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Research article

Municipal solid waste management for reaching net-zero emissions in ASEAN tourism twin cities: A case study of Nan and Luang Prabang

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HIGHLIGHTS

- Three waste management scenarios were developed to achieve net-zero GHG emissions from waste sector in Nan and LPB by 2030.
- All developed scenarios in both cities could achieve net-zero emissions by 2030.
- On-site waste sorting is the key for waste management to achieve net-zero emissions.
- The composition of waste is a significant impact on greenhouse gas emissions.
- At average carbon price of 28.42 USD/tCO₂e, all scenarios in Nan and LPB were feasible, except for scenario 2 in LPB.

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ABSTRACT

Waste generation rates have increased with rapid population and economic growth worldwide, especially in tourism cities. Nan Province and Luang Prabang (LPB) are twin cities that have been popular tourist destinations. The impact of unmanaged waste threatens the socioeconomic environment in both places. Three waste management scenarios were developed to achieve net-zero greenhouse gas (GHG) emissions from the municipal solid waste (MSW) sector in Nan and LPB by 2030. Sensitivity and benefit–cost (B/C) analyses were performed, and alternative scenarios were proposed. With the use of available waste management technology, all developed scenarios in both locations could achieve net-zero emissions within the difference contexts of the city such as waste composition. From this study, on-site waste sorting is the key for waste management to achieve net-zero emissions. Sensitivity analysis revealed that, with an average carbon price of 28.42 USD/tCO₂e, all scenarios in Nan and LPB were feasible, except for scenario 2 (off-site waste sorting) in LPB. This study found that it would be challenging but achievable to reach the net-zero emissions target. The challenge includes the increased on-site waste separation rate and raising public awareness concerning municipal solid waste management as well as its importance for effective waste management. These developed scenarios show a pathway for the waste sector to achieve net-zero emissions by 2030 with available waste management technology in Nan and Luang Prabang, and the possibilities for other locations facing similar situations.

1. Introduction

Following the adoption of the Paris Agreement in December 2015, the goal of “achieving net-zero emissions” has gained political and economic momentum in the context of sustainable development. Countries in regions around the world have explored initiatives to raise the awareness and participation of all stakeholders to reach net-zero emissions by 2050 (World Bank, 2021). The 26th UN climate change conference of the

parties (COP26) in 2021 was the most important summit since the 2015 Paris Agreement. At the end of COP26, new climate plans were submitted by countries with ambitious emission reduction goals by 2030 that aligned with achieving net-zero by the middle of the century (Mountford et al., 2021). The concept of “net-zero emissions” is the balance between greenhouse gas (GHG) emissions and removal by sinks or “negative emissions” (Emele et al., 2019). It affects the direction of development internationally, particularly concerning policies, technology

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development, and the production process. Carbon neutrality, sometimes referred to as zero emissions, means that activity releases net-zero carbon emissions into the atmosphere. Therefore, many countries have explored cost-effective pathways to achieve net-zero emissions. The pursuit of long-term targets by achieving net-zero emissions must be implemented through the substantial transformation of key carbon-emitter sectors (Rogelj et al., 2015). Establishing the implementation of the Paris Agreement will require the development of policies and measures toward the “net-zero” goal. Thus, the long-term scenarios explore the options and determine possible pathways to meet the purpose.

Municipal solid waste (MSW) is a significant anthropogenic source of methane (CH₄) emissions (Singh et al., 2018). The anaerobic decomposition of MSW in open dumps and landfills generates gas consisting of approximately 60% methane (CH₄) and 40% carbon dioxide (CO₂). The uncontrolled CH₄ emissions from landfills and other waste disposal have been listed as the second-largest anthropogenic CH₄ emissions source, contributing up to 19% of global CH₄ emissions (67–90 million tons of CH₄ per year) (IPCC, 2013). According to the World Bank report, about 2.01 billion metric tons of MSW are produced worldwide each year. This figure is expected to grow to 3.40 billion tons by 2050 (Kaza et al., 2018). With increased urbanization, changing lifestyles, and intensifying consumption, solid waste management is expected to become more complicated, particularly in developing countries. Differences in the amount of MSW generated should reflect each nation's or municipal area's state of socioeconomic growth and the nature of specific lifestyles. At present, waste management is a serious problem in low-income and middle-income nations in Southeast Asia because of the environmental pollution from waste disposal (Tun and Juchelkova, 2019). Rapid economic growth has overloaded the capacity of municipal authorities to provide even basic services in many cities in developing countries. Tourism is an important industry driving economic and social development in many regions, especially in developing countries with unique cultural, historical, and natural resources (Munoz and Navia, 2015). It has become an important business sector in recent years, contributing 9.8% of global GDP and representing 7% of the world's total exports (UNWTO, 2019; Rasool et al., 2021). However, the expansion of tourism has caused waste problems. Solid waste generation is a relevant environmental aspect arising from touristic activities (Munoz and Navia, 2015). The impact of tourism on MSW generation threatens the ecological balance because of its waste production in many emerging economic cities in ASEAN (Chheang, 2013; Vilaysouk and Babel, 2017; Manomaivibool and Noithammaraj, 2018; Agarwal et al., 2019; Widayarsana and Agustina, 2019). Nan Province in Thailand and Luang Prabang (LPB) city in Lao People's Democratic Republic (Lao PDR) are cities in Association of Southeast Asian Nations (ASEAN) that have been popular tourist destinations for many years (NESDC, 2016; JICA, 2016). The rapid expansion of tourism has resulted in problems and negative side effects that threaten cultural and local identities (Chheang, 2013; Agarwal et al., 2019). The number of tourists has been increasing rapidly in recent years, and environmental problems have arisen with the increasing amount of waste produced (Mateu-Sbert et al., 2013). As a result, the trend of MSW generated annually in Nan city grew at a combined annual growth rate (CAGR) of approximately 4.69% during 2011–2017. In LPB, the MSW generated during 2005–2018 increased at a CAGR of approximately 9.77%. The Booklet on Thailand State of Pollution by the Pollution Control Department (PCD) reported that the total amount of Nan Province MSW generated in 2018 was 166,450 tons (PCD, 2019). MSW is collected by local administrative organizations that have solid waste management systems, which then deliver it to disposal sites. Approximately 16% of the total MSW was disposed of in a landfill, while another 35% of the total MSW was sorted at its source and re-utilized. Most of the re-utilized waste was used for recycling and natural fertilizer-making purposes. Approximately 49% of total MSW, including uncollected waste from uncovered areas of MSW collection services, was still disposed of improperly. For LPB, JICA reported that the total amount of MSW generated in 2012 was 24,820 tons (JICA, 2012). A prediction of

29,419 tons of waste by 2015 was also reported (Vilaysouk and Babel, 2017). The Urban Development Administration Authority of LPB and local private contractors handle MSW collection and disposal. Approximately 68 % of the MSW collected was disposed of in an unmanaged landfill, with only 3% of MSW being recycled. The amount of uncollected waste, which comes from uncovered areas of MSW collection services, is 29 percent, and the disposal method is unknown (Vilaysouk and Babel, 2017). The cities of Nan and LPB aim to sustain their cultural and traditional identities by using the tourism sector as their main source of revenue to stabilize economic growth, preserve natural resources, and protect the environment. Both cities focus on ecotourism or low-carbon development to ensure sustainable tourism. The concept of a low-carbon city, which integrates GHG emission options with resource management and the needs of the local people, is introduced to Nan and LPB to achieve net-zero emissions (Pongthanasawan et al., 2018). Therefore, appropriate MSW management must be implemented to reduce GHG emissions and MSW and to protect the environment in the cities. A clean city offers an attractive environment for investment and tourism, resulting in it being economically competitive and more able to create new jobs and business opportunities for local entrepreneurs (World Bank, 2017).

The present study aimed to develop waste management scenarios to achieve net-zero GHG emissions from the MSW sector in the twin cities (Nan and LPB cities) by 2030 in the area context. The GHG emissions and projection during 2017–2030 from the MSW sector in Nan and LPB were evaluated to design appropriate waste management scenarios. In addition, sensitivity and benefit–cost (B/C) analyses of the developed scenarios were performed, and alternative scenarios for the MSW waste management that fit the local context of the selected cities were proposed. The remainder of this paper is organized as follows. Section 1 represents the introduction. Section 2 reviews the related literature. Section 3 presents the background of study areas and methodology. Section 4 provides results and discussion. Finally, Section 5 contains conclusions and possible directions for future research.

