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DEVELOPING A METHOD FOR ESTIMATION OF PLASTIC WASTE LEAKED INTO THE OCEAN

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Abstract

The Vietnamese Government has committed to fighting against plastic waste and reducing 75% of marine plastic debris by 2030. However, the information on the actual amount of plastic waste released into the sea in Vietnam is still uncertain. Estimates of plastic waste leaks into the ocean become essential for assessing baseline data and monitoring marine plastic litter reduction. The lack of standardised methods reliably be applied worldwide due to local conditions of the waste management system is a constraint for plastic waste management. The study developed a method for simulating plastic waste flow in solid waste management system based on material flow approach, which can estimate the amount of plastic waste mismanaged and leaked into the ocean. The estimation model was applied to Quang Ninh, a famous tourist province in Vietnam. The mismanaged plastic waste accounts for 25% of total plastic waste generation and approximately 4.5% of generated plastic waste leaking into the ocean. The results of the study also indicated the source of plastic waste leakage and possible interventions for solving the problem.

Keywords: collection system; estimates of plastic waste; marine plastic waste; recycling; waste management.

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1. Introduction

Plastic products have become an essential part of our daily life as a basic need. Its broad range of applications is in packaging films, wrapping materials, shopping and garbage bags, fluid containers, clothing, toys, household and industrial products or building materials. It is a fact that the rising production and consumption of plastic and the low recycling rate of the plastic economy have led increasing the amount of leaking plastic debris into the marine environment. Low- and middle-income countries, including Vietnam, contributed a significant share of global plastic leakage into the ocean due to a weak municipal waste management system. Plastic waste enters the ocean from either marine or land-based sources. Faris and Hart estimated that 80% of the marine litter entered the ocean by land and assumed the remaining 20% is derived from maritime activities such as commercial and recreational fishing, cruises and shipping [1]. Most marine litter originates from unsustainable waste management practices, particularly in low and middle-income countries [2]. Sound solid waste and resource management is significant effective prevention. It can significantly reduce the quantities of plastics released into the marine environment.

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Macro-plastic waste items are the primary source of future microplastics due to their transformation before and after entering the marine environment (i.e. large plastic items fragment into smaller pieces) and their transportation to other places beyond their source (e.g., ocean gyres or the coastlines of other countries). They cannot be effectively intercepted after being degraded. Thus, preventing the leakage upstream of enormous plastic waste is the best place to take action. The plastic amounts entering water environments depend on various factors such as climatic conditions and topography of the area, plastic waste management practices, economic and social status, and other activities [3–5]. Therefore, the quantity of plastic flowing into waterways and, ultimately, into the oceans is still not possible to be reliably estimated [6, 7].

Methodologies for quantifying the amount of plastic waste from land to the sea have been developed in recent years. However, there is a lack of standardised methodology to assess the amount of plastic leaking into the ocean and monitor the transportation of plastic debris from the river to the sea. Some methods have been developed to estimate global plastic waste discharged to the ocean by general waste management data reported by countries [5, 8, 9]. Nevertheless, estimations at a global scale are uncertain due to statistical weaknesses. Kylili et al. developed an intelligent method formulated on a deep learning technique which can identify, localise and map the shape of plastic debris in the marine environment by visualisation [10]. Similarly, González-Fernández and Hanke applied visual counting to monitor and estimate plastic debris on water surfaces [11]. Apparently, the visual counting approach can only calculate the amount of plastic waste in the photo captured at a particular time and does not consider the plastic waste flow and the amount of plastic suspended in the water, which has not appeared in the picture. Thus, it is suitable for monitoring a hot spot of plastic pollution rather than estimating the total amount of plastic waste of a country or a province leaking into the ocean.

The solid waste management sector relates to primary sources where interventions can be planned and implemented. The Government of Viet Nam has shown firm political commitments and has carried out practical activities to manage and reduce plastic waste, including marine plastic debris. In particular, a National Action Plan on Marine Plastic Debris (NAP) was issued in December 2019 (Decision No. 1746/QĐ-TTg). To monitor and guide the NAP at a more operational level in Viet Nam, quantification of plastic waste leak into the ocean to provide the baseline data of marine plastic waste generation and its sources are essential. However, there is a paucity of study quantifying marine plastic debris in Vietnam. Previous studies reported plastic waste into the ocean from all countries [5] or from all rivers [12] worldwide, including Viet Nam. However, the method for a global scale estimation is uncertain due to lack of consideration for local conditions of each country. Other studies in Viet Nam have previously focused on riverine plastic debris [13–16]. Lack of reliable and scientific methods for marine plastic debris estimation is a knowledge gap in the action against plastic pollution in Vietnam [17].

