo products, such as bamboo straws to replace single-use plastic, the practice is still in its early stage. It needs to become commercially viable due to cost concerns. The utilization of bamboo straws has limitations in terms of carbon footprint reduction. According to a literature review, the carbon footprint of a bamboo straw is greater than that of a plastic straw, ranging from 257 to 292 % in the case of single use of both straws [64,65]. However, there is considerable variation in the results due to assumptions about the bamboo product's reuse numbers, bamboo cultivation, product manufacturing, and life-cycle assessment methodological choices [66]. Furthermore, several studies have shown that bamboo products could yield lower CO_2e values [66].

3.3. Integrated solid waste management and combined BbS scenarios

Fig. 5 depicts the GHG emissions and credits resulting from the combined solid waste management scenarios compared to the base case. The net GHG reduction from the combined scenario is estimated to be 90.3 t CO_2e/year. The BbS1 scenario individually yielded the highest GHG reduction potential due to avoiding food waste in landfills. Integrating all four waste management scenarios could reduce 41 % of waste going to landfills. The remaining MSW that needs to be sent to landfills is estimated to be about 36.4 t/year (as illustrated in Fig. 6).

However, the study has identified a challenge in handling mixed waste that tourists and the community cannot separate, which amounts to around 36.5 t/year. To address this issue, upstream measures for MSW management, such as separating food waste and leaves from the major sources, training and raising awareness on recyclable waste separation, increasing separate waste collection by type and day of collection, and rewarding communities for good waste separation should be promoted. It is also essential to establish a partnership program, hold regular meetings with relevant stakeholders, develop an action plan, and monitor the implementation of measures to enhance waste recycling. One of the critical barriers to successful MSW management in the tourism destination is the attitude and participation of tourists. The results from the questionnaire survey of stakeholder perceptions regarding waste management and waste separation in the walking street revealed that 93 % of the participants agree that solid waste generated by tourism is a problem that can affect the destination. In comparison, only 3 % disagree, attributing the problem to people's lack of awareness of waste disposal. The major problem with the existing waste management system in the walking street is the need for more drop-off areas for waste and signs informing people of the location of garbage bins.

3.4. Recommendations for sustainable MSW management approaches

3.4.1. Residual waste (mixed waste) management

At present, there is still residual waste (mixed waste) sent to landfills, which BbS options could potentially manage if that residual waste was properly sorted. It was estimated that if those residual waste were properly handled, the carbon footprint of waste management could be reduced from 106.7 t CO_2e/year (Scenario: RE+BbS1+BbS2+BbS3) to 32.7 t CO_2e/year, resulting in a potential reduction of 164.3 t CO_2e per year compared to the base case (BC). The additional GHG emissions arise from the assumption that food waste and garden and park waste, accounting for approximately 20 t/year, are separated and used as fertilizer. The nitrogen content of

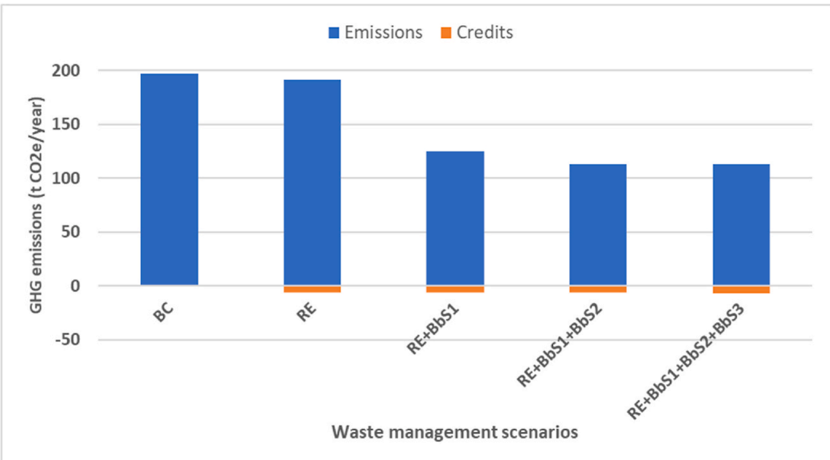

Fig. 5. GHG emissions comparison between the base case and the combined waste management scenarios.

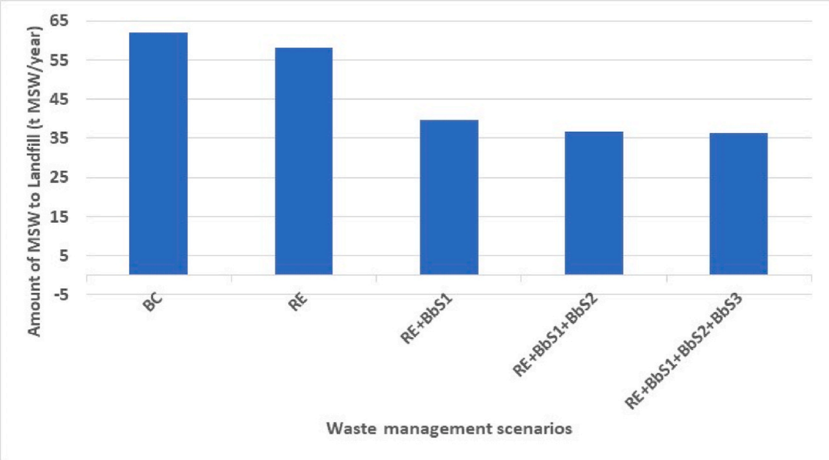

Fig. 6. Comparison of the amount of solid waste to landfill.