2. Literature review

Many countries are implementing mitigation strategies in MSW to reduce GHG emissions. Various studies focused on waste management and GHG emission reduction to achieve net-zero emissions. MSW management, including waste management scenario development and waste management optimization, is the main action aimed at reducing GHG emissions.

Various studies have attempted to develop different waste management scenarios to reduce GHG emissions from the waste sector. Such scenarios are essential for policymakers to develop strategies for future planning, investment, and implementation of improved MSW management. For example, Dong et al. (2017) studied waste reduction scenarios to reduce GHG emissions from the waste sector in Hong Kong. They also evaluated GHG emissions from the waste sector and developed future scenarios. The study proposed appropriate scenarios of future carbon emissions from the waste sector. Hoa and Matsuoka (2015) analyzed waste management scenarios for reducing GHG in Vietnam and, Tun and Juchelkova (2019) studied waste management scenarios for reducing GHG in Myanmar. Pujara et al. (2019) designed three waste management case scenarios for 2001–2051 based on sustainable development goals 2030 of India. Moreover, Kristanto and Koven (2019) designed the four waste management scenarios to select the best scenario based on the greatest potential reduction of GHGs. Several studies showed that improved waste management could directly reduce GHG emissions from the waste sector. Obersteiner et al. (2021) examined the potential GHG emission reduction from three selected waste management options: prevention of food waste, reductions in single-use plastic, and increase of separate collection and recycling waste.

Management of MSW has become a momentous environmental issue in many countries (Alam and Qiao, 2020). Several studies on MSW

disposal have focused on optimizing waste management. Optimization models for MSW management were developed to serve as a solid waste decision support system for MSW management considering socioeconomic and environmental factors. For instance, [Habibi et al. \(2017\)](#) proposed an optimization model to establish an MSW management system considering social development, economy, and environment and to minimize the cost and GHG emissions. [Hoa and Matsuoka \(2015\)](#) constructed a holistic quantification model that can be used to estimate waste generation and evaluate the potential reduction of GHG emissions in the waste sector. [Ooi et al. \(2021\)](#) developed an optimization model to determine the optimum allocation of different types of MSW management in Malaysia from the perspectives of cost and GHG emissions. They also reviewed several optimization studies in MSW management. Results revealed that the cost of waste management is the most frequently used objective of studies. Analysis of waste management costs is helpful to local policymakers in various aspects, such as designing waste management tax/charges or subsidies at the municipal level. Some studies performed the cost analysis of MSW management in many cities. [Papargyropoulou et al. \(2015\)](#) evaluated the environment and economic performance of several low-carbon measures in the waste sector at a city level. They also suggested the most cost-effective and carbon-effective low-carbon measures for the waste sector at a city level. [Bong et al. \(2017\)](#) applied the GHG emission and B/C analyses of community organic waste composting in Iskandar Malaysia. [Asefi and Lim \(2017\)](#) analyzed the fixed cost, transportation cost, and total suitability of the MSW management system in Tehran. [Ayeleru et al. \(2021\)](#) conducted a B/C analysis of setting up a MSW recycling facility in Soweto, South

Africa and proved the viability of the project based on five scenarios tested in the sensitivity analysis.

Review of the literature shows that the reduction of GHG emissions from MSW management could contribute significantly to the mitigation of GHG. It can also contribute to achieve net-zero emission in the waste sector. Existing works related to waste management focused on the environmental, economic, and social aspects. The waste composition and waste management technology differ in every city or region; thus, reaching an optimum waste management for reducing environmental impacts is necessary for each local context. However, few studies focused on GHG emission reduction in the MSW sector at a city level within a developing country. Moreover, the environmental, economic, and social aspects and local context area of the options to manage waste must be considered. Therefore, MSW management must be studied to estimate suitable methods for waste management to achieve net-zero emission in the waste sector. Nan and LPB were selected as a case study of the small-size city in a developing country with relevance or similarity to other developing countries facing similar challenges.

3. Methodology

3.1. Background of study areas

Nan city in Thailand and LPB city in Lao PDR, twin ASEAN cities with collaboration in their cultural, environmental, and tourism sector aspects, were selected as the study areas. [Figure 1](#) shows the location of the study areas. Both plan to become sustainable cities through a low-carbon



Figure 1. The location of the study areas (source: Google Map, 2020).

approach. Tourism has an impact on municipal solid waste generation in both cities. Recently, Lao PDR and Thailand have improved their connectivity with a new road connecting the Thai border at Nan Province with LPB Province in Laos (NEDA, 2019). Nan and LPB are important tourist destinations when traveling between both cities is easier, which encourages foreign tourists from LPB to travel to Nan Province (ITD, 2019). This connectivity helps cut travel time for visitors and boost tourism in both cities. The scope of this study is to evaluate the GHG emission from MSW at the city level (Nan and LPB cities). Table 1 shows the background information for Nan and LPB. Nan is a province of Thailand that is located in the east region of northern Thailand. Nan Province has become a popular destination for many years since the concept of sustainable tourism. Tourism with environment- or ecological-friendly activities has been widely recognized. In 2015, revenue from the tourism sector in Nan was estimated to be 1882.03 million baht, which is 19% greater than that in 2013 (Nan NSO, 2018). The number of tourists has been increasing rapidly in recent years, which negative impacts the natural environment. Luang Prabang is located in the north of Laos. The town of LPB has been a United Nations Educational, Scientific and Cultural Organization World Heritage site since 1995. LPB is a center of economics, education, and trading in northern Laos. It is a popular tourist attraction since it was proclaimed as a world heritage site. Since 2010, international visitor arrivals have grown by 77% (MICT, 2015). The rapid expansion of urbanization and tourism has increased the amount of MSW in both cities. The trend of MSW generated annually in Nan city grew at a CAGR of approximately 4.69% during 2011–2017. In LPB, the MSW generated during 2005–2018 grew at a CAGR of approximately 9.77%.

3.2. Calculation and estimation of GHG emissions from solid waste disposal to landfill

This study focused on the major GHG generated from MSW management which was directly generated by waste and the solid waste disposal sites. Secondary data (i.e., waste composition, amount of waste) were collected from reports, government organizations, and field surveys. GHG emissions were estimated in accordance with the methods of the Intergovernmental Panel on Climate Change (IPCC) Guidelines (IPCC, 2006). The first-order decay model recommended by IPCC guidelines was used in the calculation for this study. Emissions factors were based on country-specific values. Default values from the 2006 IPCC Guidelines were used when country-specific values were unavailable.

CH₄ emissions were converted to 25 times of global warming potential higher than carbon dioxide equivalents (CO₂e) (IPCC, 2006). On the basis of the availability of the MSW data in the study area, the CH₄ generated from open dump and landfill was estimated as described in Eq. (1):

$$CH_4 \text{ Emission} = [(MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times (16 / 12) - R) \times (1 - OX)] \tag{1}$$

where CH₄ Emission is methane emissions from landfill in gigagrams per year; MSW_T is the total solid waste generation (Gg/year); MSW_F is the fraction of solid waste disposed of in wet weight basis; MCF is the methane correction factor (0.8 and 1 as recommended values of IPCC for the unmanaged landfills and managed landfills, respectively); DOC is degradable organic carbon in MSW (Gg C/Gg MSW); DOC_F is the fraction of DOC that can decompose (fraction) (0.5 as a default value of IPCC); F is a fraction of CH₄ by volume in generated landfill gas (0.5 as a default value of IPCC); R is recovered CH₄ in year T; 16/12 is the molecular weight ratio of CH₄/C; and OX is the oxidation factor (0.10 and 0.00 or sanitary landfills with landfill covers and open dumpsites, respectively, as a recommended value of IPCC).

3.3. Scenario development

According to the waste hierarchy model, solid waste management practices have identified the reduction, recycling, and reuse of waste as being essential for the sustainable management of resources (Pires and Martinho, 2019). By following the waste hierarchy concept, the potential waste treatment technologies were selected to follow the waste composition of the selected cities, which is appropriate to the local area. The chosen base year was 2017 because of the data availability in both cities during that time. This study formulated three waste management scenarios to achieve net-zero GHG emissions from the waste sector by 2030. The on-site waste sorting ratio and off-site waste sorting ratio were also explored to achieve this goal. On-site and off-site waste sorting are described below.

