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Application of Material Flow Analysis to Municipal Solid Waste in Urban Areas in Developing Countries and Possible Solutions Under Circular Economic Framework

N. A. Hemali† and A. A. P. De Alwis
Department of Chemical & Process Engineering, University of Moratuwa, Sri Lanka
†Corresponding author: N. A. Hemali; arosha.hemali@gmail.com

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ABSTRACT

The understanding waste flow of a country is important to identify the main problems associated with waste management and identify opportunities in material flow management. A tool such as material flow analysis (MFA) is a widely used method in waste management studies, to provide a comprehensive analysis of material movements, support for material characterization analysis to identify the severity of a problem, identify the real root cause, and propose suitable management methods. This paper presents an application of MFA for municipal solid waste (MSW) management in Western provinces in Sri Lanka. The outcome includes the identification, and quantification of the main input and output flows of the system in the present context, from waste generation, collection, unaccounted and unidentified flows, material recovery, and final disposal of MSW. Results are evaluated under treatment mechanisms of Recycling, Reusing, and repurposing the materials.

Overall results show per capita per day of waste generation in Sri Lanka stood at 0.43 kg, whereas, the Western province represents that 0.56 kg due to the high population area with the highest rate of urbanization. However, the global average per capita per day of waste generation stood at 2.22 kg. The material and energy recovery represent 31% and 33% respectively in the study area from total collected waste. 36% of the material finally ended up in open dumpsites even after collection. Further research needs to be done on material and energy recovery potential identification in dumping waste, as this can convert to valuable results with proper management practices with available resources.

INTRODUCTION

Rapid economic growth, urbanization, and increasing population have caused (material-intensive) resource consumption to increase, and the consequent release of large amounts of waste to the environment. The current waste and resource management system lack a holistic approach that covers the entire chain of product design, raw material extraction, production, consumption, recycling, and waste management.

In 2018, it was estimated that MSW generation is expected to grow 3.4bn Mt by 2050 given the way things are handled at present. By 2050, the amount of waste generated in developing countries will see a threefold increase (Kaza et al. 2018). Asia and the Pacific region will generate most of the world's waste- a considerable 23%. In developing nations, food and green waste amount to more than 50%. Recyclables such as paper, cardboard, plastic, metal, and glass make up a substantial fraction of waste streams, ranging from 16% in developing countries to about 50% in developed countries.

In Sri Lanka, more than 60 % of municipal solid waste is a bio-degradable organic material and the rest is non-biodegradable materials (Visvanathan et al. 2006). There is no proper segregation of waste at the household level before disposal (Warunasinghe & Yapa 2016). Also highlighted, there is a vital need to have in place an integrated solid waste management system in the country (Bandara 2011)

PAST STUDIES

The composition of MSW includes food waste, paper, biomass, glass, metals, plastics, rubbers, and textiles. (Ashani et al. 2020). The technologies discussed include Recycling (Ragaert et al. 2017), Composting (Bekchanov & Mirzabaev 2018), pyrolysis (Lu et al. 2020), Refused Derived Fuel (RDF) for co-fueling, and Waste to Energy (WTE) (Anoop et al. 2016), which are practicing for Municipal Solid Waste management.

The technologies are categorized into material recovery (Recycling, Composting & Pyrolysis), and energy recovery (RDF, and WTE). The technology mentioned is discussed accordingly with its pros and cons being highlighted.

Recycling is the process of converting waste materials into new materials and objects in a mechanical process or chemical process (Ragaert et al. 2017). The recyclability of a material depends on its ability to reacquire the properties it had in its original state. This can apply to main material types such as plastic, metal, glass, rubber, and compostable bio-degradable materials.

Pyrolysis is the thermal process in the absence of oxygen that breakdowns the long chain of polymer molecules into smaller, less complex molecules at a temperature higher than 400°C, with oil, gas, and char as the main products (Lu et al. 2020).

MSW which are received as mixed form can be diverted to RDF this can substitute alternative fuel in the WTE process or thermal intense processes such as cement and glass manufacturing. It is recommended to separate biological waste at the source to lower moisture and ash content and increase heating value for potential fuel production from waste (Arina et al. 2020).