This study aims at developing a method for estimating the amount of plastic waste leakage into the ocean by considering the input and output flow of waste elements in the solid waste management system. Factors to reduce marine plastic waste litter was evaluated from the result of estimates. The plastic in manufacturer and consumption process but not end up to waste was not considered in this study. Data from Quang Ninh province, a big coastal province in the Northern Viet Nam was adopted for applying the estimation model.

2. Materials and methodologies

2.1. Waste flow approach to estimate of plastic waste amount leaked into the ocean

Fig. 1 presents the model of plastic waste leaking into the ocean from waste management activities. The solid waste management sector relates to major sources where interventions can be planned and implemented. The key land-based leaking sources of plastic marine litter include mismanaged waste from municipal sources.

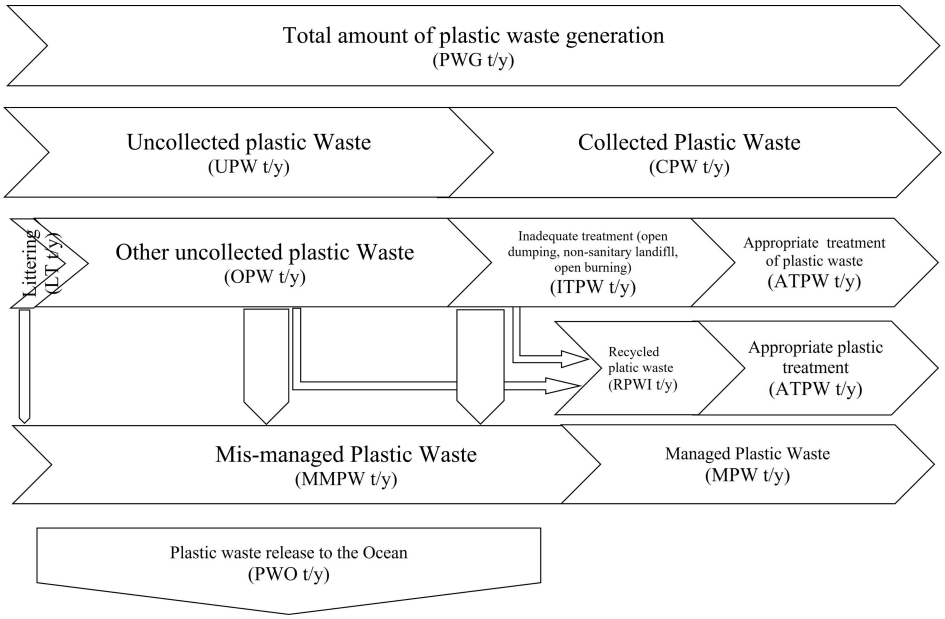

Figure 1. Flows of plastic waste into the ocean

Mis-managed waste includes uncollected waste and inadequate treatment. It refers to the disposal of wastes outside of a waste management system that collects and disposes of them to protect the environment and human health. This definition is extended, also considering waste to be mismanaged when its collection or disposal route creates a chance to be lost and potentially released into the environment. This includes not appropriately transporting, collecting, storing, or handling waste. Additionally, there can also be leakage of collected plastic during disposal, waste treatment, and the processing of recycled materials. It is a critical issue in low and middle-income countries where collection systems for waste may be inadequate, leading to householders having no option but to dispose of their waste by dumping it in a location within or close to the community. Also, where there are insufficient waste collection systems and treatment facilities, uncontrolled dumping of solid waste into watercourses is common [18].

Uncollected waste includes fly-tipping and litter. Fly-tipping is the illegal dumping of waste without a waste management license, and it is a criminal offence punishable by a fine in many countries. Littering by people in public (e.g. through tourism, major public events, or in busy areas of cities), either in their day-to-day activities or during specific leisure activities, is a key source of plastics that eventually find their way into the marine environment. If not collected, these littered materials often enter drains and, in due course, streams and rivers.