On-site waste sorting is the process by which waste is separated into different elements at the sources of waste generation, such as household, office, hotel, store, supermarket, and restaurant waste.

Off-site waste sorting is the process by which waste is separated into different elements at the landfill site where wastes are sorted and dumped. Off-site sorting includes the recycled waste collected by scavengers.

Table 1. Background information of Nan and Luang Prabang.

Items	Nan city	Source	Luang Prabang city	Source
Population	20,595	(Nan NSO, 2018)	90,400	(LSB, 2015)
Area (km²)	7.6	(Nan NSO, 2018)	857	(LSB, 2015)
Population density (people/km²)	2,710	(Nan NSO, 2018)	106	(LSB, 2015)
Gross Provincial Product (GPP) (USD/Capita)	2,370	(NESDC, 2020)	1532	(JICA, 2016)
MSW generated rate (kg/capita/day)	0.85	(TGO, 2018)	0.65	(IGES, 2012)
MSW Component (%wt)	Nan	(TGO, 2018)	Luang Prabang	(IGES, 2012)
- Food waste	6		51	
- Garden and Park waste	27		23	
- Paper/Cardboard	16		8	
- Textiles	3		1	
- Plastics	13		9	
- Metal	10		1	
- Glass	11		6	
- Others	14		1	
Total	100		100	
Combined annual growth rate (CAGR) of MSW (%)	4.69%		9.77%	
MSW management method	Landfill		Landfill (Open dump)	

Table 2. Waste management scenario description.

Scenario	Description
Business-as-usual (BAU)	BAU represents the current situation of MSW management. MSW is assumed to be unsorted in this scenario. In this case, waste management would proceed as normal practice in 2030, in which all MSW would be disposed of in a landfill.
Scenario1 (On-site waste sorting + Landfill) <	S1 aims to increase the amount of <i>on-site waste sorting</i> ($x\%$) in both cities. In this scenario, MSW is assumed to be sorted at the sources of waste generation. Where paper, plastic, metal or glass have been separately collected, they must not be mixed with other waste or materials, such as food waste. The combination of composting, recycling is proposed as an option for on-site sorting. Finally, the secondary waste amounts from on-site sorting would be disposed of in a landfill without off-site sorting (Figure 2).
Scenario2 (Off-site waste sorting + Landfill)	S2 aims to increase the amount of <i>off-site waste sorting</i> ($Y\%$) in both cities. MSW is assumed to be sorted at the landfill site where waste is sorted and dumped. The waste amounts from off-site sorting would be disposed of in a landfill without on-site sorting. In this scenario, the combination of composting, recycling, and refuse-derived fuel (RDF) is proposed for off-site sorting (Figure 3).
Scenario3 (On-site waste sorting + Off-site waste sorting + Landfill)	S3 aims to increase the amount of <i>on-site waste sorting</i> ($x\%$) and <i>off-site waste sorting</i> ($y\%$) in both cities. In this scenario, the proportion of on-site waste sorting is assumed equal to that of off-site waste sorting ($x = y$). For the process in scenario 3, waste is sorted at the source of waste generation, and the secondary waste amounts from on-site sorting are separated at the landfill site where wastes are sorted and dumped. Then, it would be disposed of in a landfill (Figure 4).

Three waste management scenarios are described in Table 2 and Figures 2, 3, and 4. The Business-as-usual (BAU) scenario represents the current situation of MSW management without any sorting in both cities. These include the generation, collection, and disposal of solid waste from

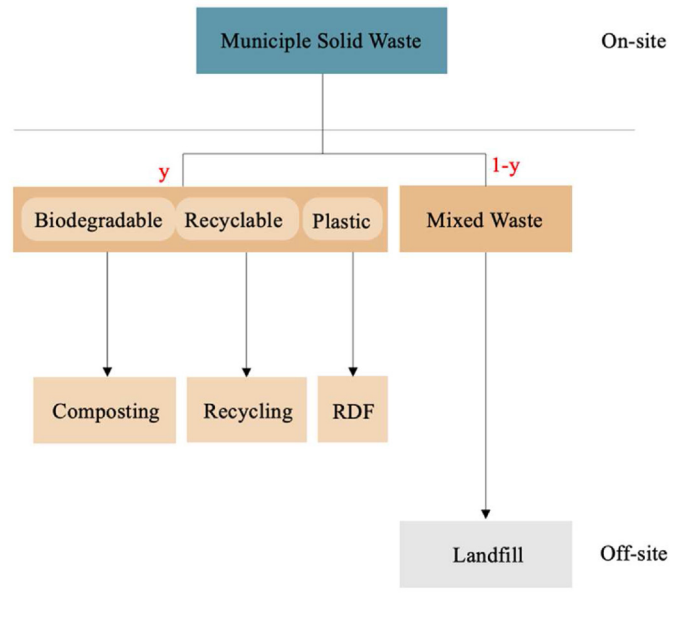


Figure 3. Waste management scenario 2 (Off-site waste sorting + Landfill).

the source. In the BAU case, all MSW would be disposed of in a landfill. In developing countries, the composition of waste changes gradually as a result of steady economic growth and changes in consumer behavior. Therefore, waste composition in this study was assumed uniform during 2017–2030 for estimation (Tun and Juchelkova, 2019).

Table 3 presents the avoided GHG emissions of waste management options to estimate avoided emissions from the developed scenario. For the waste management method, composting and recycling were selected because the MSW of the study area mostly constitutes organic and recyclable waste. Composting can constitute a viable alternative for the management of the organic fraction of MSW in developing countries

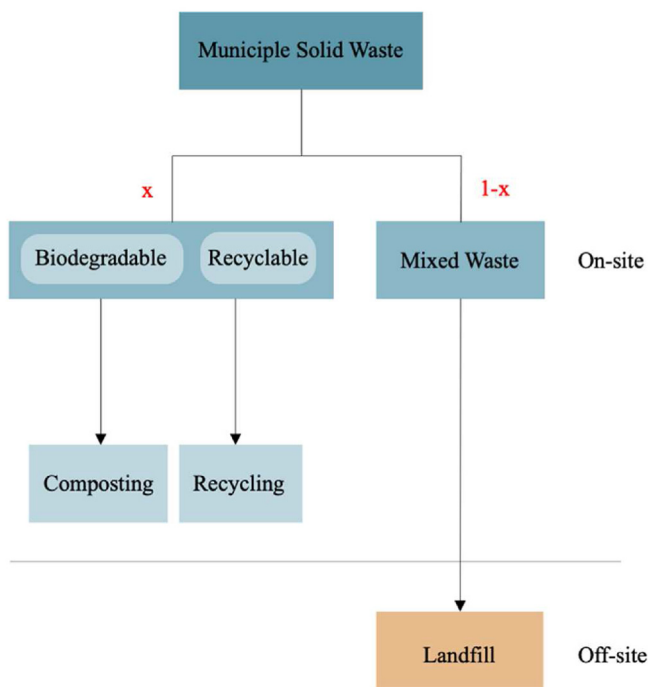


Figure 2. Waste management scenario 1(On-site waste sorting + Landfill).

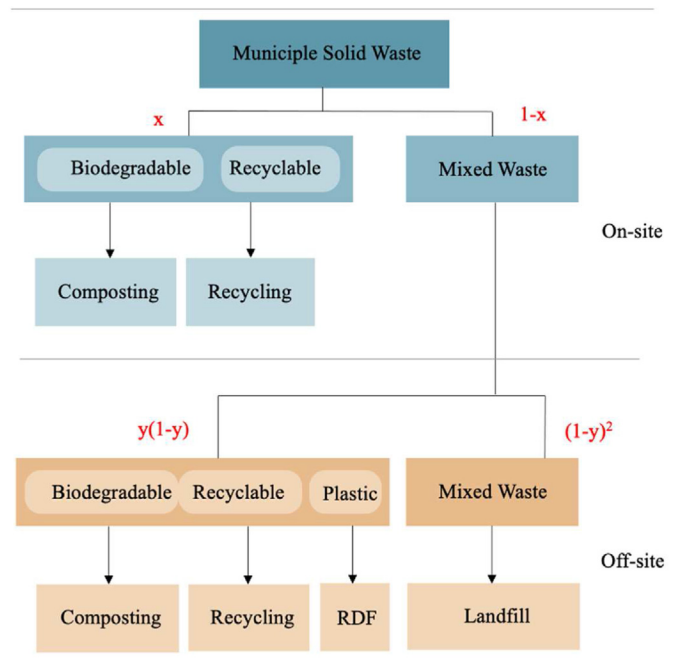


Figure 4. Waste management scenario 3 (On-site waste sorting + Off-site waste sorting + Landfill).

