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RESEARCH ARTICLE

Toward sustainable waste management in small islands developing states: integrated waste-to-energy solutions in Maldives context

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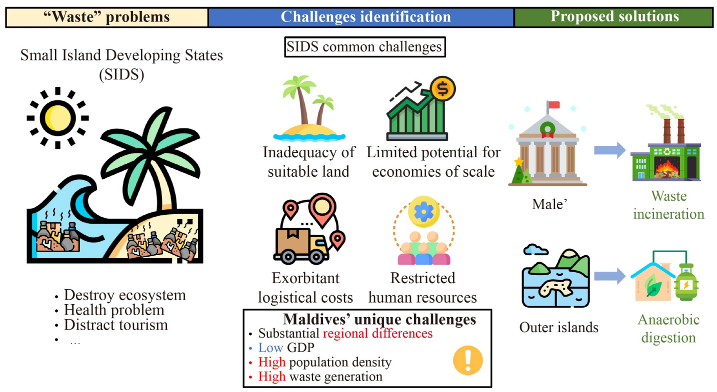
HIGHLIGHTS

- Maldives' unique natural and socioeconomic status cause waste management challenges.
- Context-specific solutions needed for sustainable waste management in Maldives.
- Waste management practices differ greatly between Male' city and outer islands.
- Waste incineration in Male' will double Maldives' renewable energy supply.
- Decentralized anaerobic digestion proposed for outer islands to recover energy.

GRAPHIC ABSTRACT



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ABSTRACT

Effective waste management is a major challenge for Small Island Developing States (SIDS) like Maldives due to limited land availability. Maldives exemplifies these issues as one of the most geographically dispersed countries, with a population unevenly distributed across numerous islands varying greatly in size and population density. This study provides an in-depth analysis of the unique waste management practices across different regions of Maldives in relation to its natural and socioeconomic context. Data shows Maldives has one of the highest population density and per capita waste generation among SIDS, despite its small land area and medium GDP per capita. Large disparities exist between the densely populated capital Male' with only 5.8 km^2 area generating 63% of waste and the ~194 scattered outer islands with ad hoc waste management practices. Given Male's dense population and high calorific waste, incineration could generate up to ~30 GW/a energy and even increase Maldives' renewable energy supply by 200%. In contrast, decentralized anaerobic digestion presents an optimal solution for outer islands to reduce waste volume while providing over 40%–100% energy supply for daily cooking in local families. This timely study delivers valuable insights into designing context-specific waste-to-energy systems and integrated waste policies tailored to Maldives' distinct regions. The framework presented can also guide other SIDS facing similar challenges as Maldives in establishing sustainable, ecologically sound waste management strategies.

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1 Introduction

The management of municipal solid waste (MSW) represents a paramount ecological predicament for the Small Islands Developing States (SIDS), which comprise small island economies grappling with distinctive socioeconomic and environmental vulnerabilities (Kelman and West, 2009; Robinson, 2020). The common challenges of waste management in SIDS are: 1) inadequacy of suitable land, 2) limited potential for economies of scale, 3) exorbitant logistical costs, and 4) restricted human resources. The situation in Maldives, a Southern Asia SIDS country located in the Indian Ocean, presents a peculiar scenario. Effective waste management is particularly formidable in Maldives due to the small land areas of the Maldivian archipelago and the highly heterogeneous distribution of its population (MHE, 2010; MEE, 2016). The Maldivian archipelago comprising 1192 low-lying coral islands spreads across an area of ~298 km^2, positioning Maldives among the world's most geographically dispersed nations. The islands vary greatly in areas ranging from 0.5 to 6 km^2. The population spreads unevenly across 194 inhabited islands and 105 self-contained resort islands. Approximately 27%–30% of the population resides in the capital island of Male', which has an area of just 5.8 km^2 and is among the most densely populated islands in the world. The rest of the country is sparsely inhabited, with 150 islands each having fewer than 1000 inhabitants and over 80 islands each having less than 500 inhabitants.

In addition to waste management challenges stemming from natural conditions, rapid economic growth, notably in the tourism sector, during the past two decades has precipitated a surge in MSW generation in Maldives. In 2019 alone, over 240000 t (Mt) of MSW were generated in Maldives, representing a staggering rise of approximately 214% since 1999. Moreover, Maldives exhibits higher waste generation per capita compared to its neighboring countries, which possess more favorable circumstances for managing their generated waste owing to homogeneous population distribution and expansive land areas (Ngoc and Schnitzer, 2009; Shekdar, 2009; Hoornweg and Bhada-Tata, 2012). The daily waste generation per capita in Maldives is between 0.8 and 1.7 kg, depending on the region (MEE, 2011, 2016). This is greater than most of the South Asian countries such as Sri Lanka, Pakistan, Bhutan, Bangladesh, India, and Nepal which have MSW generation rates of 0.89, 0.65, 0.53, 0.41, 0.37, and 0.32 kg/(capita·d), respectively. Obstacles further hindering solid waste management in Maldives include institutional, financial, technical, regulatory, and public participation shortcomings.

Current waste management strategies in Maldives predominantly rely on landfilling and open burning. In the absence of an organized waste management system, the MSW is disposed of in an ad hoc and unsanitary manner. This results in environmental deterioration, loss of terrestrial habitat, and generation of conditions prejudicial to public health and safety. Uncontrolled burning, burying, and dumping of waste in the ocean is common (MEE, 2016; UNSCAP, 2021). Emissions from informal burning and dumping of solid waste contribute to up to 10% of the national greenhouse gas (GHG) emissions with grave local and global significances (Bernard et al., 2010; MEE, 2011). In view of the extreme environmental vulnerability of the Maldivian archipelago with 80% of the islands being just over a meter above sea level and the adverse effects of GHG emissions from waste disposal sites (Fei et al., 2021), it is imperative to devise and implement sustainable MSW management strategies to safeguard ongoing and future development goals.

Despite several general reviews outlining waste management practices in SIDS (Mohee et al., 2015; Fuldauer et al., 2019), there exists a dearth of quantitative research examining SIDS waste management strategies in relation to local socio-economic conditions. Consequently, the formulation of national-level strategies for Maldives and other SIDS lacks scientific guidance. Moreover, dedicated research on MSW management pertaining to the specific case of Maldives is lacking. Applying strategies effective in countries with larger land masses and homogeneous population distribution to Maldives is impractical, e.g., India (Malav et al., 2020; Prajapati et al., 2021), Thailand (Habib et al., 2021), and the US (Nanda and Berruti, 2021). Furthermore, in line with Maldives' carbon neutral initiative (MEE, 2012), the continuous increase in MSW generation and a recent sharp rise in global fuel prices have elevated the priority of developing waste-to-energy (WtE) technologies in Maldives (Leong et al., 2021). However, given the significant regional disparities in Maldives, further analysis is required to enhance WtE efficiency, economic viability, scalability, and end-user friendliness in each region.

This study fills a crucial gap in the existing literature by providing an in-depth analysis of waste management practices in Maldives. The objectives of this work are twofold. Firstly, we aim to analyze the relationships between waste management practices and socioeconomic status in Maldives and other SIDS. This analysis provides a deeper understanding of the factors influencing effective waste management strategies in SIDS. Secondly, we conduct a detailed examination of waste management practices in three different regions of Maldives. Through literature review and field interviews, we gather information on various aspects of waste management, including waste generation, collection, transportation, disposal, and the potential for WtE initiatives. Thirdly, by considering the unique natural and socio-economic conditions of each region, we propose feasible WtE solutions that can address the waste management challenges in Maldives. These solutions are evaluated based on their economic viability, scalability, and potential benefits for both waste management and energy constraints in the country. By focusing on Maldives unique case, this study aims to contribute valuable insights and recommendations that can be applied not only in Maldives but also in other SIDS facing similar challenges.