Recycled materials in Viet Nam including plastic-, is mainly recovered by informal sectors such as waste pickers, junkers, collection worker, junk buyers, etc. The plastic is recycled in several pathways,

from both collected waste and uncollected waste. Collection workers picked up recyclable materials from waste bins, waste stations that they were dealing with, and the collection vehicle they used. Also, junk buyers buy recyclable materials such as metals, plastic, papers, and cardboard from householders who separate those materials for selling/giving. Plastic recovered from collected waste also account for those collected from disposal site by waste pickers and workers working there and sold to the local junk shops. Uncollected waste is dumped at illegal dumping sites or fly-tipping sites. There is a small amount of plastic waste from those places recovered by waste pickers.

2.2. *Estimation of plastic waste leaking into the ocean*

The material flow analysis approach was applied for estimating plastic waste based on the municipal solid waste flow of the target urban. Sets and equations used in the model for estimating plastic debris are explained as follows.

Table 1. Explanation of sets used in the calculation

Set	Explanation
i	Presents the type of waste composition in municipal waste, i = degradable waste, plastic, paper, metal, glass, ...
j	Presents the technology of waste treatment practice in the province/city, j = incineration, composting, sanitary landfill, opened landfill, ... Appropriate treatment for plastic waste in this study includes incineration, sanitary landfills

The plastic waste leaking into the ocean was estimated using the waste flow approach containing the following equations.

The amount of waste i generation WG_i was estimated from the total amount of solid waste generation MWG in the province by Eq. (1):

$$WG_i = MWG \cdot \alpha_i, \quad \text{tons/year} \tag{1}$$

where α_i is the percentage of plastic waste in municipal solid waste of the city/province. The percentage of plastic in municipal waste accounts for 5 – 16% [19, 20]. This parameter is varied spatially and temporally and need to be collected from the province's report for secondary data or field sampling in a long time period for primary data.

The amount of waste type i uncollected is different from its generation WG_i and the amount of waste i collected CW_i, by the following equation:

$$UW_i = WG_i - CW_i, \quad \text{tons/year} \tag{2}$$

where CW_i is the amount of waste type i of the province/city collected and equals to its generation WG_i multiplied by collection rate c.

The amount of waste i transported to inappropriate treatment facilities ITW_i is the difference between the amount of waste collected CW_i and the total amount of waste i transported to appropriate treatment facilities ATW_j:

$$ITW_i = CW_i - \sum_j ATW_j \cdot \alpha_i, \quad \text{tons/year} \tag{3}$$

Managed waste type i MW_i is the sum of waste i transported to appropriate treatment facilities and recycled waste i:

$$MW_i = \sum_j ATW_j \cdot \alpha_i + r_i \cdot MWG, \quad \text{tons/year} \tag{4}$$

The percentage of waste recycled from both informal and formal sectors of the province/city. It also contains the amount of recyclable waste collected by waste pickers, junk buyers or collection workers from uncollected waste and inappropriate disposal sites, and treatment facilities by scavengers. There is still no official, consistent and scientifically-based data regarding the recycling rate of any kind of waste at a national level in Vietnam. According to a study carried out by World Bank in 2018, materials that typically are recycled are papers, plastics and metals, and the recycling rate is around 10% [21]. The portion of plastic recycled in recyclable wastes was determined by Lieu et al. of about 19 – 29%. However, the rate of waste recycled will be varied in provinces and cities. Thus, field survey activity to get reliable data should be conducted.

The parameter r_i is the percentage of waste type i in waste recycling. Typically, plastic waste recycled accounts for about 20 – 25% of plastic waste collection [22]. The amount of plastic waste recycled will be varied in provinces and cities. Thus, field survey activity should be conducted to get reliable data for estimation.