Table 3. Avoided GHG emission and mitigation cost of waste management options.

Waste management options	Avoided GHG emission (tCO ₂ e/tons waste)	GHG Mitigation Cost (USD/tCO ₂ e)	Sources
RDF (Paper, Plastic, Textile)	0.48	50.30	(TGO, 2016)
Composting (On-site sorting)	0.53	32.00	(TGO, 2016)
Composting mixed waste (Off-site sorting)	0.38	32.00	(TGO, 2016)
Recycling (On-site)	1.15	0	(IGES, 2013)
Recycling (Off-site)	1.08	5.57	(IGES, 2013)

because of its simplicity, easy implementation, and low operation cost (Jara-Samaniego et al., 2017). In addition, RDF was selected for mixed waste from off-site sorting waste. This technology can provide significant benefits not only to reduce GHG emission but also to increase the added value of waste for both cities (Beradi et al., 2016). The combination of composting, recycling, and RDF is proposed as an option in each scenario. Net GHG emissions from developing scenarios were calculated using Eq. (2):

$$\text{Net GHG Emission} = \text{GHG Emission from landfill} - \text{Avoided GHG Emission} \quad (2)$$

4. Results and discussion

4.1. Projection of GHG emission from the MSW sector in Nan and LPB from 2017 to 2030

Given the necessity to develop a projection of GHG emissions from MSW, the time period was extended from 2017 to 2030. Under the BAU scenario, the amount of MSW generated and GHG emissions from Nan and LPB city were forecasted by using the CAGR as a driver. The number of tourists and the population were assumed to increase linearly in both cities. The data used to evaluate the GHG emissions of Nan and LPB were based on 2017, which was the latest and most complete data. Thus, the

base year for projection was 2017. For LPB, CAGR of 9.77% from 2005 to 2018 was selected as a driver for the projection of MSW generated and GHG emissions in the future. The MSW generated and GHG emission in Nan during 2017–2030 were projected using a CAGR of 4.69%. The projections of GHG emissions from MSW in Nan and LPB from 2017 to 2030 are presented in Figure 5. In LPB, MSW generated and GHG emissions in 2017 totaled 28,040 tons/year and 13,890 tCO₂e/year, respectively. In 2030, the GHG emissions from MSW under the BAU scenario would emit GHG approximately 3.9 times (54,257 tCO₂e/year) greater than the emissions in 2017. The projection of Nan municipal MSW generated and GHG emissions in 2017 was 22,826 tons/year and 11,117 tCO₂e/year, respectively. Under the BAU scenario, emissions from MSW in 2030 would emit GHG at a rate of approximately 2.8 times (31,128 tCO₂e/year) greater compared with those in 2017. GHG emissions from MSW in Nan and LPB have increased continuously with population increase and economic growth until 2030. The results have raised concerns regarding the climate change impact of MSW.

4.2. Scenario analysis

Figure 6 presents the share of on-site waste sorting ratio versus off-site waste sorting ratio of scenario development that achieved the 2030 net-zero emissions in Nan (Fig. 6d–f) and LPB (Figure 6a–c). For each scenario, net GHG emissions from the solid waste sector in 2030 are shown in Figure 7.

Scenario 1 aims to increase the amount of on-site waste sorting in Nan city and LPB city. In this scenario, MSW is assumed to be sorted at the sources of waste generation. Where paper, plastic, metal or glass have been separately collected, they must not be mixed with other waste or materials, such as food waste. The secondary waste amounts from on-site sorting would be disposed of in a landfill without off-site sorting. The on-site waste sorting ratios for Nan and LPB that achieved net-zero emissions in the solid waste sector were evaluated. The on-site waste sorting ratio in LPB was estimated at a minimum of 50.65% (Figure 6a) with the introduction of waste management technologies, such as composting and recycling, to reach the net-zero emissions in 2030. The percentage of MSW disposed of in the landfill decreased to 49.35% (Figure 6a). The avoided GHG emissions account for 27,035 tCO₂e. In addition, GHG emissions from landfilling in this scenario account for only 27,035 tons/year CO₂e. The on-site waste sorting ratio was estimated at a minimum of

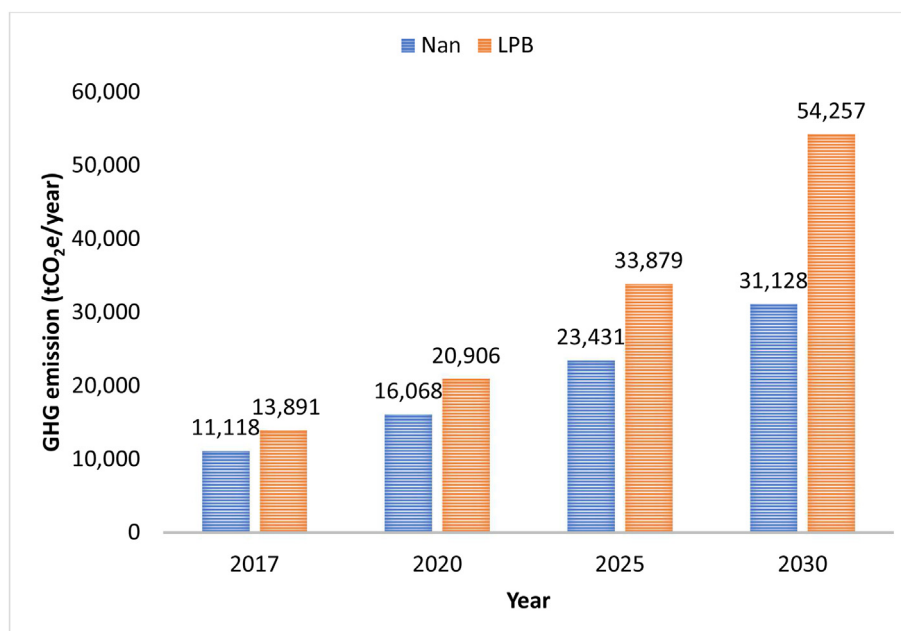


Figure 5. Projection of GHG emission from MSW sector in Nan and Luang Prabang from 2017 to 2030 (BAU).