food waste compost ranges from 0.3 to 0.9 %. Fig. 7 compares the environmental sustainability indicators between the combined scenario of RE+BbS1+BbS2+BbS3 and the scenario that residual waste is sorted and managed using BbS options or the so-called "Residual waste management scenario." The results demonstrate that the latter could significantly reduce GHG emissions, reduce waste to landfill, and increase nitrogen regeneration in the soil for agriculture compared to the former. It must be noted that all four waste management scenarios proposed in the study are in line with the national policy of the Royal Thai government on Bio-Circular-Green economy promotion. The nutrient recovery for agriculture from food waste has clearly shown as the advantage of the biological cycle in the circular economy model.

3.4.2. *Factors for successful implementation of BbS scenarios for MSW management*

The successful implementation of BbS scenarios for solid waste management in the tourism destination required participation from all stakeholders. BbS1 and BbS2, which involve food waste separation for animal feed and using bagasse container waste as soil amendments, were acceptable by the community. This justification was based on the evidence in the actual situation that those two scenarios have been widely implemented by merchants in the tourism destination. The questionnaire survey about stakeholder perception on the BbS options has shown only the concern about limitations in the use of bamboo straw (BbS3), such as the costs and

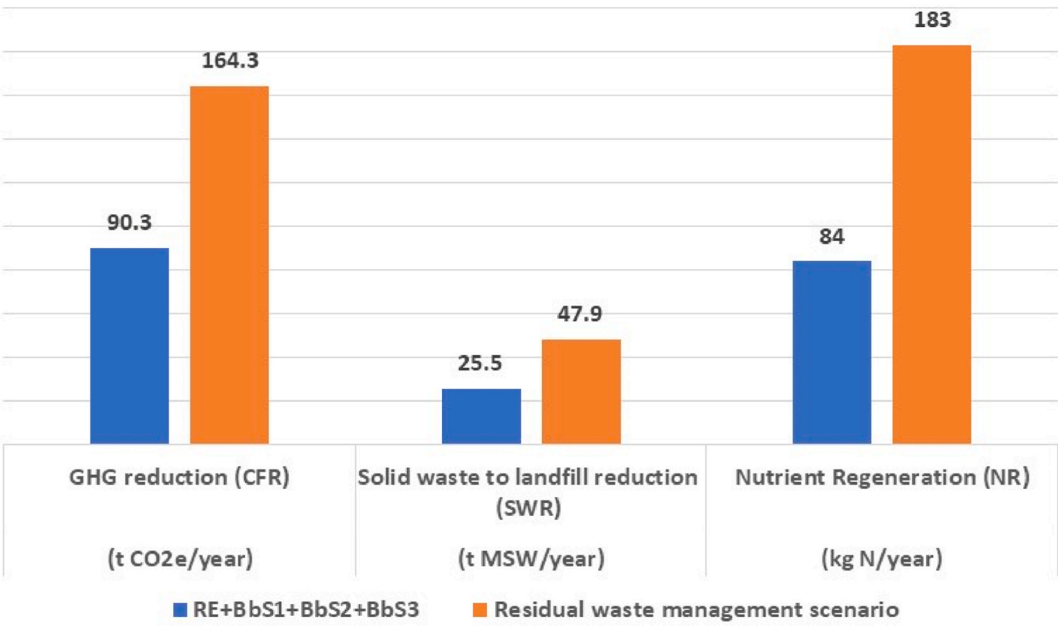

Fig. 7. Comparison of CFR, SWR, and NR indicators between the combined scenario: RE+BbS1+BbS2+BbS3 and the residual waste management scenario.

difficulty in using the bamboo straw to substitute the single-use plastics. In addition, the operational constraints are about the waste separation and collection system for reuse and recycling. In terms of environmental sustainability, life cycle GHG emissions for bio-based products such as bagasse containers and bamboo straws are uncertain. They may result in greater GHG emissions than plastic-based containers due to factors such as the higher weight of bagasse containers needed to deliver the same performance as plastic containers and the reuse numbers for bio-based products [37,66]. It must be noted that the environmental performance result such as the nutrient regeneration rate could be varied in practice. The variations stem from several factors, such as types and quality of organic waste used for fertilizer/soil conditioner production [67], soil properties, and types of agricultural fields and how the practice used to apply the fertilizer to the soil such as surface spreading or put in the underground [68,69].