The mismanaged waste MMW_i is the difference between waste generated and managed waste, defined by Eq. (5):

$$MMW_i = WG_i - MW_i, \quad \text{tons/year} \tag{5}$$

The amount of plastic waste leak into the ocean is estimated as the following equation:

$$PWO = RR \cdot MMW_i, \text{ tons/years; with } i = \text{ plastic} \tag{6}$$

Boucher, J. et al. provided a method for estimating release rate, which is presented in Eq. (7):

$$RR = RR_f \cdot RR_h, \% \tag{7}$$

where RR_h is the highest release rate from the literature review, chosen as 25% by Jambeck et al., and RR_f is calibrated factor for release rate due to the influence of distance to the shore and the catchment run-off data. The release rate factor is identified by the catchment run-off of the watershed RD and the distance to shore of area D, obtained from the release rate matrix developed by Boucher et al. [23]. The release rate calibrated factor identified by the method of Boucher et al. is presented in Table 2.

Table 2. The release rate calibrated factor matrix [23]

Run-off (RD, mm/day)	Distance to shore (D, km)		
	$D \leq 10$	$10 < D \leq 50$	$D > 50$
$RD \leq 0.4$	30%	20%	10%
$0.4 < RD \leq 0.8$	60%	40%	20%
$RD > 0.8$	90%	60%	30%

The following equation can estimate the catchment run-off of different river basins:

$$RD = \frac{24 \cdot 3.6 \cdot Q}{A}, \text{ mm/day} \tag{8}$$

where A is the river basin area (km^2), and Q is the average discharge of the river (m^3/s). A and Q are collected from meteorological and hydrological reports of the province [24].

2.3. A case study in Quang Ninh province

Quang Ninh is a province along the northeastern coast of Vietnam which owns Ha Long Bay, a World Heritage Site with 1969 islands. The province covers an area of 8,239 km^2, of which approximately 6,000 km^2 is mainland with a 250 km coastal line and a population of 1.3 million people.