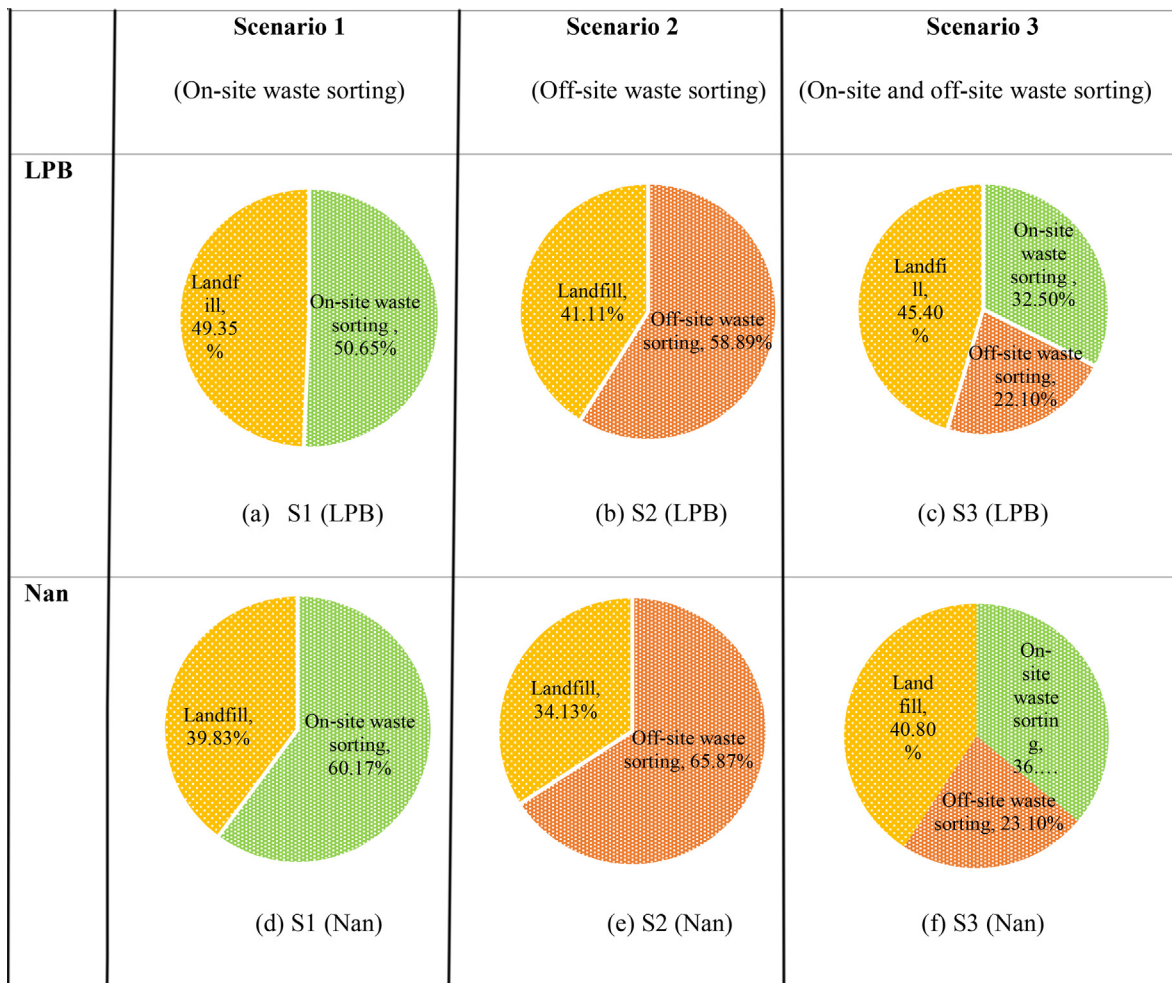


Figure 6. Share of on-site waste sorting ratio versus off-site waste sorting ratio for achieving the 2030 net-zero emissions in Nan and Luang Prabang.

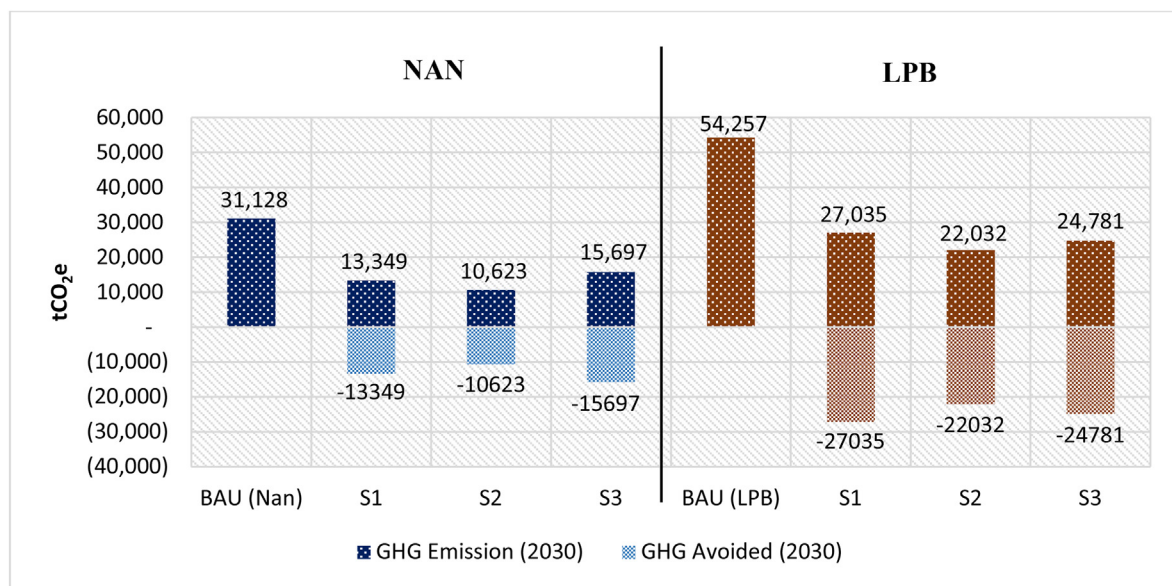


Figure 7. Net GHG emissions from the solid waste sector in 2030.

60.17% to reach net-zero emissions in Nan (Figure 6d). The percentage of MSW disposed of in the landfill decreased to 39.83%. The total avoided GHG emission is 13,349 tCO₂e. GHG emissions from landfilling in this

scenario account for only 13,349 tons/year CO₂e. Nan required greater effort to sort waste than LPB to reach net-zero emissions because of the composition of MSW waste. In LPB, most of the waste (74%) is

composted while 53% of waste in Nan is recyclable of which plastic, glass, and metal that do not generate GHGs (methane).

Scenario 2 aims to increase the amount of off-site waste sorting in Nan and LPB cities. The off-site waste sorting ratio of Nan and LPB achieved net-zero emissions in the solid waste sector. MSW is assumed to be sorted at the landfill site where waste is sorted and dumped. The waste amounts from off-site sorting would be disposed of in a landfill without on-site sorting. In this scenario, the combination of composting, recycling, and RDF is proposed for off-site sorting. The off-site sorting ratio in LPB was estimated at a minimum of 58.89%, where the percentage of MSW disposed of in the landfill decreased to 41.11%, to reach net-zero emissions by 2030 (Figure 6b). The avoided GHG emission is 22,032 tCO_{2e}. In addition, GHG emissions from landfilling in this scenario account for only 22,032 tons/year CO_{2e}. The off-site waste sorting ratio was estimated at a minimum of 65.87% to reach net-zero emissions in Nan (Figure 6e). The percentage of MSW disposed of in the landfill decreased to 34.13%. The avoided GHG emission is 10,623 tCO_{2e}. GHG emissions from landfilling in this scenario account for only 10,623 tons/year CO_{2e}. Similarly, in the previous scenario, Nan required greater effort to sort waste than LPB to reach net-zero emissions because of the composition of MSW waste.

Scenario 3 aims to increase the amount of on-site and off-site waste sorting in Nan and LPB cities. In this scenario, the proportion of on-site waste sorting is assumed equal to that of off-site waste sorting. For the process in scenario 3, waste is sorted at the source of waste generation, and the secondary waste amounts from on-site sorting are separated at the landfill site where wastes are sorted and dumped. Afterward, it would be disposed of in a landfill. To reach net-zero emissions by 2030, the on-site sorting ratio and off-sorting ratio in LPB were estimated minimally at 32.50% and 22.10%, respectively (Figure 6c). The percentage of MSW disposed of in the landfill decreased to 45.40%. The avoided GHG emission is 24,781 tCO_{2e}. The on-site sorting ratio and off-sorting ratio were estimated minimally at 36.10% and 23.10%, respectively, to achieve net-zero emissions by 2030 in Nan (Figure 6f). The percentage of MSW disposed of in the landfill decreased to 40.80%. The avoided GHG emission is 15,697 tCO_{2e}. GHG emissions from landfilling in this scenario account for only 15,697 tons/year CO_{2e}.

Results show that Nan requires greater effort to sort waste than LPB to reach net-zero emissions by 2030. Organic waste, being the primary and most biodegradable component of MSW, is the main source of GHGs (CH₄) at a landfill site. The composting of organic waste can significantly reduce GHG emissions. The methane reduction is mainly reached due to avoiding methane emissions from landfilling or dumping organic waste. Taking into consideration the comparison of MSW in Nan and LPB, the MSW composition in LPB is composed of approximately 74% biodegradable waste. Composting could reduce the waste disposed of in the landfill. Hence, introducing composting for biodegradable waste is effective as an intermediate treatment to reduce the waste and GHG emission at the landfill site in LPB. The waste in NAN is composed of approximately 33% biodegradable waste and approximately 50% recyclable waste, such as plastic, paper, and metal. Introducing recycling is effective as an intermediate treatment to reduce GHG emissions from MSW in NAN. Therefore, comparison of on-site and off-site waste sorting ratios shows that Nan requires greater effort to sort waste than LPB to reach net-zero emissions by 2030 because of the proportion of waste composition. In summary, on-site waste sorting has potential for reducing GHG emissions. Starting from waste management at the source is one of the most practical and cost-effective waste management approaches. Waste recycling has potential for reducing GHG emissions by converting raw materials, while composting of organic waste enables it to be recovered and transformed into fertilizer.