Materials flow analysis (MFA) has been extensively applied for environmental research, particularly in waste management to identify material chain composition and the stages of the supply chain. In previous studies, many articles were found in other countries on MFA for quantifying the material flow and accumulation of tire waste in Thailand, (Jacob et al. 2014), analytics to make decisions on waste management policy (Allesch & Brunner 2015), as the MFA for assessing solid waste management in Germany (Hartlieb et al. 2005), MFA to evolve the waste management solution in Oahu, Hawaii (Matthew & Marian 2009), derived the results of a municipal solid waste management planning based on an extensive utilization of material and substance flow analysis (Arena & Gregorioa 2014), MFA is used to assess the current status of MSW management system in Lahore, Pakistan (Masood et al. 2014), MFA to draw plastic flow in Austria and Poland for presenting plastic waste management (Bogucka et al. 2008), MFA to assess the amount of plastic materials flow and stock in Serbia (Vujić, 2010). Similarly, there is a study on using the MFA method as a tool to monitor the flow and stock of Thailand, whereas the work is aimed to deploy planning on plastic waste management (Chanchampee 2010). Most of the past studies supported policymakers in waste management. However, there was no study using MFA for MSW which supports policymakers in Sri Lanka to identify the application of results of MFA for integrated material and energy recovery technologies.

RESEARCH OBJECTIVE

At present, the responsibility to manage the MSW falls under the purview of the local government network constitutes 24 Municipal Councils, 41 Urban Councils, and 276 Divisional Councils in the country. However, different local government bodies follow different waste management activities based on their capabilities instead of having an integrated waste management system throughout the country. Hence, to establish an integrated waste management system, a proper evaluation of the waste material flow is essential. Based on the material categorization waste management technologies can be defined.

Given this context, this study focuses on the waste generation volumes, characterization, waste management, and waste material recovery potential in the municipal solid waste in Western Province in Sri Lanka. The research results will facilitate the identification of the potential in terms of waste management solutions for mismanaged waste. Simulation of possible material and energy recovery options are presented under the study based on the Circular Economic framework. Further, the study will promote material recovery options and contribute to future research in terms of finding solutions for mismanaged waste in the household waste material chain. The study area records 25 open dumping sites and the dumped waste is collected through a channel operated by local authorities, which is the key institutional setup to handle waste in Sri Lanka. The authors aim to identify potential material recovery and energy recovery which are currently in these sites. The results are expected to be useful for the authorities who are involved in policymaking on waste management, to careful planning on the waste management policy framework.

MATERIALS AND METHODS

Study Area

Sri Lanka's Western Province (WP) which has a population of 5.8 million (amounts to 27% of the country's entire population) was selected as the pilot study area as per

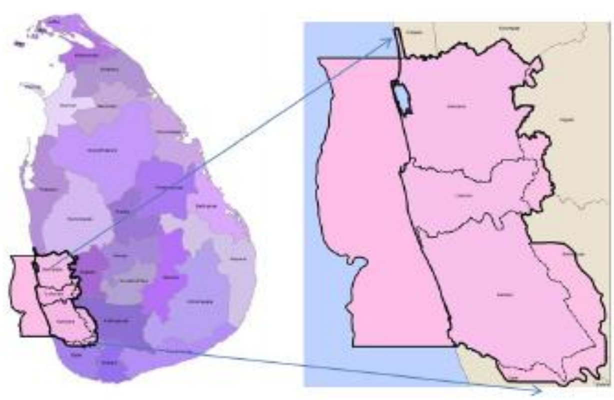

Fig.1: Western Province, Sri Lanka.

Fig. 1. The Western Province constitutes about 6 % of the land area in Sri Lanka and accommodates the highest population among the other provinces. It produces more than 39% of the total GDP of Sri Lanka thereby making a significant contribution to the national economy (Central Bank of Sri Lanka (CBSL) 2019). The dense population coupled with rapid development in this area had led to a considerable increase in the generation of MSW.

The waste generation in Sri Lanka has increased from around 6,400 tons per day in 1999 to 10,768 tons per day in 2021 due to population increase, economic growth, and the end of the civil war (Ministry of Environment (MOE) Sri Lanka 2021). Among the nine provinces in the country, the generation amount of the Western Province is the largest, accounting for 40% of the total waste generation while that of other provinces contributes to 60% of total generation.