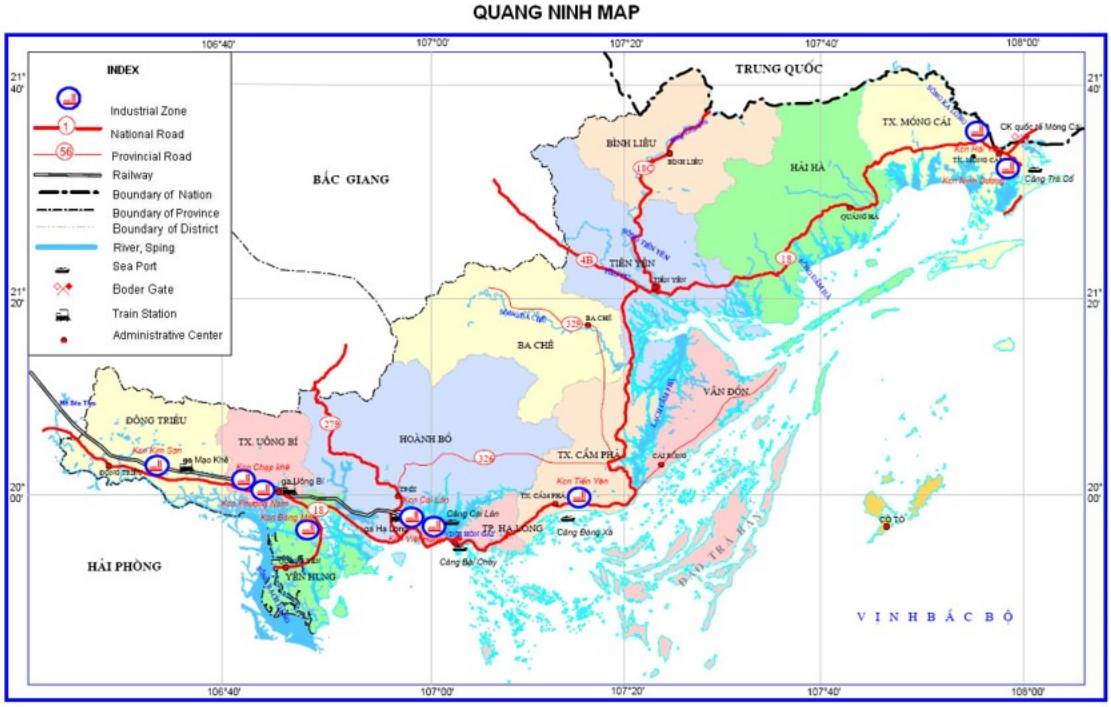

Figure 2. Map of Quang Ninh province – the case study

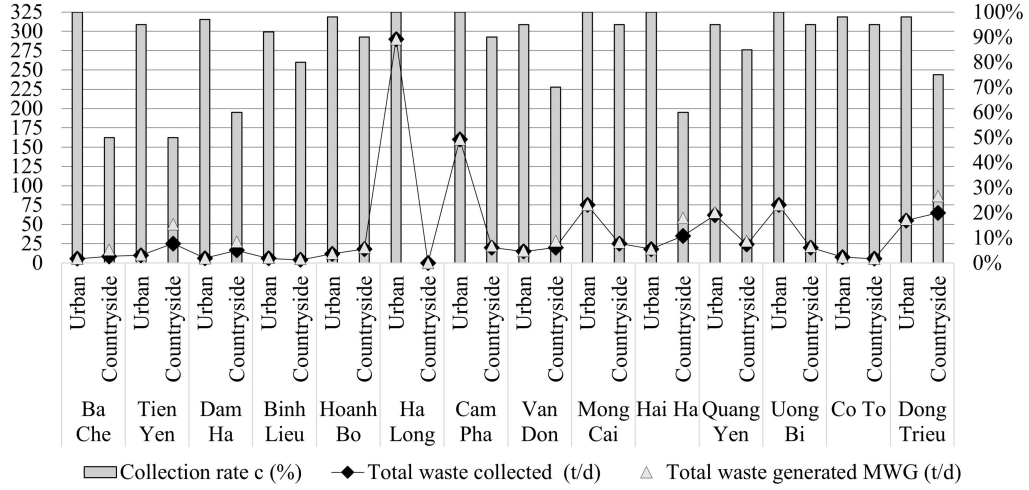

Figure 3. Amount of waste generated and collected among districts/cities in Quang Ninh in 2019 (Data source: [25])

The rapid urbanisation and high development of the tourist industry in Quang Ninh have led to a huge increase in waste generation. According to the report on solid waste management in Quang Ninh province in 2019, the total amount of waste generated was about 1400 thousand tons/day, and the amount of waste collected was about 1200 tons/day. The collection rate was approximately 90% [25]. The waste generation, collected waste amount and collection rate c in districts and cities of Quang Ninh in 2019 were presented in Fig. 3.

Municipal solid waste is collected and treated by landfills and incinerations. The rate of waste amount incinerated and landfilled is shown in Table 3. Most landfills in Quang Ninh are unsanitary disposal and open dumping sites, which can cause plastic leakage into water bodies due to rain or flood. Therefore, in this study, landfills are considered inappropriate treatment practices for plastic [25].

Table 3. Percentage of waste incinerated and landfilled in Quang Ninh province

City/District	Incineration	Landfill
Ba Che	100.00%	0.00%
Tien Yen	0.00%	100.00%
Dam Ha	0.00%	100.00%
Binh Lieu	100.00%	0.00%
Hoang Bo	100.00%	0.00%
Ha Long	100.00%	0.00%
Cam Pha	100.00%	0.00%
Van Don	48.57%	51.43%
Mong Cai	75.00%	25.00%
Hai Ha	20.75%	79.25%
Quang Yen	100.00%	0.00%
Uong Bi	100.00%	0.00%
Co To	55.38%	44.62%
Dong Trieu	0.00%	100.00%

The percentage of plastic waste and single-use plastic bags in municipal solid waste in Vietnamese cities has been increasing. This was because of the rapid increase in plastic consumption habits of people. The amount of plastic waste in Vietnamese cities accounted for from 5 to 16% of municipal solid waste [19, 20]. However, a study by Toan et al., (2020) presented that the amount of plastic waste in different districts in Da Nang City ranged from 15 to 20%, in which the percentage of single-use plastic bags and nylon was from 7 to 14% (accounted for 50% to 70% of plastic waste) [26]. Also, the national environment report indicated that the plastic composition increased significantly from about 5% in the two decades to about 20% in recent years [20]. Due to the lack of official and scientific data on plastic waste composition in Quang Ninh province, this study assumes that the percentage of plastic waste (α_i,with i = plastic) on the order of 15% [27–29]. Also, the other coefficient r_i is assumed to be 25%.

The release rate calibrated factors RR_f for cities/districts in Quang Ninh is calculated from river basin areas A and river average flow Q, which are reported in the Detail Irrigation Planning of Quang Ninh province approved by the Decision No. 4839/QD-UBND on December 15, 2017 [30], shown in Table 4.