2 Methods and materials

2.1 Data acquisition

To elucidate the influence of socio-economic determinants on waste management practices, we collated extensive data from multiple repositories. Socio-economic indicators, specifically GDP per capita, population, and population density, were retrieved from the World Bank database (data.worldbank.org). Waste management metrics such as waste generation, disposal, and composition were referenced from the "What a Waste 2.0" database (Kaza et al., 2018). Employing regression and correlation analyses, we discerned quantitative relationships between socio-economic factors and waste management strategies prevalent in SIDS.

We conducted a comprehensive assessment of waste management protocols in the Maldives. To derive primary insights into MSW collection, composition, transportation, and disposal, we relied on reports from international agencies (e.g., UNEP, UNSCAP) and local governmental bodies (e.g., MEE, MHE). Additionally, the authors also engaged in onsite investigations to enrich the study's empirical foundation.

2.2 WtE potential estimation

2.2.1 Energy benefits from incineration

Waste incineration offers an effective means of volume reduction while also allowing energy recovery, reduction of contaminants, and elimination of pathogens. The average lower heating value (LHV) of the MSW composition was first evaluated to determine its suitability for incineration with energy recovery, based on the threshold of 6285 kJ/kg suggested in World Bank guidelines (Liu and Nishiyama, 2020). The total potential energy output from incineration was then calculated using the LHV of each waste component and the mass of waste generated annually, as per Eq. (1).

$$E = f \times \sum_{n} (LHV_i \times W_i), \quad (1)$$

where E represents the total electricity generated (MWh); LHV_i signifies the lower heating value (MMBtu/t) of the MSW component i, sourced from US Energy Information Administration (EIA); W_i is the generated mass (t/a) of the MSW component i; f denotes the energy efficiency of incineration, fixed at 20% for this study (Liu and Nishiyama, 2020).

2.2.2 Energy benefits from anaerobic digestion

Anaerobic digestion (AD) is a biological process that recovers energy and nutrients by the microbial degradation of organic materials in the absence of oxygen. Energy is recovered in the form of biogas, a gaseous mixture that comprises methane (50%–70%), carbon dioxide (25%–45%), and small fractions of other gases such as water vapor and hydrogen sulfide. Nitrogen, phosphorous, potassium, and other valuable nutrients that can be utilized as fertilizers are recovered from the digester effluent (Pham et al., 2015; Garfí et al., 2016). A large variety of organic wastes are amenable to AD. Kitchen waste along with animal manure and fish waste have been widely utilized for biogas production. Typically, burning one cubic meter of biogas is equivalent to 5.5 kg of firewood, 1.6 kg of charcoal, 0.45 kg of LPG, 0.75 L of kerosene, and 1.5–2.4 kWh of electricity (assuming 35% efficiency) (Murphy et al., 2004; Pham et al., 2015).

The energy benefits of AD were calculated using Eq. (2). Some basic assumptions were made to proceed the calculation. This study considered 1–5 m^3 household digesters fed with food waste and animal manure (cattle and goat) which are locally available feedstocks. A per capita food waste generation of 0.25 kg/d was assumed based on a total waste generation of 0.85 kg/d and food waste constituting 30% of the waste. For households with cattle or goats, an average of 1–2 heads of cattle or 3–4 goats was assumed based on local surveys. Literature data on methane yields for food waste, cattle manure and goat manure were used (Table 3). Using these data and assumptions, the daily methane production potential from AD was estimated and compared against the household energy requirements to evaluate the decentralized self-sufficiency potential of AD.

$$E = \eta \times HHV_{CH_4} \times \sum (G_i \times VS_i \times Y_i), \quad (2)$$

where E represents potential energy benefits from AD for typical households (kWh); η is the energy efficiency, set at 50% in this study; HHV_{CH_4} denotes the higher heating value of methane (39.71 MJ/m^3); G_i is the daily generation amount of waste type i (food waste, cattle waste, goat waste) (kg/d); VS_i signifies the volatile solid content in waste type i (fraction); Y_i represents the methane yield of waste type i via AD (m^3/kg VS).

3 Waste management and socio-economic status in Maldives and other SIDS

Waste management encompasses much more than technological issues; it is primarily an intricate socioeconomic conundrum. Local policies, economic development, population, and lifestyles, to different extents, affect all aspects of waste management, including waste generation, transport, recycling, treatment, and disposal. To date, no study has conducted a granular quantitative correlation between diverse indicators of socioeconomic status and practices of waste management across SIDS. In this study, we dedicate to executing a quantitative examination of such correlations from the perspective of Maldives and other SIDS. Our analysis provides novel insights into context-specific strategy design. Figure 1(a) delineates the correlation between waste generation and per capita Gross Domestic Product (GDP/capita) across 236 global regions and countries. It is generally observed that waste generation escalates with an increase in a nation's GDP, a truism applicable to Small Island Developing States (SIDS) coherently with the global trend. Municipal Solid Waste per capita (MSW/capita) within SIDS deviates from 0.14 to 4.45 kg/d, juxtaposed with a GDP/capita fluctuation from 631 to 56,746 USD. Therefore, notwithstanding the shared challenges of SIDS, the broad disparities of economic development necessitate custom strategies for waste management. For Maldives specifically, it falls into the upper-middle income range (GDP/cap = 9,802 USD, Fig. 1(e)), but also has a relatively high MSW/cap (1.29 kg/d, Fig. 1(d)). Maldives has a territory of only 300 km^2 (Fig. 1(b)), which is among the smallest 10% even in SIDS. Meanwhile, its population (475,500) falls into the top 40% of all SIDS (Fig. 1(c)), placing Maldives in the top 5 percentile for population density (Fig. 1(f)). Consequently, the conflict between high PD, limited land area, and high waste generation is starkly pronounced in the Maldives relative to other SIDS.

To further correlate the socio-economic status and waste management strategies, we divide SIDS into four different groups according to their GDP/capita and population density (PD): 1) low GDP and low PD, 2) low GDP and high PD, 3) high GDP and low PD, and 4) high GDP and low PD (Fig. 2). We empirically consider 500 capita/km^2 and 12695 USD/capita as the thresholds to distinguish between high or low PD and GDP/cap, respectively (World Bank, 2022). Each group of countries should have its own waste management strategy according to its socio-economic status. Maldives falls in the group of low GDP and high PD, the same as Mauritius, Nauru, and Micronesia. The countries with high GDP and high PD includes Singapore, Bahrain, Barbados, and Aruba. Most SIDS are classified into low GDP and low PD group (26 out of 51) and high GDP and high PD group (17 out of 51).

Figure 3 elucidates the correlations between GDP/capita and actual waste management practices in the grouped SIDS, including waste generation/cap (a), waste composition (b–d), and disposal methods (e–f). The trend shown in Fig. 3(a) aligns consistently with that shown in Fig. 1, indicating that SIDS with higher GDP/capita commonly incur greater MSW/capita. Maldives, dubbed by high PD and substantial tourism dependence, has the highest MSW/cap in the low GDP cohorts. It also should be noted that Maldives is in the progression toward the