4.3. Benefits and costs (B/C)

This section calculates the benefits and mitigation costs (B/C) of each scenario. The benefits of avoided GHG emissions and mitigation costs

Table 4. Input parameters of benefits and costs (B/C) analysis.

Scenario	Mitigation options	Mitigation cost (USD/tonneCO _{2e})
Scenario 1	On-site Recycling	0.00
	Composting	32.00
Scenario 2	Composting (off-site)	32.00
	Off-site recycling	5.57
	RDF	50.30
Scenario 3	On-site Recycling	0.00
	Composting (on-site)	32.00
	Off-site recycling	5.57
	Composting (off-site)	32.00
	RDF	50.30

were estimated. The result is called the B/C ratio. If the B/C ratio of a developed scenario is greater than one, then this scenario possesses high potential in terms of avoided GHG and mitigation cost. In addition, the sensitivity analysis of the costs of GHG emission reductions from developed scenarios was evaluated by using the carbon price as a driver. Table 4 presents the input parameters used in this analysis. The GDP per capita in Nan municipal was 2370 USD/year in 2017, whereas the GDP per Capita in LPB was 1532 USD/year in 2015 and was used in this section. The average cost of collection and disposal in a landfill (Open dump) was 6.50 USD/ton waste (Claire and Silpa, 2016).

Table 5 shows the waste management cost for scenario development in Nan and LPB. The population growth of Nan and LPB is assumed at constant rates of 0.35% and 1.57%, respectively, between 2017 and 2030 (World Bank, 2018). The total cost for mitigation of LPB was higher than the total cost for mitigation of Nan in all scenarios. The volume of MSW in LPB was higher than that in Nan; as a result, the mitigation cost in the former was also higher than that in the latter. Furthermore, the total cost for mitigation of LPB was higher than that of Nan because of its high organic waste proportion. As shown in Table 5, the mitigation cost for composting was 32 USD/tonneCO_{2e}, which was higher than that for recycling (on-site recycling and off-site recycling). In the case of Nan, the composition of waste consists of approximately 33% biodegradable waste and approximately 50% recyclable waste, which made lower mitigation cost. However, the mitigation cost per capita in Nan was higher than that in LPB because of the population size. When considering the mitigation cost per capita, the results revealed that scenario 1 could be considered to have the lowest mitigation cost per capita for MSW management in both cities. On-site waste sorting at the source is a practical and cost-effective waste management approach. The success of waste separation at the source is dependent on public awareness and participation. Therefore, scenario 1 could be considered the best for MSW management in Nan and LPB for the reduction of GHG emissions and the appropriate integration of MSW management options.

Table 5. Total waste management cost of scenario development in Nan and Luang Prabang 2030

		Total waste management cost (USD)	Waste management Cost per Capita* (USD/year)	GHG Avoided (tCO _{2e})
LPB	Baseline	549,686	2.37	0
	S1	1,132,117	4.87	27,035
	S3	1,188,280	5.11	24,781
	S2	1,285,920	5.53	22,032
	Nan	Baseline	248,409	8.94
	S1	353,658	12.72	13,349
	S3	379,739	13.66	15,697
	S2	514,259	18.50	10,623

* Tipping fee.

Table 6. B/C ratio analysis of scenario development in Nan and Luang Prabang.

Carbon price (USD/tCO ₂ e)	Nan (B/C ratio)			LPB (B/C ratio)		
	S1	S3	S2	S1	S3	S2
39.79 (+40%)	5.05	4.76	1.59	1.85	1.53	1.21
34.10 (+20%)	4.32	4.08	1.36	1.58	1.31	1.03
28.42 (Avg. price 2017)	3.60	3.40	1.14	1.32	1.09	0.86
22.74 (−20%)	2.88	2.72	0.91	1.06	0.87	0.69
17.10 (−40%)	2.17	2.04	0.68	0.79	0.66	0.52

The benefits of avoiding GHG emissions and mitigation cost (benefit–cost ratio) were investigated in this section by using carbon price as an economic driver. The average CO₂ European emission allowance price in 2017 was 25.15 Euros or 28.42 USD/tCO₂e (2017 average exchange rate 1.13) (ECB, 2017). The assumed carbon price changes are as follows: (1) carbon price increase 20% and 40% from the present value and (2) carbon price decrease 20% and 40% from the present value. The results of the sensitivity analysis in Table 6 provide the impact of carbon pricing sensitivity analyses relating to the B/C ratios for each scenario. At an average carbon price of 28.42 USD/tCO₂e, the analysis revealed that the benefit–cost ratios for all scenarios in Nan and LPB were greater than one, except for scenario 2 in LPB at present. While carbon price increase from current price accounted for 20% and 40%, the result revealed that the B/C ratios for all scenarios in Nan and LPB were greater than one, indicating that all scenarios are efficient (benefits exceed costs). At a carbon price decrease from the current price account for 20%, the result indicated that the three scenarios were efficient. Scenarios 1 and 3 in Nan were efficient for all changes in the carbon price rate. In summary, the B/C ratio is sensitive to changes in the carbon price rate. Thus, carbon price highly impacted the plausibility of GHG mitigation options in the waste sector. This might be an important tool to reach net-zero emissions for the waste sector in Nan and LPB. This analysis allows policymakers to prioritize the alternative scenarios based on cost effectiveness.

Waste generation will increase continuously in Nan and LPB with population growth and economic growth because these locations are famous tourist destinations in ASEAN. Consumption by tourists will produce more waste, and MSW is a major city with a carbon footprint. On the basis of current practices, projection results show that total GHG emissions from the waste sector in LPB in 2030 are estimated at 54,257 tCO₂e/y (approximately 3.9 times greater than the emissions in 2017), whereas the GHG emissions from the waste sector in Nan were estimated at 31,128 tCO₂e/y (approximately 2.8 times greater than the emissions in 2017). This result brings about concern regarding the climate change impact of MSW. According to the scenario development, Nan requires greater effort to sort waste than LPB to reach net-zero emissions. The MSW composition in LPB is composed of biodegradable waste, suggesting that organic waste is the main source of GHG (CH₄) at the landfill site.

Therefore, on-site waste sorting is the key for waste management to achieve net-zero emissions. The composition of waste is an important factor that affects greenhouse gas emissions. The sorting of organic waste can significantly reduce GHG emissions through the reduction of methane emissions from landfilling or dumping organic waste. Comparison for the total waste management cost of scenario development in Nan and LPB showed that the total cost for mitigation of LPB was higher than the total waste management cost of Nan in all scenarios. The MSW volume and organic waste proportion in LPB were higher than those in Nan, which caused the mitigation cost of the former to be higher than that of the latter. The mitigation cost for the composting method was 32 USD/tonneCO₂e, whereas the mitigation cost for recycling (on-site recycling and off-site recycling) was less than that for composting. In the case of Nan, the composition of waste consists of less biodegradable waste than LPB, approximately 50% of recyclable waste, which means less mitigation cost than LPB. When considering the mitigation cost per capita, scenario 1 could be considered to have the lowest mitigation cost per capita for MSW management in both cities. Thus, on-site waste

sorting at the source is a practical and cost-effective waste management approach. Sensitivity analysis of the waste management cost of avoided GHG emissions from developed scenarios indicated the average carbon price in 2017 (28.42 USD/tCO₂e). The benefits from prevented GHG emissions and mitigation cost (benefit–cost ratio) for all scenarios in Nan and LPB were greater than others, except for scenario 2 in LPB. In addition, scenarios 1 and 3 in Nan were efficient at all changes in the carbon price rate. Thus, carbon price had a high impact for setting GHG mitigation options to reach the goal of net-zero emissions in Nan and LPB. Reducing organic waste from landfilling not only benefits the environment but also provides an opportunity to implement sustainable management solutions that better fit the circular economy. This study also concludes that the implementation of the proposed scenarios provides can reduce the volume of waste entering the landfill site, enable recycling of waste materials, and minimize GHGs.