Table 4. River watershed characteristics of Quang Ninh

Districts	River basin	Flow Q_{tb} (m^3/s)	Area A (km^2)	Calibrated factor RR_f (%)
Ba Che	Ba Che	39.10	978.00	90%
Tien Yen	Tien Yen	49.20	1070.00	60%
Dam Ha	Dam Ha	5.94	106.00	90%
Binh Lieu	Tien Yen	49.20	1070.00	60%
Hoang Bo	Ba Che	39.10	978.00	90%
Ha Long	-	-	-	90%*
Cam Pha	Ba Che	39.10	978.00	90%
Van Don	-	-	-	90%*
Mong Cai	Ka Long	50.20	773.00	90%
Hai Ha	Ha Coi	9.80	122.30	60%
Quang Yen	Da Bac	-	-	90%*
Uong Bi	Da Bac	-	-	60%*
Co To	-	-	-	90%*
Dong Trieu	Da Bac	-	-	60%*

*Assumption made based on local conditions and similarities in river basin characteristics

3. Result and Discussion

3.1. Plastic waste flow in Quang Ninh province

Fig. 4 shows the plastic waste flow in Quang Ninh province. As can be seen from the figure, mismanaged plastic is the main source of plastic waste leakage into the ocean. Mismanaged plastics are

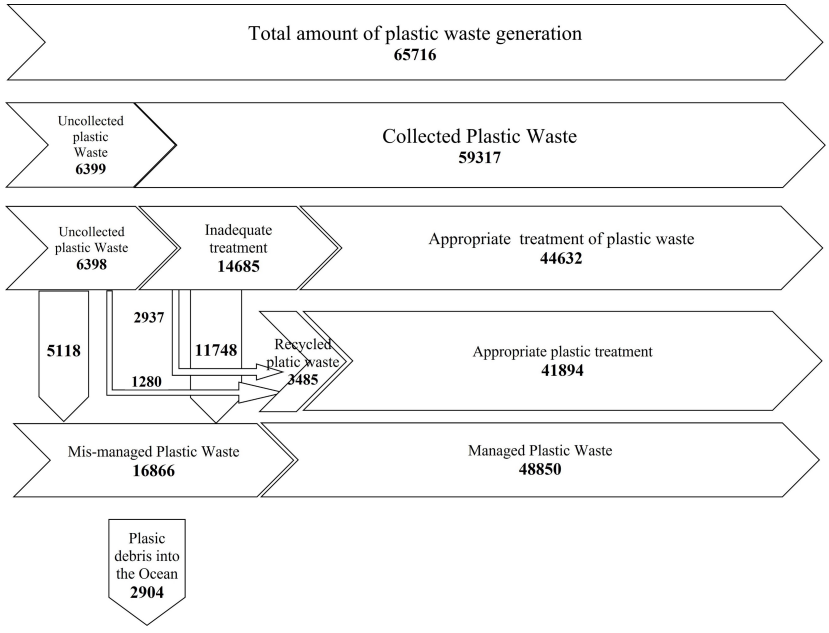

Figure 4. The plastic waste flow of Quang Ninh province in 2019 (tons/year)

contributed by uncollected plastic and plastic with inadequate treatment practices. The plastic waste leaking into the ocean in 2019 was about 2.9 thousand tons/year, accounting for 4.5% amount of plastic waste generated in Quang Ninh province. Only approximate 49 thousand tons/year of plastic waste is appropriately managed by sanitary landfills or incineration. And a percentage of 15% of managed plastic waste was recycled by the informal sector. About 26% of total plastic waste generation becomes mismanaged plastic waste which highly threats the environment.

3.2. Impact factors on marine plastic litter

Low efficiency of waste collection activities leads to plastic waste leaking into the environment. Fig. 5 presents the status of plastic waste management in cities/districts of Quang Ninh Province. The bar charts are the amount of plastic waste collected (white bars) and uncollected (black bars) in Quang Ninh province in 2019. Meanwhile, the lines present the amount of managed and mismanaged plastic waste. As can be seen from Fig. 4, the uncollected waste is highly correlated with the amount of mismanaged plastic. Rural areas in districts such as Tien Yen, Hai Ha, Dong Trieu, Van Don are the major contributors to mismanaged plastic waste due to low efficiency in waste collection.