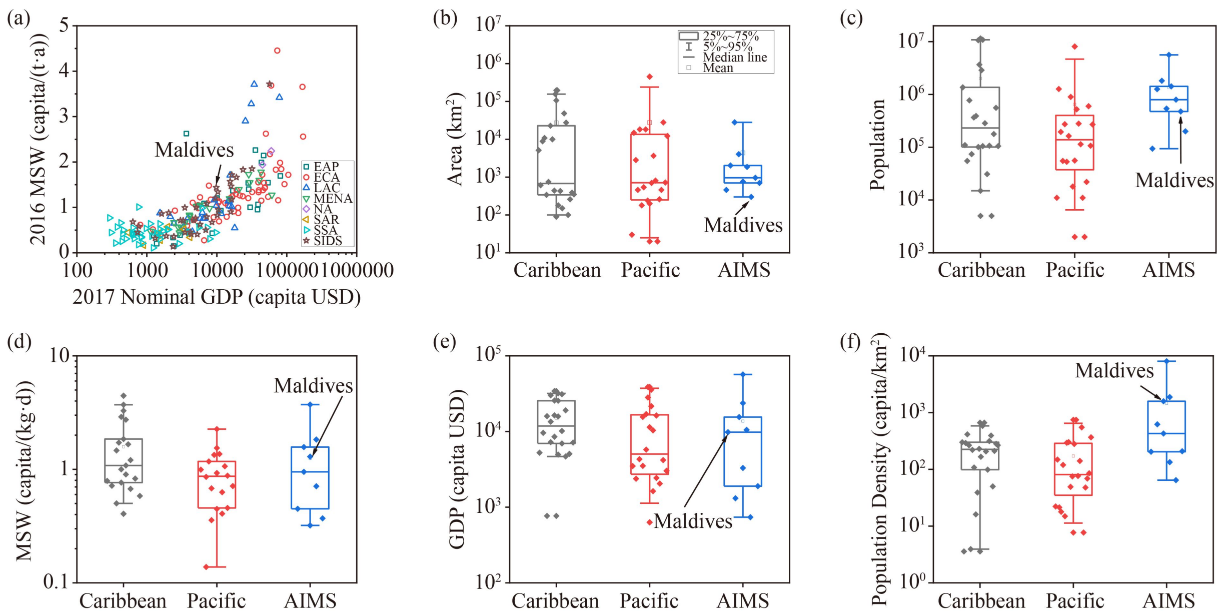

Fig. 1 Socio-economic status and MSW generation in 51 SIDS. (a) Waste generation versus Gross Domestic Product (GDP) per capita of 236 countries and regions in seven major regions and SIDS in the world, which are classified according to the World Bank: East Asia and Pacific (EAP), Europe and Central Asia (ECA), Latin America and the Caribbean (LAC), Middle East and North Africa (MENA), North America (NA), South Asia (SAR), and Sub-Saharan Africa (SSA). Other socio-economic indicators including (b) area, (c) population, (d) MSW generation per capita, (e) GDP per capita, and (f) population density of 51 SIDS are also illustrated (Kaza et al., 2018).

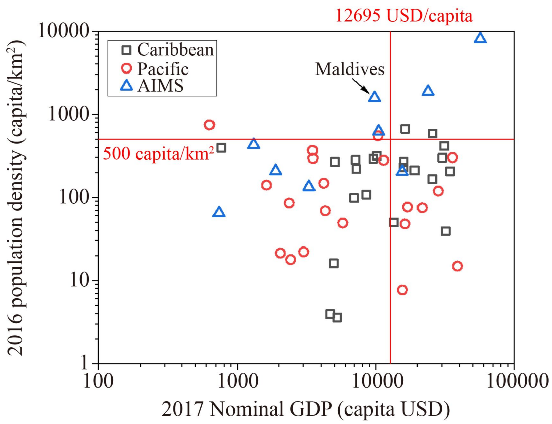

Fig. 2 Grouping of SIDS according to their population density and GDP/capita.

high GDP and high PD group. Thus, the high incineration and recycling rates in Singapore (Fig. 3(f)), which possesses the highest GDP and PD among all the SIDS, presents a laudable model for future emulation for Maldives, and for other high GDP high PD SIDS with low recycling rates, including Bahrain, Barbados, and Aruba.

Figures 3(b)–3(d) encapsulate discernible fluctuations in waste composition (organic waste, recyclable and incinerable waste, and recyclable and non-incinerable waste) with the GDP/capita in SIDS. Generally, the percentage of organic waste decreases with increasing GDP/capita, while the percentages of recyclable and incinerable waste (paper and plastics) and recyclable and non-incinerable waste (glass, metal, etc.) both increase with increasing GDP/capita. Particularly, Maldives has the highest organic waste percentage and lowest recyclable and incinerable waste percentage among all the SIDS. The future economic development will certainly lead to changes in the waste composition of Maldives, especially a predictable decrease in the percentage of organic waste and an increase in recyclable waste. Thus, the waste management strategies concerning collection, transport, recycling, treatment, and disposal have to be adjusted accordingly in advance. Figures 3(e)–3(f) clarify how GDP affects waste disposal methods in the SIDS. The correlation between the percentage of landfilling and GDP/cap is in surprisingly good agreement with the environmental Kuznets curve. Landfilling remains the first choice for low- and middle-income countries, while high-income countries will decrease the percentage of landfilling and opt for recycling and incineration. There is no data for the percentages of recycling and incineration in Maldives now. Maldives will still rely on landfilling for a while but have to gradually embrace recycling and incineration due to economic development and limited land availability. To achieve such transition, improvements should be made to all current waste management practices according to the peculiar situation of each region in Maldives, as discussed in the next section.

4 Current solid waste management practices in Maldives

In terms of geographical features, Maldives consists of 19 atolls and two cities, Male' and Addu. For administrative purposes, the greater Male' area is referred to as Region 1, the northern and northern-central atolls as Region 2, and the southern atolls as Region 3. Waste management responsibilities are divided accordingly, with the Male' city council overseeing waste management in Region 1, while the respective island councils are responsible for solid waste management within their jurisdictions (MEE, 2011). Solid waste disposal practices in the Maldives vary significantly across different regions due to factors such as access to waste collection and disposal facilities, environmental awareness among residents, local customs, and the involvement of municipal authorities or island councils.

Figure 4(a) illustrates the annual municipal solid waste (MSW) generation from three major sources between 1999 and 2019: Male', other islands, and resorts. Over the past 20 years, MSW generated in Male' and other islands has gradually increased, whereas the MSW generated from resorts highly has experienced significant fluctuations, closely tied to the tourism market, with a peak in 2013. It is worth noting that despite its small area of just 5.8 km^2, Male' generates approximately 63% of the total MSW, while the remaining waste is generated across more than 1000 small islands spanning 292 km^2. These substantial regional disparities necessitate distinct waste management approaches even within the Maldives. Figure 4(b) exhibits the MSW/capita versus PD in Male, other islands, and the other SIDS and regions. Obviously, Male's situation is similar to Singapore, characterized by high population density, high MSW per capita, and relatively comprehensive waste-related services and infrastructure. On the other hand, other islands exhibit lower population density and MSW per capita, with many facing challenges due to limited financial, manpower, and technical resources for the development and management of proper waste collection and disposal infrastructure. Consequently, designated waste disposal sites may be absent or the existing waste disposal centers may exceed their operational and storage capacities. Currently, the Maldivian government recognizes three landfills and 134 island waste management centers, out of which only one landfill on Thilafushi island and less than 40% of the island waste management centers are operational (MEE, 2011; 2016).