It should also be emphasized that a one-size-fits-all approach might not yield optimal results. There are several limitations to borrowing the BbS options of the study to implement in other tourism destinations. The differences in socio-cultural factors can significantly influence how waste management practices are adopted and sustained within a community. For example, implementing waste management options in rural may differ from in urban areas due to the variations in infrastructure, waste collection services, and population densities. Food waste for fertilizer/soil conditioner production proposed in Nan may be challenging to implement in the urban area as there is not enough space for fertilizer production and no demand for agricultural fields. However, for a small cultural tourism destination in Thailand, which has a smaller population of tourists than Nan, traditional packaging like banana leaf packaging and waste management practices like composting, mulching, and rural recycling can be suitable. The use of bamboo straw, as suggested in Nan, may not be applicable to other tourism sites because of the lack of bamboo resources. Hence, it is recommended that, for future study in other tourism destinations, the bio-based options should also be designed specifically for the available bioresources.

Stakeholder perceptions have been identified as a key success factor in implementing nature-based solutions [48]. However, stakeholders' awareness and perception of solid waste problems and climate change risks can be diverse [70]. How people perceive waste problems and waste management approaches can vary by factors such as knowledge, experience, education, and awareness about environmental issues. Well-informed individuals can understand the consequences of improper waste disposal and respond actively to the survey questionnaire. It is important to ensure that stakeholders are fully aware of the challenges posed by solid waste and climate change. Hence, the trained staff as interviewers are required to avoid non-response bias, i.e., when a subset of stakeholders chooses not to participate in the survey or does not respond appropriately, which can result in different opinions from those who do respond and lead to the results perception biases. Activities that raise awareness and understanding of these issues are necessary for all stakeholders.

Additionally, adoption rates of innovative MSW management measures or technologies can differ according to the diffusion of innovation theory [71,72]. Therefore, it would be helpful to understand the characteristics of stakeholders in the tourism destination to appropriately assign responsibilities to relevant groups [73]. Although the study's findings potentially make several contributions, some limitations should be addressed in future research. First, the purposive sampling survey is used in this study for the groups of merchant and municipality officers to cover the responsibility of officers and types of merchants; hence, for future studies, the random sampling should be fully applied in the future along with the statistical analysis. Second, the study applies only three environmental sustainability indicators to address the site's environmental issues i.e., solid waste generation and climate change of the study site. The other sustainability indications, e.g., financial performance and socio-economic impact, can be integrated to cover all the sustainability dimensions. Finally, the recommended key activities for implementing bio-based solutions include (1) clearly defining goals and objectives, (2) engaging stakeholders, (3) selecting appropriate solid waste management and BbS approaches based on the tourism destination's context, (4) designing and implementing BbS based on best practices, (5) monitoring and evaluating performance, and (6) ensuring long-term maintenance and management by establishing partnerships or other support mechanisms.

The findings of this study can significantly contribute to formulating policies that prioritize low-carbon and bio-based waste management solutions. Until now, the community's focus has largely centered on the issue of plastic packaging, with an emphasis on promoting bio-based containers. Nevertheless, the study has brought about the critical role of food waste volume in contributing to global warming. In line with the Thai government's objectives of achieving low-carbon tourism and creating low-carbon cities, addressing the challenge of food waste has taken precedence. Consequently, the local government is expected to intensify efforts related to food waste separation and management. Bio-based options, such as utilizing food waste as animal feed and raw material for soil conditioner production, have been identified as promising options. Moreover, implementing the study's framework, along with the outcomes of using the quantitative assessment approach, such as the waste composition and the environmental performance indicators, can catalyze policy changes. These changes include data-driven decision making, setting targets for waste reduction, prioritizing bio-based options with superior environmental outcomes, i.e., CFR, SWR, and NR, and promoting global collaboration by sharing best practices with similar tourism destinations.

4. Conclusions

The study has developed a framework to identify and evaluate low-carbon MSW management scenarios for the tourism destination using a real-world case of "Kad Khuang Muang", Nan province, Thailand. Bio-based Solutions have been developed as the low-carbon waste management scenarios. The environmental performances of four MSW management scenarios were assessed and compared using the three indicators, i.e., CFR, SWR, and NR. The results revealed that, in the BbS1 scenario, the use of food waste as animal feed showed the highest GHG reduction performance, followed by the scenarios of increasing recycling rate (RE), use of bagasse containers waste as a soil conditioner (BbS2), and replacing single-use plastics with bamboo products (BbS3), respectively. Nevertheless, the BbS2 scenario has the additional benefit, i.e., returning around 84 kg N/year to soil. The implementation of combined all scenarios, i.e., RE, BbS1, BbS2, and BbS3, could reduce the amount of waste sent to landfills by around 25.5 t MSW/year and mitigate GHG emissions by about 90.3 t CO_2e/year. Enhancing residual waste (mixed waste) management is recommended, which in turn could totally mitigate the GHG emissions by about 164.3 t CO_2e/year or equivalent to about 83 % GHG emissions reduction compared to the base case. The study results contributed to prioritizing low-carbon and bio-based waste management solutions. The use of a real case study has provided tangible and actionable insights. The community engagement in the waste management implementation showed the acceptability of the proposed waste management scenarios. The framework proposed can be further used by other researchers or policymakers in other contexts.

Data availability statement

Data included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Thammananya Sakcharoen: Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Wilailuk Niyommaneerat:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Bualuang Faiyue:** Methodology, Resources, Writing – original draft. **Thapat Silalertruksa:** Conceptualization, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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