5. Conclusion

This research highlighted specific waste management scenarios to achieve net-zero GHG emissions from the MSW sector in Nan and LPB by 2030. Three scenarios were considered as alternative approaches to waste management in the selected cities. The findings and recommendations are summarized as follows:

- With available waste management, all developed scenarios in both cities could achieve net-zero GHG by 2030. From this study, on-site waste sorting is the key for waste management to achieve net-zero emissions. Scenario 1 (on-site waste sorting) in Nan and LPB represents the best waste management approach to achieve net-zero emissions with the highest benefits from prevented GHG emissions and mitigation cost ratio.
- To achieve net-zero emissions, Nan requires greater effort to sort waste than LPB to reach net-zero emissions by 2030 because of the proportion of waste composition. The composition of waste is a significant impact on greenhouse gas emissions.
- Municipal waste in LPB is composed of a higher proportion of organic waste than that in Nan, which is the main source of GHG (CH₄) at the landfill site. Therefore, the sorting of organic waste can significantly reduce GHG emissions by avoiding methane emissions from landfilling organic waste. However, when considering the waste management cost of scenario development in Nan and LPB, the total cost for mitigation of LPB was higher than of Nan in all scenarios. The volume of MSW and population in LPB were higher than those in Nan; thus, the mitigation cost of the former was higher than that of the latter.
- Considering the plausibility of the scenario with only one benefit in this study, with an average carbon price in 2017 (28.42 USD/tCO₂e), the benefits from prevented GHG emissions and mitigation cost ratio for all scenarios in Nan and LPB were greater than one, except for scenario 2 in LPB. In addition, scenarios 1 and 3 of Nan were feasible for all changes in the carbon price rate between decrease to 20%–40% and increase to 20%–40%.

This study proposed alternative solutions of MSW waste management to achieve net-zero emissions for policymakers and local authorities on planning for municipal solid waste management. From the global effort to reach net-zero emissions, the novelty in this study showcases how to achieve such a goal by 2030 in the waste sector through available waste management technology. The different scenarios help decision-makers select the optimal solution considering the combination of waste management to decide the scenario to be implemented. This study found that it is challenging but achievable to reach the net-zero emission targets. Under different limitations and contexts, different scenarios may be chosen based on the constraints of each location if Nan and Luang Prabang want to achieve the net-zero emissions goals. For example, the scenario of disposing at the destination will be selected if a city has

restrictions on separating waste from the source, etc. In the case of scenario 1 that focuses on waste management at the source, the challenge is the increased on-site waste separation rate to achieve the net-zero emissions goals. Additionally, raising public awareness about municipal solid waste management is critical to effective waste management. In scenario 2 that focuses on waste management at the destination, there will be challenges concerning investment in waste management technology.

The selected integrated mitigation option for waste management should deliver economic and environmental sustainability. In addition, the benefits of carbon prices are significant in receiving incentives to reduce emissions. Furthermore, promoting on-site waste sorting and providing incentives for stakeholders is necessary to increase the effectiveness of waste management to achieve net-zero emissions in the waste sector. Furthermore, city could potentially help national government to achieve their GHG emission reduction target. This study may serve as a reference for other places that face the same MSW management issues.

The current study investigated the plausible waste management scenarios to achieve net-zero GHG emissions. Future research should consider the life cycle of waste management system and evaluate the GHG emission of different activities involved in waste management systems, considering the entire waste management stream. Indirect GHG emission from waste management activities, including waste sorting, collection, transportation of waste and recycle cost, can be included to provide comprehensive insights into the MSW system.

Declarations

Author contribution statement

Kannaphat Chuenwong: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Weerin Wangjiraniran & Jakapong Pongthanaisawan: Conceived and designed the experiments; Analyzed and interpreted the data.

Sulak Sumitsawan: Analyzed and interpreted the data.

Tassamon Suppamit: Analyzed and interpreted the data; Wrote the paper.

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Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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References

Agarwal, R., Kariyapol, T., Pienchob, N., 2019. Positive and negative impacts of tourism on environment: a case study of Pattaya city, Thailand. *Sripatum Rev. Humanit. Soc.*

- Sci.* 19 (1), 136–147. <https://so05.tci-thaijo.org/index.php/spurhs/article/view/193591>. (Accessed 30 April 2020).
- Alam, O., Qiao, X., 2020. An in-depth review on municipal solid waste management, treatment and disposal in Bangladesh. *Sustain. Cities Soc.* 52, 101775.
- Asefi, H., Lim, S., 2017. A novel multi-dimensional modeling approach to integrated municipal solid waste management. *J. Clean. Prod.* 166, 1131–1143.
- Ayeleru, O.O., Okonta, F.N., Ntuli, F., 2021. Cost benefit analysis of a municipal solid waste recycling facility in Soweto, South Africa. *Waste Manag.* 134, 263–269.
- Beradi, P.C., Almeida, M., Dias, J.M., 2016. Municipal solid waste – study of refuse derived fuel viability in Portugal with focus on regional planning. In: *Proceedings Venice 2016, Sixth International Symposium on Energy from Biomass and Waste*, November 2016, Venice, Italy. https://www.researchgate.net/publication/315049253_MUNICIPAL_SOLID_WASTE_-_STUDY_OF_REFUSE_DERIVED_FUEL_VIABILITY_I_N_PORTUGAL_WITH_FOCUS_ON_REGIONAL_PLANNING. (Accessed 30 April 2020).
- Bong, C.P.C., Goh, R.K.Y., Lim, J.S., Ho, W.S., Lee, C.T., Hashim, H., Abu Mansor, N.N., Ho, C.S., Ramli, A.R., Takeshi, F., 2021. Towards low carbon society in Iskandar Malaysia: implementation and feasibility of community organic waste composting. *J. Environ. Manag.* 203, 679–687.
- Chheang, V., 2013. *Tourism and Regional Integration in Southeast Asia*. V.R.F. Series No. 481. Institution of Developing Economies. Japan External Trade Organization.
- Claire, M., Silpa, K., 2016. Financing landfill gas projects in developing countries. In: *Urban Development Series Knowledge Papers*, no.23. World Bank, Washington, DC. <https://openknowledge.worldbank.org/handle/10986/2630>. (Accessed 30 April 2020).
- Dong, Y.H., An, A.K., Yan, Y.S., Yi, S., 2017. Hong Kong's greenhouse gas emissions from the waste sector and its projected changes by integrated waste management facilities. *J. Clean. Prod.* 149, 690–700.
- ECB, 2017. Average Exchange Rate 2017. https://www.ecb.europa.eu/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html. (Accessed 29 March 2020).
- Emele, L., Marignac, Y., Petrovic, S., 2019. Modelling net zero emissions. In: *Climate Recon 2050 Dialogues on Partway and Policy*.
- Google Map, 2020. Nan and Luang Prabang [Map]. <https://www.google.co.th/maps/dir/Nan,+Nai+Wiang,+Mueang+Nan+District,+Nan/Luang+Prabang,+Laos/@19.0850055,99.2280158,7z/data=!4m1!4m1!3m1!1s0x31278de0eb65e185:0xa2db020da92e8fe8!2m2!1d100.7789631!2d118.7838757!1m5!1m1!1s0x312f2a3f413d1ba3:0xac9749a9608e6a56!2m2!1d102.1387166!2d119.8832851!3e2!7h=en>. (Accessed 20 June 2020).
- Habibi, F., Asadi, E., Sadjadi, S.J., Barzinpour, F., 2017. A multi-objective robust optimization model for site-selection and capacity allocation of municipal solid waste facilities: a case study in Tehran. *J. Clean. Prod.* 166, 816–834.
- Hoa, N.T., Matsuoka, Y., 2015. The analysis of greenhouse gas emissions/reductions in waste sector in Vietnam. *Mitig. Adapt. Strategies Glob. Change* 22, 427–446.
- IGES, 2012. Institute for Global Environmental Strategies, A Guide for Improving Municipal Solid Waste Management and Promoting Urban Organic Waste Utilization in Lao PDR. <https://www.iges.or.jp/en/pub/guide-improving-municipal-solid-waste/en>. (Accessed 30 April 2020).
- IGES, 2013. Institute for Global Environmental Strategies, Estimation Tool for Greenhouse Gas (GHG) Emissions from Municipal Solid Waste (MSW) Management in a Life Cycle Perspective, the Project of Measurement, Reporting and Verification (MRV) for Low Carbon Development in Asia (FY2013). <https://www.iges.or.jp/en/pub/estimation-tool-greenhouse-gas-ghg-and-black/en>. (Accessed 30 April 2020).
- IPCC, 2006. Intergovernmental Panel on Climate Change, IPCC Guidelines for National Greenhouse Gas Inventories. <http://www.ipcc-nggip.iges.or.jp/public/2006gl>. (Accessed 15 November 2019).
- IPCC, 2013. Climate Change 2013: the Physical Science Basis: Summary for Policymakers. https://www.ipcc.ch/site/assets/uploads/2018/03/WG1AR5_SummaryVolume_FINAL.pdf. (Accessed 26 December 2021).
- ITD, 2019. International Institute for Trade and Development, Trade Facilitation and Logistics Development. http://www.itd.or.th/wp-content/uploads/2015/05/ITD_Nan_Laung_present_1.pdf. (Accessed 25 March 2020).
- Jara-Samaniego, J., Perez-Murcia, M.D., Bustamante, M.A., Perez-Espinosa, A., Paredes, C., Lopez, M., Lopez-liuch, D.B., Gavilanes-Teran, I., Moral, R., 2017. Composting as sustainable strategy for municipal solid waste management in the Chimborazo Region, Ecuador: suitability of the obtained composts for seedling production. *J. Clean. Prod.* 141, 1349–1358.
- JICA, 2012. Laos Pilot Program for Narrowing the Development Gap toward ASEAN Integration, Progress Report 1: Supplement 2 (Luangprabang). Vientiane, Laos.
- Kaza, S., Yao, L.C., Bhada-Tata, P., Van Woerden, F., 2018. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. World Bank, Washington DC.
- Kristanto, G.A., Koven, W., 2019. Estimating greenhouse gas emissions from municipal solid waste management in Depok, Indonesia. *City. Environ. Interac.* 4, 100027.
- LSB, 2015. Lao statistic bureau. In: *The 4th Population and Housing Census (PHC) 2015*. <https://www.lsb.gov.la/pdf/PHC-ENG-FNAL-WEB.pdf>. (Accessed 30 April 2020).
- Manomaivibool, P., Nonthammaraj, P., 2018. Tourism and municipal solid waste management in developing economies: challenges and opportunities. *Open Access J. Waste Manag. Xenobiotics*.
- Mateu-Sbert, J., Ricci-Cabello, I., Villalonga-Olives, E., Cabeza-Irigoyen, E., 2013. The impact of tourism on municipal solid waste generation: the case of Menorca Island (Spain). *Waste Manag.* 33 (12), 2589–2593.
- MICT, 2015. Ministry of Information, Culture & Tourism. 2014 Tourism Statistical Report. <https://mekongtourism.org/wp-content/uploads/Laos-2014-Statistica-1-Report-on-Tourism-in-English-Version.pdf>. (Accessed 30 March 2020).
- Mountford, H., Waskov, D., Gonzalez, L., Garjar, C., Cogswell, N., Holt, M., Fransen, T., Bergen, M., Gerholdt, R., 2021. COP26: Key Outcomes from the UN Climate Talks in Glasgow. <https://www.wri.org/insights/cop26-key-outcomes-un-climate-talks-glasgow>. (Accessed 29 December 2021).