4.1 Region 1: Male' city and greater Male' region

Region 1 generates the most MSW in the country. In 2014, an estimated 137000 MT of MSW was collected in the region and constituted ~63% of all the MSW (220000 MT) generated in the country. Rapid urbanization has

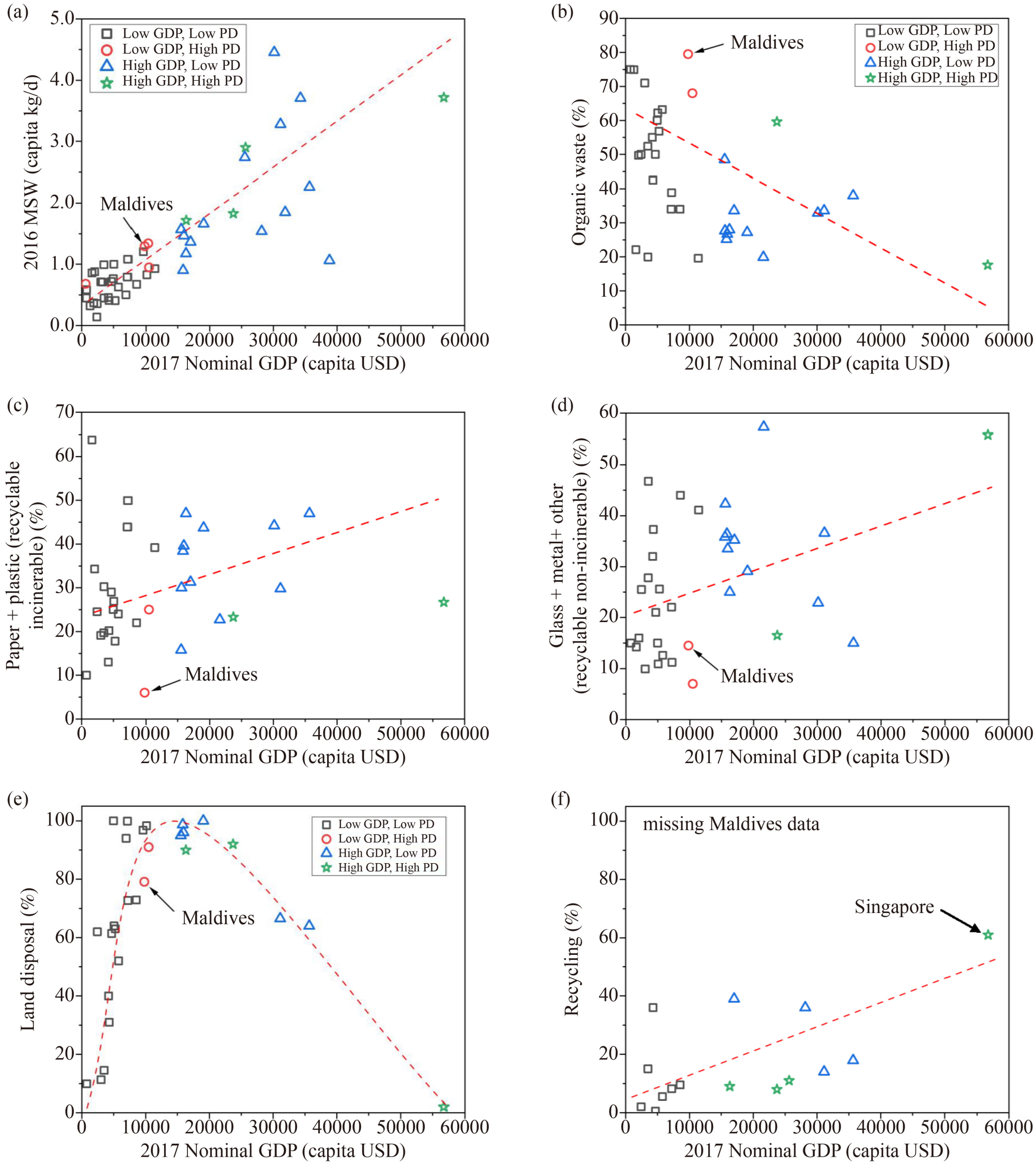

Fig. 3 Waste management practices versus GDP/capita in the SIDS in different groups: (a) MSW generation per capita per day, (b) weight percentage of organic waste, (c) weight percentage of recyclable and incinerable waste (paper and plastics), (d) weight percentage of recyclable and non-incinerable waste (glass, metal, etc.), (e) percentage of MSW landfilling, and (f) percentage of MSW recycling.

resulted in a sharp increase in MSW generation in the region, an increase of over 53% in the last decade (Fig. 4(a)) (MEE, 2016). The composition of the MSW in Region 1 is shown in Fig. 5(a). Organic waste constituted 48% of the MSW, with food and yard waste (leaves, twigs, grass, etc.) accounting for a considerable proportion of the organic waste (MEE, 2011). Previous waste audits also reported that food and yard waste comprised 30% and 51% of organic waste, respectively (EPA, 2010). Scrap metal, plastics, glass, and other inorganic wastes formed the rest of the MSW.

Although almost 100% of households dispose their waste at the designated disposal sites in Male', segregation of waste at source is largely absent. As per a survey by the city council, 82% of the households in Male' did not practice segregation in any form (EPA, 2010). Private contractors are paid a monthly fee of 6–22 USD to carry out solid waste collection. The solid waste is predominantly collected by individual expatriate laborers, who work after hours in this sector, and other

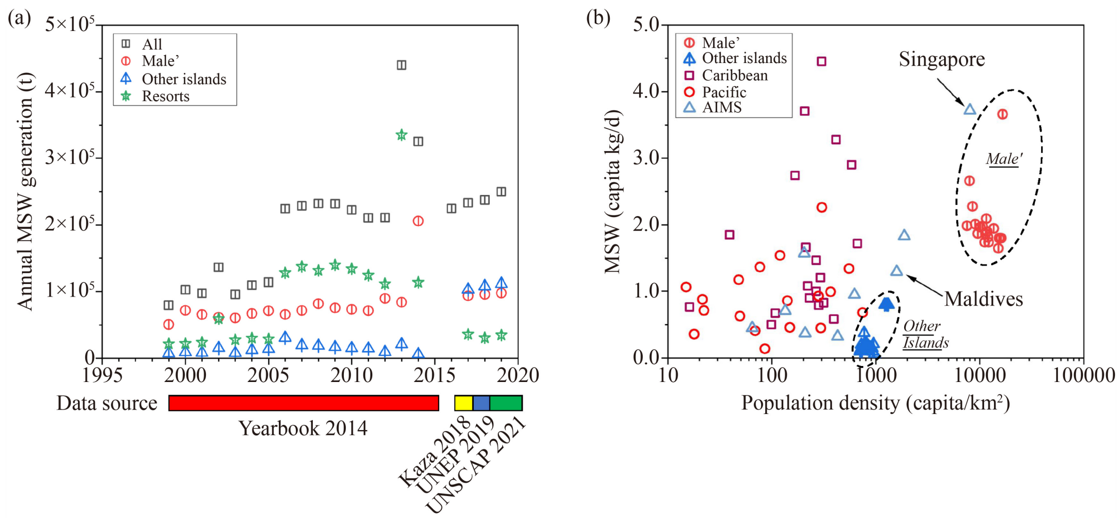

Fig. 4 (a) Annual MSW generation in the whole Maldives, Male', other islands, and resorts (Kaza et al., 2018; UNEP, 2019; UNSCAP, 2021), and (b) MSW/capita versus PD in Male', other islands, and the other SIDS and regions.

unregulated private contractors involved in the waste collection business. The wastes are carried to one of the two dedicated secondary storage and collection sites on bicycles, small lorries, or wheelbarrows. Wastes from the two collection sites are then transferred in dump trucks and barged to the landfill on Thilafushi Island, a reclaimed land serving as the primary landfill for the region (EPA, 2010; MEE, 2011). Governmental initiatives are underway to improve the overall management and capacity of waste infrastructures across the region. The state-owned Waste Management Corporation recently initiated formal waste collection services under a pilot project in Male'. Currently, the waste collection service is being offered in selected zones in Male' but is expected to extend to the entire city in the coming years (World Bank, 2017).

Rudimentary sorting of waste is undertaken at the collection site on Thilafushi by a group of 2–3 expatriate laborers employed by the city council. Due to the copious quantities of waste received and the lack of technical resources, the extent and effectiveness of segregation remains limited. An informal sector is active in the recycling of metal and plastic waste. However, such parties are only the "middlemen," who handpick metal scraps and export them to neighboring countries such as India (EPA, 2010; MEE, 2011). Approximately 10% of the annual plastic waste transported to Thilafushi is shredded and exported to India for recycling. In the absence of waste handling practices such as composting or a formal recycling sector, the MSW including plastics and other inorganic wastes is routinely burned in open spaces for volume reduction, resulting in large plumes of smoke and foul odor. Medical and other hazardous wastes are either buried or simply burned along with MSW. The unburnt wastes and residues are dumped in an enclosed lagoon area with bund walls for land reclamation purposes. The potential risks to human health and the environment due to open burning and improper waste disposal are immense (Cook and Velis, 2021).