Material Flow Analysis (MFA)

The study uses Material Flow Analysis (MFA) to identify the waste material chain from the household level to final disposal in the pilot area. MFA is an analytical method to quantify flows and stocks of materials or substances in a well-defined system (Hunt et al. 2014). This is based on the law of mass conservation. and is the widely used methodology in waste material flow analysis in most of the research (Allesch & Brunner 2015, Gehrmann et al. 2017). It has been widely applied for environmental education, particularly in waste management as analytics to make decisions on various issues related to waste-related analysis.

The mass that enters a system must, by conservation of mass, either leave the system or accumulate within the system. Mathematically, the mass balance for a system is as follows in equation 1;

$$\sum_{k_I} \dot{m}_{input} = \sum_{k_O} \dot{m}_{output} + \dot{m}_{storage} \quad \ldots(1)$$

where the number of the system flow is denoted by k, I, and O are input and output and denotes flow or flux. In general, $\dot{m}_{storage}$, or stock is calculated by the difference in input and output from the overall system. In this research, a material balance approach was adopted as the main methodology to investigate the stocks and flows of waste generation (Brunner et al. 2017). The basic mass balancing principle is applied.

Calculation of Waste Recovery Percentage

This study applies the principles of circular economy to assess the waste material recovery factor. A circular economy is an economic system aimed at eliminating waste while continuously regenerating resources (Tamine et al. 2020). Progress toward a circular economy should include not only responsible use of natural resources but also enabling reuse, repurposing, recycling, and recovery of the value-locked materials traditionally viewed as waste (Bouton et al. 2016).

The waste recycling factor was developed using the following equation 4 supported with material flow structure as per fig. 2:

$$\sum_a^n [CaR(P + T + Pl + R + M + G) + CaCoCm + CmaCm - Bua - Bra - Da - Oo - CaL] \quad \ldots(2)$$

Where a is the total MSW generation at the area an (area can be a province) in tons per day.

Ca- MSW collection percentage by local authorities

R- MSW recyclable volume percentage out of the collection

Co- Compostable material percentage out of collected volumes by local authorities.

P, T, Pl, R, M, G, Cm are the percentage of recyclable volumes percentages in Paper, Textile, Plastic, Rubber, Metal, and Glass. and compostable material respectively at the waste yard.

Bua, Bra, Da, Oo L represents the Burn, Burry, Open dump & landfill respectively

To identify the total recyclable material percentage out of the whole MSW generation.

Where total MSW generation

$$\sum_a^n [a + \cdots + n) \quad \ldots(3)$$

Therefore, the portion of the recyclable volume is given by:

Equation (2)/Equation (3) …(4)

Data Collection Procedure

The system boundary identified for the study includes the

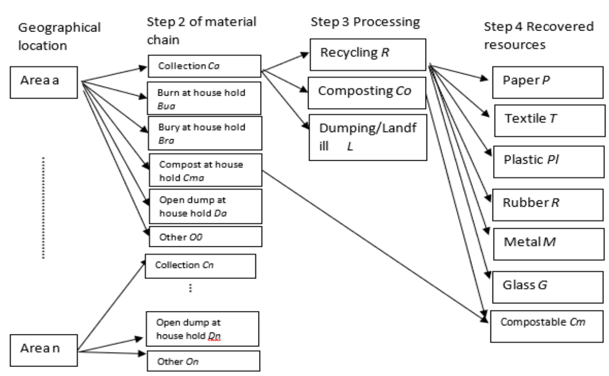

Fig. 2: Material flow structure.

household waste generation point to final disposal as per Fig. 2. The required data for analysis was obtained through the identification of municipal solid waste generation and waste management practices as well as types and quantity of wastes and disposal methods.

The generated waste materials in the study area were characterized. Furthermore, the required information to study the composition and management status of waste was obtained through published surveys, questionnaires, interviews, and feedback from local authorities as per the framework in Fig. 3. Author's survey data used for Western Province.

RESULTS AND DISCUSSION

Materials Follow the Analysis of Waste Generation, Collection, And Primary Treatment.

Fig. 4 shows the WP household level waste generation and primary disposal methods. The waste material flow was analyzed to identify material composition at different points of the material chain. Step 1 of Fig. 4 represents the disposal methods at the household level. 58% of the total waste generation gets collected by the local authority waste collection channel. 38% is identified as a burn or burry at the household level where the results of the study highlight the need for further research on unaccounted and unidentified material composition under burry and burn.