- Munoz, E., Navia, R., 2015. Waste management in touristic regions. *Waste Manag. Res.* 33, 593–594.
- Nan NSO, 2018. Nan Provincial Statistical Office, Nan Provincial Statistic Report: 2018.
- NEDA, 2019. Neighbouring Countries Economic Development Cooperation Agency, the Route of Nan Twin City to Luang Prabang. <https://www.neda.or.th/2018/en/news/detail?d=qQEcaUtm>. (Accessed 25 March 2020).
- NESDC, 2016. Office of the National Economic and Social Development Council. Project for Promoting Sustainable in Future Cities of Thailand. <https://www.nesdc.go.th/download/document/Nan%20Town%20Municipality.pdf>. (Accessed 25 March 2020).
- NESDC, 2020. Office of the National Economic and Social Development Council. Gross Regional and Provincial Product Chain Volume Measure 2018 Edition.
- Obersteiner, G., Gollnow, S., Eriksson, M., 2021. Carbon footprint reduction potential of waste management strategies in tourism. *Environ. Develop.* 39, 100617.
- Ooi, J.K., Woon, K.S., Hashim, H., 2021. A multi-objective model to optimize country-scale municipal solid waste management with economic and environmental objectives: a case study in Malaysia. *J. Clean. Prod.* 316, 128366.
- Papargyropoulou, E., Colenbrander, S., Sudmant, A.H., Gouldson, A., Tin, L.C., 2015. The economic case for low-carbon waste management in rapidly growing cities in the developing world: the case of Palembang, Indonesia. *J. Environ. Manag.* 163, 1–19.
- PCD, 2019. Pollution Control Department, Ministry of Natural Resources and Environment, Booklet on Thailand State of Pollution 2018. PCD. No. 06-069.
- Pires, A., Martinho, G., 2019. Waste hierarchy index for circular economy in waste management. *Waste Manag.* 95, 298–305.
- Pongthanasawan, J., Wangjiraniran, W., Chuenwong, K., Pimonsri, L., 2018. Scenario planning for low carbon tourism city: a case study of Nan. *Energy Proc.* 152, 715–724.
- JICA, 2016. Data Collection Survey on Region Development in Luang PraBang, LAO P.D.R., Final report 2016. <https://openjicareport.jica.go.jp/pdf/12268025.pdf>. (Accessed 15 November 2019).
- Pujara, Y., Pathak, P., Sharma, A., Govani, J., 2019. Review on Indian municipal solid waste management practices for reduction of environmental impacts to achieve sustainable development goals. *J. Environ. Manag.* 248, 109232.
- Rasool, H., Maqbool, S., Tarique, M., 2021. The relationship between tourism and economic growth among BRICS countries: a panel cointegration analysis. *Futur. Bus. J.* 7, 1.
- Rogelj, J., Schaeffer, M., Meinshausen, M., Knutti, R., Alcamo, J., Riahi, K., Hare, W., 2015. Zero emission targets as long-term global goals for climate protection. *Environ. Res. Lett.* 10, 105007, 2015.
- Singh, C.K., Kumar, A., Roy, S.S., 2018. Quantitative analysis of the methane gas emissions from municipal solid waste in India. *Sci. Rep.* 8, 2913.
- TGO, 2016. Thailand Greenhouse Gas Management Organization, Waste Management Options for Greenhouse Gas Reduction. http://conference.tgo.or.th/download/tgo_or_th/Article/2017/Waste_GHG.pdf. (Accessed 30 November 2019).
- TGO, 2018. Thailand Greenhouse Gas Management Organization, Development of Provincial Greenhouse Gas Reduction Project, Final report 2018.
- Tun, M.M., Juchelkova, D., 2019. Estimation of greenhouse gas emissions: an alternative approach to waste management for reducing the environmental impacts in Myanmar. *Environ. Eng. Res.* 24 (4), 618–629.
- UNWTO, 2019. World Tourism Organization International. *Tourism Highlights, 2019 Edition*. UNWTO, Madrid.
- Vilaysouk, X., Babel, S., 2017. Benefits of improved municipal solid waste management on greenhouse gas reduction in Luang Prabang, Laos. *Environ. Technol.* 8 (13-14), 1629–1637, 28278091.
- Widyarsana, W., Agustina, E., 2019. Waste management study in the archipelago tourism area (case study: Nusa Penida District, Bali Province, Indonesia). *E3S Web of Conf.* 148, 05002.
- World Bank, 2017. Annual Report 2017. <http://pubdocs.worldbank.org/en/908481507403754670/Annual-Report-2017-WBG.pdf>. (Accessed 20 March 2020).
- World Bank, 2018. Population Growth 2017. <https://data.worldbank.org/indicator/SP.POP.GROW>. (Accessed 30 April 2020).
- World Bank, 2021. World Bank Knowledge Sharing Series on Low Carbon and Climate-Smart Cities. <https://www.worldbank.org/en/events/2021/04/28/world-bank-knowledge-sharing-series-on-low-carbon-cities>. (Accessed 29 December 2021).