4.2 Region 2: northern and northern-central atolls

Region 2 comprises 14 atolls: Haa Alifuu, Haa Dhalu, Shaviyani, Noonu, Raa, Baa, Lhaviyani, Kaafu (excluding Male' Atoll), Alifu Alifu, Alifu Dhaalu, Vaavu, Faafu, Meemu, Thaa, and Laamu atoll. This region collectivity generates ~50000 MT of MSW annually and accounts for 23% of the MSW generated in the country (MEE, 2011). With the increase in various activities such as boat building, agriculture, and immigration, the regional MSW generation is forecasted to increase by 200% by 2030. As shown in Fig. 5(b), organic waste dominates by constituting 55%–60% of the MSW, followed by inorganic waste (26%), metals (6%), glass (4%), and plastics (4%). Food and yard waste comprise 85% of the organic waste in the region (MEE, 2011).

Segregation of waste at source is absent throughout the region. The main methods of waste disposal in Region 2 are presented in Fig. 5(d). Contrary to Region 1, less than 10% of the islands in the region have the provision of a fee-based system for waste collection and transfer. Consequently, it is left to the householders to carry the waste to the designated disposal sites. The wastes are transported on wheelbarrows generally by a female member of the family (MHE, 2004; Shumais, 2010). As the disposal sites are often at a considerable distance from the village or the residential area due to limited land availability for waste disposal, ill-defined dumping grounds and burning areas are common. Open burning of waste with little or no segregation poses immense environmental damages and threats to public health. Vegetation die-off, damage to plant roots, and accelerated

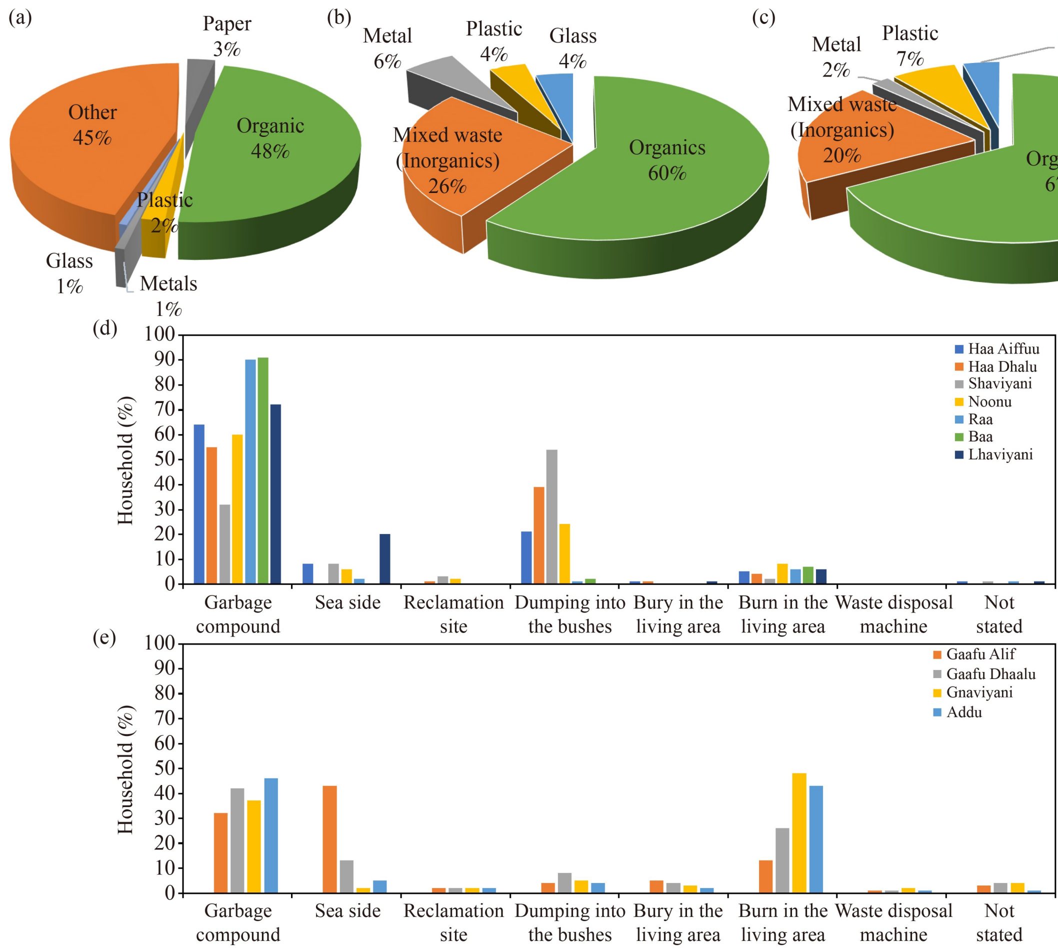

Fig. 5 MSW generation and disposal methods in the three regions in Maldives: MSW composition in (a) Region 1, (b) Region 2, and (c) Region 3; MSW disposal methods in (d) Region 2 and (e) Region 3.

coastal erosion due to open burning has been reported on many islands including Dhonfanu (Baa atoll), Ungoofaaru (Raa atoll), and Lhohi (Noonu atoll) island. In addition, the designated disposal sites on many islands are inappropriately placed by being too close to the shoreline. As a consequence, windblown litters such as polythene bags and unburned waste residues enter the marine environment. Further leakage of waste and leachate from such locations has the potential of causing irreversible damages to the marine ecosystem.

The commitment of the island councils and the government of Maldives to improve the existing system of waste management across the region has led to improved waste collection and disposal practices at some islands such as Kulhudhuffushi (Haa Dhaalu atoll), Holhudhoo (Noonu atoll), and Velidhoo (Noonu atoll). Kulhudhufushi island has now been provided with mechanical transport and waste processing equipment that include shredders, balers, bulldozers, and tractors. The island disposal facility is managed by a private company that also provides waste collection services on a weekly basis. Segregation of waste is undertaken at the collection site, but it is limited to the segregation of PET containers, metals, glass, and other recyclable waste into combustible and non-combustible ones. While the combustible wastes are disposed of by burying, open burning, and sea dumping, there is little provision for the disposal of non-combustible wastes, which are often transported to Thilafushi island or sold to private contractors. However, the island faces the problem of irregular collection of non-combustible wastes due to high transportation costs, which results in the leachate from stockpiled wastes becoming a threat to public health due to the breeding of mosquitoes and other vectors.

Proper segregation and recycling of waste are being encouraged on Holhudhoo island. Waste sorting is undertaken at a small walled sorting site by the local inhabitants or expatriate workers employed by the island council. The island council also provides waste pick-up service for households far from the disposal site for a nominal fee. The island has also been provided with a metal compactor. Metal waste is sold to a Male' based contractor, who also partially pays for the salaries of the waste collectors and sorters. Recycling of tin and melting of aluminum to make kitchen and storage items is being encouraged. However, the waste management system is limited and suffers from a lack of available land for expansion and capacity upgrading. Similar to Holhudhoo island, sorting of waste by local inhabitants is also practiced on Velhidoo island. The island also contains a waste sorting facility and the waste disposal center is located at a considerable distance from the beach. However, the site lacks waste processing equipment such as compactors or shredders, which results in burying or dumping non-combustible waste into the sea. As in the case of other islands, wastes are openly burned to reduce their volumes.