Overall results of the study show per capita waste generation of WP represents 0.56 kg per day whereas in Sri Lanka stood at 0.43 kg per day. Also, it is stated that the pattern of waste generation in different countries in the same continent or different provinces/states in the same country is not the same (Adeleke et al. 2020). There is a direct relationship between population and urbanization to waste generation (The World Bank n.d) reflects in the data for the study scope. Another study done for Indonesia shows the direct relationship between waste generation to population (Supangkat & Herdiansyah 2020). However, as per the literature, various models have been developed to predict waste generation using input variables such as population (Liu & Yu 2007, Oumarou et al. 2012), income level (Thanh 2010, Liu & Yu 2007), and education (Keser et al. 2012).

The dense population coupled with rapid development in this area had led to a considerable increase in the generation of municipal solid waste. Therefore, the main waste management system requirement is essential for WP.

The collection mainly happens in the western province, being the key economic hub of the country. At present, the responsibility to collect municipal solid waste falls under the purview of the local government network under the ministry of Local government and provincial councils.

However, different local government bodies follow different waste management activities based on their capabilities instead of having an integrated waste management system throughout the country.

Primary Waste Streams and Treatment Methods

In the results of the study presented in Table 1, each waste category in the selected location was prioritized by arranging them in descending order of magnitude. A Pareto chart is used for preliminary identification of the most significant waste streams. The outcome of the analysis is given in Table 1 presenting the results following the application of the Pareto principle. Fig 5 shows the waste generation in the study location (WP). The total waste generation accounted for 3248 tons per day, of which 1881 tons per day (58%) is collected by the collection channel.

The wastes stream quantities in the surveyed area were evaluated during the study. Biodegradable waste from kitch-

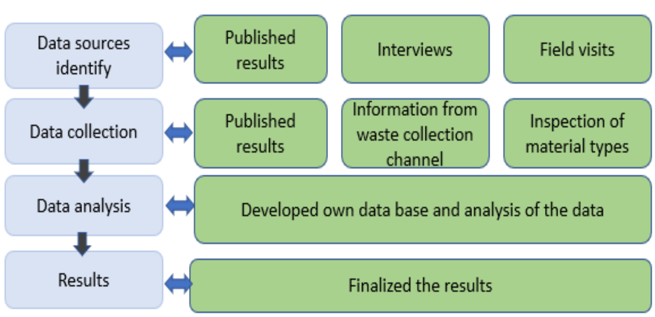

Fig. 3: Methodological framework for data identification, collection and analysis.

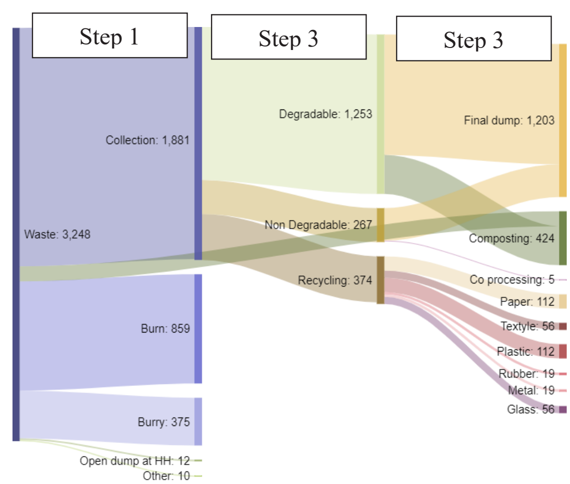

Fig. 4: Waste generation at house hold level in Western Province, Sri Lanka.

en waste accounted 52.5 % of the total wastes collected, followed by biodegradable grass and wood (14.1%), paper (13.6%), plastic (10.5%), textile (4.3%), stones & ceramic (2.3%), glass (1.2%), metal (0.7%) rubber (0.6%) and other mixed waste (0.3%). The remaining wastes constituted less than 5% of the total waste. The accuracy of results could be affected due to challenges with various data collection points of local authorities. The data in this instance is the associates with a visual inspection and judgmental understanding of the waste categories in the collection channel.

M1, M2, M3, M4, M5, and M6: represent material recovery methods whereas E1, and E2: represent energy recovery methods in Fig.5.