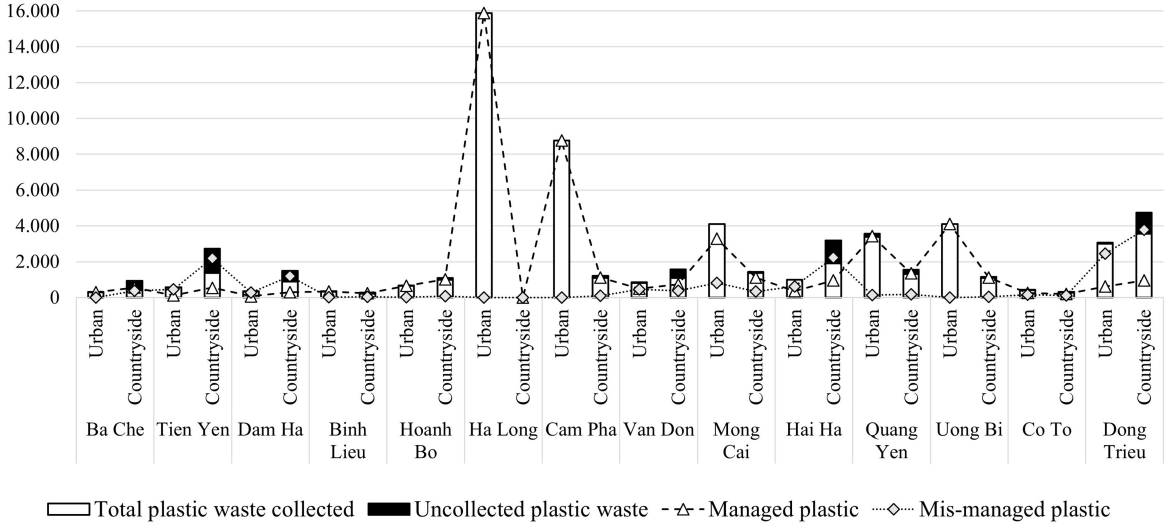

Figure 5. Plastic waste managed and mismanaged (tons/year)

Waste collection and transportation are essential steps in municipal waste management. Without proper collection systems, plastic waste and other materials continue to litter the environment. By using a variety of collection vehicles such as trucks, tricycles, and carts, the collection system in Vietnamese cities, including Quang Ninh shows huge advantages in densely populated urban areas, where the route to travel are not so far, and houses are close to each other [29]. However, the deficiency of infrastructure and equipment in rural areas needs a different approach. Also, the rummaging by animals for leftovers and the activity of waste pickers cause pollution and plastic loss in the environment [31]. Mis-managed plastic waste on the ground may drift into the sewer system or be dispersed into the environment by rain and wind. Hence, improving waste collection systems must be a priority in Quang Ninh province to solve the mismanaged waste challenges, especially in rural areas [32]. As such, business needs to explore ways of partnership between the private sector and local municipalities, which may be an appropriate approach for waste collection in distance areas.

Not only collection systems, but waste treatment and recycling activities also affect plastic leakage into the environment [33]. The recycling and recovery practices effectively reduce waste and plastic waste leakage into the environment. They are circular pathways of plastic waste from waste to material and play a vital role in controlling the loss of plastic waste. The more efficient the recycling practice and the more abundant the recycled materials are, the less plastic waste will be leaked. Incineration is also an effective practice to prevent leaking plastic into the environment, whereas landfilling poses a high risk of emitting plastic waste into the environment. According to Bez et al. [34] the degradation of plastic waste in landfills is approximately 1–5% in a 100-year time period, leading to potential air and groundwater emissions. This indicates that landfill is the least preferred treatment option for plastic waste management [35]. The result of this study also indicated that districts in Quang Ninh province with landfills have a higher potential for leaking plastic waste into the ocean. Fig. 6 shows the amount of plastic waste leaking into the ocean as the result of model estimation. As can be seen from the figure, Dong Trieu district is the most significant contributor of marine plastic waste from Quang Ninh province, followed by Mong Cai, Tien Yen, Hai Ha, Dam Ha, Co To and Van Don districts. These districts have landfilled most of the waste and do not recycle properly (Table 3). Therefore, rural areas are the main contributors to the leakage of plastic litter due to the high percentage of landfills and lack of recycling technologies.