4.3 Region 3: southern atolls

Region 3, which comprises Gaafu Alif, Gaafu Dhaalu, Gnaviyani, and Addu atoll, collectivity generates 30000–35000 MT of MSW annually (MEE, 2016). The composition of MSW in the region is presented in Fig. 5(c). Organic waste such as kitchen and garden waste constitutes 67%, followed by mixed waste (20%), plastic (7%), glass (4%), and metal (2%). In the absence of proper waste disposal approaches and facilities, the wastes are disposed of by open burning, burying, and dumping in the sea (MEE, 2016). The detailed solid waste disposal methods in Region 3 are depicted in Fig. 5(e). The waste management practices and infrastructures in Region 3 suffer from the same limitations as those confronted by Region 2. Despite limited mechanization and standardization attempts in Addu and Gaafu Dhaalu atoll, waste management in this region highly relies on manual labor and lacks uniform standards due to limited financial revenue and manpower and technical recourses. The high volume of open dumped and burned waste has brought environmental and health concerns.

Our categorization and quantitative analysis of the stark differences between the three distinct regions systematically establish the complete waste profile in Maldives, including waste generation, composition, collection, transportation, and disposal. Our study provides new and granular insights into the highly heterogeneous waste management landscape within Maldives. The knowledge gap filled by the above analysis provides the foundation for developing sustainable waste management strategies and proposing feasible WtE solutions as discussed in the next section.

5 Waste to Energy (WtE) potential in Maldives

5.1 WtE practices in SIDS

SIDS with limited land areas and resources commonly have sensitive economic and energy supply structures. Thus, they are aggressively increasing the penetrations of renewable energy and embracing WtE technologies to reduce the reliance on traditional fossil fuels. Anaerobic digestion (AD) and incineration are widely used WtE technologies in SIDS. Table 1 summarizes the reported AD and incineration practices in SIDS. The early AD facilities can be dated back to the 1940s, till now many more anaerobic digestors have been built to convert organic waste to biogas. Due to the affordable costs, simple setup, relatively small scales, and considerable energy outputs, SIDS with different GDP and PD levels have been reported to adopt AD. Since the percentage of organic waste increases with decreasing GDP/cap (Fig. 4(b)), AD penetrates even deeper in less-developed SIDS. The scale of AD facilities is commonly related to PD. Small-scale anaerobic digestors at home or community levels are adopted by countries with low PD, e.g., Cuba (~700 digestors) and Jamaica (~120 digestors). These digestors are often set in areas with rich organic waste to maximize their overall efficiency, e.g., on farms. SIDS with high PD, e.g., Singapore and Barbados, have large biogas plants serving the whole island to realize the economies of scale.

Unregulated waste burning, an ancient way of waste disposal, is prevalent in most SIDS. In contrast, regulated waste incineration facilities for energy recovery have not been established till the 21st century. The expenditure for an incineration plant construction is much higher than for an anaerobic digestor. Apart from Singapore, which has the highest GDP per capita among SIDS and incinerates around 60% of MSW, incineration facilities in other SIDS are still in rudimentary stages. Singapore and British Virgin Islands, with mature technology and management systems, are the only two SIDS utilizing incineration to treat MSW. Most other countries only incinerate hospital waste, which has lower moisture content than MSW and is thus easier to handle. Many SIDS rely heavily on international investments or aids for incineration plant constructions, e.g., Word Bank's WtE plant investment in Seychelles and Japan's technical support to Federated States of Micronesia (Jackson, 2021). Population density is another principal factor in determining the feasibility of an incineration plant. Samoa, a country with low GDP and low PD, previously had one WtE incineration plant but was abandoned due to limited energy output (Holder et al., 2020). The health and environmental concerns of local residents should also be taken into consideration when building an incineration plant. Mauritius shut down its 300,000 t/a WtE plant plan in 2006 due to severe public protests (Mohee et al., 2015; Neehaul et al., 2020). Hence, each country should optimize its WtE strategy according to its geographical and socio-economic status.

5.2 Current WtE status in Maldives

The restricted land availability and geographical remoteness of many islands in the Maldivian archipelago make any form of integrated and long-term development and planning difficult to implement, as many aspects of the economy are beyond the real control of the local planners

Table 1 Reported WtE practices in SIDS

Country	Region	Category	AD practices	Incineration practices	Ref.
Mauritius	AIMS	Low GDP, High PD	A large-scale biogas plant for sludge treatment	Initiated a 300000 t/a WtE plant but abandoned due to protest, two small WtE plants operating	Bundhoo et al. (2016); Neehaul et al. (2020)
Seychelles	AIMS	High GDP, Low PD	Multiple biogas plants on animal farms	An incinerator treating oil and hospital waste; expects to set up a MSW WtE plant	Martin (2010); REEEP (2012); Bonnelame (2022)
Singapore	AIMS	High GDP, High PD	A few biogas plants for household waste treatment	Four WtE plants treating over 4000000 t/a of MSW, expect to build a new integrated WtE facility in 2027	Mohee et al. (2015); NEA (2019)
Belize	Caribbean	Low GDP, Low PD	Small-scale animal manure digestion	Not available	Ortega (2009)
Guyana	Caribbean	Low GDP, Low PD	~30 anaerobic digesters in farms	Not available	Rooplall (2017)
Suriname	Caribbean	Low GDP, Low PD	Not available	Two small-scale incinerators treating hospital waste	Zuilen (2006)
Cuba	Caribbean	Low GDP, Low PD	~700 small digestors for organic waste treatment, 450 new in build	Not available	Karagiannidis (2012); González Lorente et al. (2020)
Dominican Republic	Caribbean	Low GDP, Low PD	~20 anaerobic digesters in pig and chicken farms	Not available	Flores (2016)
Grenada	Caribbean	Low GDP, Low PD	Not available	Not available	Grenada (2017)
Haiti	Caribbean	Low GDP, Low PD	A few anaerobic digestors for agricultural waste treatment, small, cheap biodigesters built at home level	Not available	Toussaint & Wilkie (2011)
Jamaica	Caribbean	Low GDP, Low PD	~120 digestors for treating garden and kitchen waste	Not available	Karagiannidis (2012)
Saint Lucia	Caribbean	Low GDP, Low PD	Up to 9% of the total energy generated from biogas	Not available	Holder et al. (2020)
Saint Vincent and the Grenadines	Caribbean	Low GDP, Low PD	Up to 8% of the total energy generated from biogas	Not available	Holder et al. (2020)
Bahamas	Caribbean	High GDP, Low PD	A 2 m^3/week anaerobic digestor	Not available	Holder et al. (2020)
Antigua and Barbuda	Caribbean	High GDP, Low PD	Plan to develop a bioreactor system to produce electricity	Not available	Holder et al. (2020); Silva-Martínez et al. (2020)
British Virgin Islands	Caribbean	High GDP, Low PD	Not available	Incineration is the main waste disposal method	Mcdevitt (2008)
Barbados	Caribbean	High GDP, High PD	Up to 18% of the total energy generated from biogas	Not available	Holder et al. (2020)
Fiji	Pacific	Low GDP, Low PD	Nine biogas plants; a new national WtE initiative for AD implementation	Not available	Holder et al. (2020)
Papua New Guinea	Pacific	Low GDP, Low PD	A pilot-scale anaerobic digestor treating farm waste	Not available	Jenangi (1998)
Samoa	Pacific	Low GDP, Low PD	Abandoned a few biogas plants	Abandoned an incineration plant	Isaka et al. (2013)
Tuvalu	Pacific	Low GDP, Low PD	A biogas plant treating pig and human sewage	Not available	Rosillo-Calle & Woods (2003)
Federated States of Micronesia	Pacific	Low GDP, High PD	Not available	An incinerator treating medical waste	Joseph & Prasad (2020); Jackson (2021)

and invariably restrict private participation (MHE, 2010; MEE, 2012). This applies to waste management and energy security, as well as other areas of national development. Waste management and energy usage are closely intertwined, with the former representing an energy-intensive process. However, with proper channeling and streamlining, waste serve as a promising renewable energy source. Energy recovery from waste would promote the diversification of energy supplies in Maldives and increase the energy obtained from indigenous resources. Consequently, it would strengthen the Maldivian energy security efforts by reducing the dependence on imported fossil fuels (Van Alphen et al., 2008). Maldives, lacking proven conventional energy sources or reserves, relies entirely on imported petroleum fuels to meet its primary energy needs (MEE, 2012). Energy fuels are heavily subsidized, which inevitably restricts capital and the availability of funds for the development of other sectors of the economy. The country spent close to 490 million USD in 2013 on oil imports, which represented ~17% of the national GDP. With fuel prices soaring caused by the Russia-Ukraine conflict in 2022, this share is expected to increase significantly. Approximately 80% of the primary energy demand is met by diesel oil, which is also used for electricity production. Petroleum, kerosene, liquefied petroleum gas (LPG), and jet fuel serve as the sources of balanced energy needs (Bernard et al., 2010).