Where M1- Composting

M2- Recycling paper

M3- Recycling Plastic

M4- Recycling Glass

M5- Recycling Metal

M6- Recycling Rubber/Pyrolysis

E1- Waste to Energy (WTE)

E2- RDF for Co-processing

As per Fig. 6, WTE represents 600 tons per day volume followed by 424 tons per day of composting, 56 tons per day of paper recycling, 55 tons per day of plastic recycling, 22 tons per day of glass recycling, 19 tons per day of metal recycling, 14 tons per day of RDF for co-processing and 11 tons per day of rubber pyrolysis under material recovery and energy recovery techniques. However, 19 tons per day of sanitary landfilling and 660 tons per day of open dumping at waste yards happen in the study areas which are not considered superior solutions for MSW management under the circular economic framework.

Table 1: Types of waste collection in Western Province, Sri Lanka.

Type of waste	Volume tons per day
Bio-degradable kitchen waste	987.5
Bio-degradable Grass and wood	265.2
Paper	255.8
Plastic	197.5
Textile	80.9
Stones & Ceramic	43.3
Glass	22.6
Metal	13.2
Rubber	11.3
Other	3.8

Analysis of Waste Circulation Factor In Terms Of Material Or Energy Recovery

Recovery can be categorized under material and energy recoveries. Composting, Recycling, and Pyrolysis (Lu et al. 2020) technologies consider material recovery techniques whereas Waste to Energy and RDF for Co-processing are considered energy recovery techniques (Arian et al. 2020). As per equation 4 of waste recovery percentage calculation, the following results were analyzed under material and energy recovery out of total waste collection and generation as per the results shown in Fig. 6 and 7.

Material & Energy Recovery Out Of The Total Waste Material Collection

As per Fig. 6, Material recovery technologies are considered based on waste material processed through Recycling, Composting & Pyrolyzing (Tang et al. 2020.). In WP material

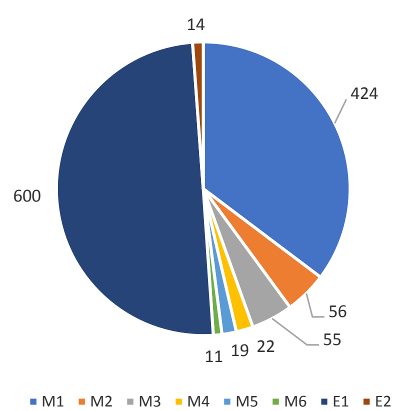

Fig. 5: Waste treatments (tons per day) of Western province, Sri Lanka.

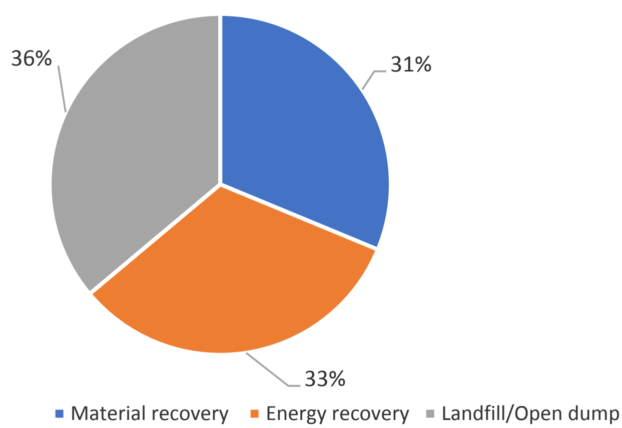

Fig. 6: Material & Energy recovery out of total MSW collection.

recovery is 31% in terms of Recycling of paper, plastic, glass, and metal, followed by composting for biodegradable waste and pyrolysis for rubber waste. 33% of the material disposed of under energy recovery techniques in terms of WTE via generation of electricity and RDF via co fueling for thermal intense industries such as cement production.

Material and Energy Recovery Out Of Total Waste Generation

As per Fig. 7, 42% of the total waste generation is burned or burry at the household level causing environmental impacts on society. Common waste management practices found included open burning, burying, reusing, disposing of MSW in backyard pit, mixed waste disposal in the backyard, selling, and recycling. Most rural households in the world are still using traditional methods of managing waste, even though recommended waste management practices such as reusing and recycling were found in some households (Nxumalo et al. 2020).

Waste Treatment Mechanisms

The following options are identified as the most common waste disposal methods used in the study area.