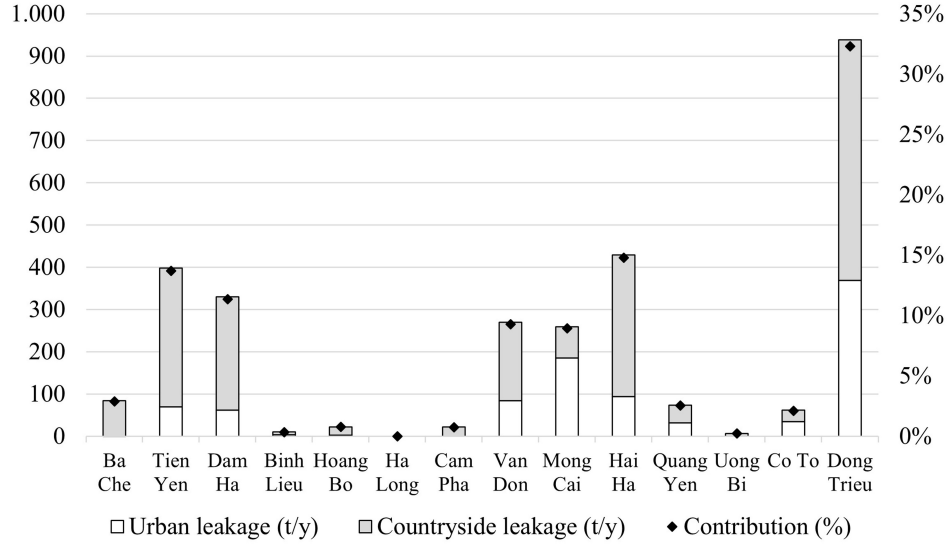

Figure 6. Plastic waste leaked into the ocean

As regards existing statistics, there is a continual increase in plastic consumption because of its wide scope of applications, resulting in increased plastic waste. However, the large number of plastic wastes released may undergo treatment with properly designed techniques to enable the production of alternatives to fossil fuels. The technique should demonstrate superiority in all aspects, especially ecologically and economically. The escalating amount of municipal solid waste poses a great challenge as regards monitoring and control to alleviate their environmental effects. Conventional waste management techniques such as burning and landfilling negatively impact the environment and humanity [36]. Novel techniques capable of converting waste to valuable products and energy are consolidating as established waste management routes. These techniques include both biological and thermochemical conversions, and research has been carried out in previous decades resulting in enhanced energy

and products yield in addition to reduced impact on the environment.

The suitable recycling application is a key intervention in plastic waste management. However, an effective recycling system includes a chain of activities supporting each other, from separation at source to the local collection and transportation and the recycling technologies. Also, other technologies are required depending on local conditions and requirements, such as sanitary landfills or thermal treatments like waste-to-energy incineration and gasification. Finally, the policy of plastic waste management is the key to controlling behaviour in plastic waste management. The clearer the regulation, the higher the effectiveness of waste management practice [37]. The institutions and policies need to be synchronised in the waste management system, consistent and corresponding to each stakeholder. The incentive policies or regulations on the packaging and replacement of plastic products should be considered valuable interventions to reduce plastic waste generation [38, 39].

4. Conclusions

The study developed a method for simulating plastic waste flow to estimate plastic leakage into the ocean with a material flow approach. The method was reliably applied on Quang Ninh province. The simulation estimate shows the amount of marine plastic litter leaked. It explains the sources of plastic leakage inside the waste management system, which plays a vital role in plastic waste management and plaster litter reduction. That provides the information for authorities and other related stakeholders in the waste management system to decide their action against plastic waste and improve the current waste management status. In the case of Quang Ninh province, the result of the model shows that the improvement of the collection system in rural areas can considerably reduce the amount of plastic waste in the environment. An increase in collection efficiency and investment in collection infrastructure will reduce waste on the ground and possibly drifting to the water body. Also, improving waste treatment practices, including recycling technology investment, thermal and biological treatment applications, or sanitary landfills, would minimise mismanaged plastic waste to the environment.

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