Electricity generation in Maldives is decentralized. Each island has its own power generating facility normally consisting of diesel generators of varying capacities. FENAKA Corporation Ltd. provides electricity to 115 out of 194 inhabited islands. The respective island councils are responsible for providing electricity to 73 islands and private companies provide electricity to the rest 5 islands. Though a majority of the Maldivians live in Region 1 and Addu city in Region 3 with full-day availability of electricity service, the remaining islands are provided with a limited 5–12 h of electricity service. Energy for cooking in the majority of the islands is commonly met by using LPG and kerosene. Roughly, 13%–15% of the households in the outer islands still depend on biomass (coconut husk, shrubs, wood waste) for domestic energy needs, with the percentage considerably higher in the northern atolls. The use of biomass for cooking purposes was reported to be higher in Regions 2 and 3 and low-income households in Region 1 (MEE, 2012).

With the national energy demand expected to increase by 8%–11% annually, continued reliance on imported energy fuels would exacerbate the country's balance of payments and increase the risk of debt burdens. In such a scenario, even small international loans could severely affect and jeopardize the government's service commitments and thus further reduce the capital availability for development (MHE, 2010; 2012). Ensuring current and future development requires multi-concurrent strategies for increasing energy efficiency, conservation of energy use, and enhancing energy supply from indigenous renewable sources such as MSW. Increasing the share of energy from MSW in the Maldivian energy portfolio is not only an environmental concern but also a matter of national economic security and social development.

The National Environmental Action Plan (NEAP) and the National Sustainable Development Strategy (NSDS) outlined the importance of developing and implementing sustainable approaches to meet the growing energy demand, enhance renewable energy supply, and effectively manage environmental risks through energy recovery from MSW. Maldives is also among the six pilot countries participating in the Scaling up of Renewable Energy Program (SREP) for low-income countries, through which it sought 30 million USD in funding in the energy sector including WtE initiatives (MEE, 2012).

5.3 Waste to energy potential in Region 1

Region 1 is densely populated with high MSW/capita, which is similar to Singapore with a high incineration rate (~80%). Incineration is effective in reducing waste volume, destroying contaminants and pathogens, and recovering energy, which effectively eases the conflict between high MSW/capita and limited disposal areas in Region 1 (Tong et al., 2018). Table 2 elucidates the potential of MSW incineration and energy capacity in Region 1. The composite averaged *LHV* is first evaluated to examine the feasibility of using a particular MSW composition for incineration. The value in Region 1 is 6,246 kJ/kg, which is on the margin of being suitable for incineration with energy recovery according to the suggested value of > 6285 kJ/kg by the World Bank (Liu and Nishiyama, 2020). The total energy capacity of incineration is calculated to reach 29.2 GWh/a in Region 1. Although it is only a small fraction of all the electricity generated in Maldives in 2019 (712 GWh), this amount already exceeds the total electricity generation from all renewable energy sources in 2019 (22 GWh) (IRENA, 2021). By introducing MSW incineration, Maldives can at least double the electricity generation amount from renewable energy and at the same time optimize energy structure and mitigate the over-reliance on fuel imports, which are critical to the energy security of Maldives.

Currently, a waste incineration project is being planned on Thilafushi Island. A private consortium will build and operate an integrated waste management system for this region. The project, upon completion, will have mobilized 50 million USD investment from the private sector. The facility will treat 200 MT of waste per day and generate 2.7 MW of electricity by a dry distillation and gasification combustion system. The project is expected to serve 120000 people in the targeted region and reduce annual GHG emissions by 16000 t (IFC, 2011). In 2020, the Asia Development Bank (ADB) also approved a 73 million USD package to develop a WtE facility for the great Male' region. This facility with a capacity of 500 MT/d is expected to generate 8 MW of electricity and includes a landfill to dispose of the incineration bottom ash.

5.4 Waste to energy potential in Region 2 and Region 3

The establishment of effective WtE systems for the islands in Region 2 and Region 3, especially in the outer islands of the region, requires a unique approach due to infrastructural and geographical constraints. Unlike Region 1, the amounts of waste generated on these islands are limited and characterized by high organic fractions (55%–67%), especially food and yard wastes. Such wastes vary in moisture content and calorific value and are therefore unsuitable for a single-technology-based approach as being implemented in Region 1. High-

Table 2 Potential energy capacity from MSW incineration in Region 1 (Male’)

	Yard	Food	Other organics	Wood	Dirt, ash, stone, sand	Metal	Paper	Plastic	Textile	Cardboard	Glass	Rubber, leather	Hazardous, pets	Total
Total mass (t/a)														84260
[a]Percentage (%)	50.85	22.22	4.64	1.74	7.6	2.84	1.87	2.5	1.75	1.55	1.37	0.77	0.31	
[a]Mass (t/a)	42846	18723	3910	1466	6404	2393	1576	2107	1475	1306	1154	649	261	
[a]Mass (t/a)	117	51	11	4	18	7	4	6	4	4	3	2	1	
Total waste (t/a)														231
[b]LHV MMBtu/t	6	5.2	5	10	0	0	6.7	23	13.8	16.5	0	14.4	0	
LHV MMBtu/a	704.3	266.7	53.6	40.2	0	0	28.9	132.7	55.8	59.0	0.0	25.6	0	
Ave LHV (kJ/kg)														6246
Total LHV MMBtu	257077	97357	19548	14661	0	0	10557	48450	20349	21549	0	9343	0	
Energy capacity GW/a														**29.2**

Note: 1 MWh = 3.413 MMBtu, 1 MMBtu = 1055000 kJ; [a] Waste composition data are in 2017 from UNEP 2020; [b] LHV data from US Energy Information Administration (EIA).

moisture food waste also has a low density, which consequently increases transportation costs. Considering these concerns, a decentralized approach for converting organic waste to energy and reducing residue volume for disposal may be more appropriate. The following paragraphs discuss the feasible technologies for waste treatment and energy recovery in Region 2 and Region 3.

In contrast to the high infrastructure investments needed for waste incineration facilities, AD enables energy recovery from organic waste using relatively simple and affordable small-scale (< 15 m^3) or household (1–5 m^3) digesters. Such decentralized AD facilities provide an effective technology for delivering energy directly to communities in the outer islands while alleviating the pressing challenges of waste collection and disposal. Household digesters can be deployed for energy recovery from food waste and also for co-digestion of food and animal waste at households involved in cattle rearing. Additionally, opportunities exist for energy recovery from human waste through AD in remote communities lacking municipal sewage treatment systems. Small-scale digesters are being increasingly deployed in SIDS with geographical and infrastructural constraints similar to those faced by Maldives. For example, AD has been implemented in Jamaica, Fiji Islands, Cuba, American and British Virgin Islands, Mauritius, and Andaman and Nicobar Islands among others. A recent comprehensive review on different WtE technologies used for energy recovery has also suggested that the most feasible solution for organic waste in developing countries is AD (Kumar and Samadder, 2017).

Methane yields of 0.15–0.3 m^3 CH_4/kg volatile solids (VS) have been reported for household digesters using food waste (Banks et al., 2008; Lou et al., 2012). The composition of the food waste used in these studies closely matches that observed in Maldives and can be considered a good indicator for the methane yield from food waste in Maldives. Considering that a typical household in the outer islands utilizes one LPG cylinder of 10 kg every 40–45 d, the utilization of biogas generated from kitchen waste can meet up to 30% of its daily energy requirement for cooking (Table 3). Thus, the utilization of biogas and marketing of AD slurry as fertilizer would relieve the economic burden on these households and result in additional sources of income and employment. The application of AD would play a pivotal role in improving the life quality of the vulnerable and rural sections of the society and those with limited access to regular energy services. Approximately, 7000 households in Maldives are still dependent on firewood for their domestic cooking. In addition, high fuel prices and high unemployment rates in various atolls such as Baa (44%) and Lhaviyani atoll (49%) further add to the economic and social pressure in the society. Almost 28% of the households in the northern region are headed by females, out of which 35% are widowed or divorced with marginal incomes, putting them in highly vulnerable positions (MHE, 2004; 2011). Therefore, AD will be useful to treat kitchen waste and at the same time provide reliable energy supplements for vulnerable residents living in the outer islands.

Around 40% of the households in Region 2 and Region 3 are involved in livestock rearing for dairy production, which is consumed locally. Many households have a small herd of 1 to 2 cattle or 3 to 4 goats. Due to the high organic content of animal manure, it can be used as an AD feedstock. Average methane yields of 0.21 m^3/kg VS for cattle manure and 0.10 m^3/kg VS for goat manure have been reported using household digesters (Bundhoo et al., 2016; Garfí et al., 2016). In the Maldivian context, the digestion of cattle and goat manure can meet between 40 and 100% of the daily energy demand for cooking (Table 3). Animal manure can also be co-digested with kitchen waste, thereby increasing biogas production and economic viability. Improved methane yields of

Table 3 Energy potential from anaerobic digestion of kitchen waste and animal manure in Maldives

				Co-digestion	
Parameters	Food waste	Cattle	Goats	Food + Cattle waste	Food + Goat waste
Waste generated per household (kg/d)	[a]1.53	[b]12.50	[b]4.50	14.03	6.03
TS content (%)	[c]25.00	[d]17.00	[e]34.00	16.09	32.00
VS content (% of TS)	[c]96.00	[d]83.00	[e]82.00	87.00	85.00
CH_4 yield (m^3/kg VS)	[f]0.25	[g]0.21	[h]0.10	[i]0.29	[J]0.10
Daily estimated CH_4 production (m^3/d)	0.10	0.37	0.12	0.56	0.16

Notes: [a] Assuming 6 members per household, per capita waste generation of 0.85 kg/d and kitchen waste to constitute 30% of the waste (conservative estimate); [b] Assuming 1 cattle or 3 goats per household (Mosquera et al., 2012; Bundhoo et al., 2016); [c] Average values from (Hussain et al., 2017); [d] Average values from (Alvarez and Lidén, 2008,2009; Bundhoo et al., 2016); [e] Average values from (Zhang et al., 2013a); [f] Average values from (Ferrer et al., 2011; Lou et al., 2012); [g] Average values from (Alvarez et al., 2006; Lansing et al., 2008; Garfí et al., 2011); [h] Average values from (Ashekuzzaman and Poulsen, 2011); [i] Average values from (El-Mashad and Zhang, 2010; Zhang et al., 2013b); [J] Methane yield assumed to be similar to mono-digestion on goat waste due to lack of relevant literature on co-digestion of food and goat waste.

0.22–0.29 m^3/kg VS upon co-digestion of kitchen waste and animal manure have been reported (Khalid et al., 2011; Garfí et al., 2016). As presented in Table 3, co-digestion results in a daily methane production of 0.37–0.56 m^3 with an equivalent energy content of 14.7–22.2 MJ (HHV of methane is 39.71 MJ/m^3), implying a net energy benefit of up to 10.3 MJ or 2.8 kWh (50% energy efficiency). This indicates that AD application cannot only meet the daily energy demand for cooking in the outer islands, but also result in excess energy production, which can accommodate for the fluctuations in energy demand.

5.5 Future research

While this study provides an analysis of the current waste management practices and WtE potential in Maldives, further research can help strengthen the implementation of sustainable waste management strategies. More extensive field surveys and waste audits should be conducted to obtain up-to-date and detailed data on waste generation, composition, and existing infrastructure in different regions of Maldives. This can optimize the design and operation of waste management systems. In addition, investigating the social acceptance of different WtE technologies through public surveys or focus groups is important to ensure proposed solutions align with community interests and values (Varjani et al., 2022). Technical feasibility analyses and detailed cost analysis should also be performed for deploying technologies like AD and incineration at larger scales. Pilot testing integrated waste management strategies on selected islands can generate insights for wider implementation. Furthermore, research is needed on crafting optimal policies and incentives to enable public-private partnerships and attract investment in the waste management sector, which requires effective regulations. Assessing the environmental impacts of existing and proposed systems using tools like life cycle assessment can also inform efforts to minimize ecological footprints and maximize overall benefits. For example, evaluating the fertilizer potential of AD digestate could provide added economic benefits (O'Connor et al., 2022). Additional research in these areas can facilitate Maldives and other SIDS in transitioning toward circular economy models for waste management. The knowledge generated can help overcome existing barriers and lead to sustainable, ecologically sound waste management practices.

6 Conclusions

This study provides an in-depth analysis of the unique waste management challenges in Maldives and examines the WtE potential as a sustainable solution. One of the key issues affecting public and environmental health in Maldives is the rapid increase in municipal solid waste (MSW) generation and the inadequate infrastructure to manage waste in a sanitary and environmentally friendly manner. Among the SIDS, Maldives has the top 5% PD and a relatively high average MSW/capita (1.29 kg/d) with low GDP/capita (9802 USD). The contradiction among the PD, waste generation, land availability, and economic capability is much more severe in Maldives compared to the other SIDS, making it necessary to explore its unique solid waste management strategies. This study reveals stark disparities in waste management practices and infrastructure between the densely populated capital Male' (Region 1) and the sparsely populated outer islands (Region 2 and Regions 3). Region 1 generates 63% of the MSW in the country within only a 5.8 km^2 area, which has relatively complete waste collection, transportation, segregation, and disposal services. Regions 2 and Regions 3 generate 23% and 14% of all the MSW, respectively, but have limited waste-related services or facilities.

Energy recovery from MSW is socially and environmentally sustainable, mitigating negative public health and environmental impacts while reducing Maldives' dependence on imported fossil fuels. Region 1 with high

PD and high waste generation is suitable for waste incineration, which can effectively reduce waste volume and increase renewable energy production. The geographical and infrastructural constraints render such an approach infeasible for the outer islands in Region 2 and Region 3. A decentralized approach for waste management and energy recovery may be more appropriate. Considering that kitchen and yard wastes constitute up to 67% of the MSW on the outer islands, the application of small-scale anaerobic digesters can be considered. This point-of-use technology aligns with the resource availability and energy demands on the outer islands. It is estimated that AD of food waste or co-digestion of food waste and animal manure can meet 40%–100% of the energy demand for cooking on the outer islands.

This study provides valuable insights into designing context-specific waste management strategies for Maldives based on natural and socioeconomic characteristics. Future work including pilot tests, life-cycle analysis, cost-benefit analysis, and surveys on public attitudes are still needed for strategy implementation and investment planning. Nevertheless, this study makes a timely contribution highlighting the potential of WtE technologies to address the pressing waste management and energy security challenges shared by Maldives and other SIDS. The framework presented in this study can guide decision-making to transition SIDS toward sustainable circular economy models with integrated waste management strategies, that are ecologically sound, economically viable, and socially acceptable.

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