- Option 1: Composting
- Option 2: Recycling (Based on material type)
- Option 3: Pyrolysis
- Option 4: Waste to Energy
- Option 5: RDF for Co-processing
- Option 6: Sanitary landfilling
- Option 7: Open dumping

The proportions of primary waste disposal methods were calculated and are shown in Fig. 8.

Waste composting

Of the total waste generation in the WP, 13% recovery is reported at waste composting (424 tons per day). There is a potential to improve compostable volume in the area. Composting is a win-win option for reducing environmental pollution derived from the open dumping of waste and recovering nutrients essential for producing fertilizers (Bekchanov & Mirzabaev 2018).

The national strategy on waste management aims to redirect 19% of the organic waste generation into composting (Bekchanov & Mirzabaev 2018). This is amounting to 7% of total waste generation. In 2008 government introduced the Pilisaru program which aimed to establish composting plants throughout the country and currently there is 119 such plant in the county as to the ministry of environment. However, the efficiency of these plants is not up to the slandered.

There is a potential to improve compostable volume in the whole country being an agricultural-based society dominated in the rural areas, especially in Central, Southern, Northern, North Central, Sabaragamuwa, and Uva provinces. WP is the least agricultural-based area and represents less composting volumes than MSW. Composting is the second preferred method of solid waste management, mainly due to the high percentage of organic material in the waste composition.

Waste recycling and repurposing

The study represents that recycling and composting are the main recovery methods adopted in the country for proper waste management even though recycling is not significant in volume. Material category wise paper, plastic, glass, metal, and rubber are considered potential recycling materials. However, the majority of the waste ends up at open dumps that need to be further evaluated for possible recyclable and repurposed materials. This is not under the scope of the study.

Most developed countries use Clean Material Recovery Facilities where clean sources segregated dry materials

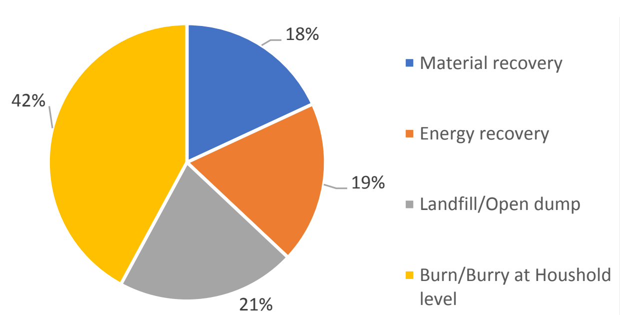

Fig 7: Material & Energy recovery out of total MSW generation.

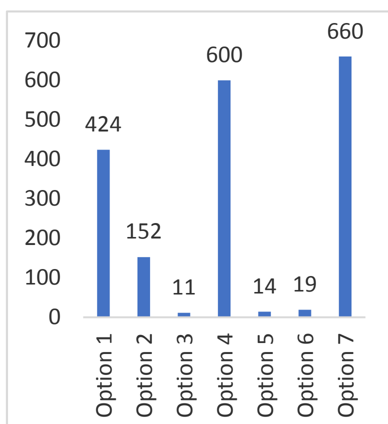

Fig. 8: The treatment methods of the primary waste streams (tons per day) in Western Province, Sri Lanka in Western Province, Sri Lanka.

are used. Source segregation is the less expensive method compared to treating mixed waste. Mostly in developing countries mixed waste is used for Dirty Material Recovery Facilities with the high cost involved during the processing stage. Hence most of the recovery and recycling techniques are not economical in developing countries, therefore less volume is diverted for recycling methods (Kaza et al. 2018).

Recent developments in the producer responsibility (PRO) model for post-consumer waste is supporting to increase in the recycling materials in the study area. The current recycle volume is 152 t per day.

Waste Pyrolysis

There are five pyrolysis plants in the country with an equal capacity of 10 t input per batch. Only one plant is in the study areas. However, 60% of the waste rubber generated from MSW in the sturdy area gets disposed of via all five plants. Apart from that industrial rubber waste is recycled through rubber industries which are out of the scope of the study. 11 tons per day of rubber volume is circulated back to the system in the study area.

However, there are other researches on energy-effective pyrolysis process with the lowest possible carbon footprint to realize the recycling of organic wastes, the generation of renewable energy, and the release of minimal quantities of greenhouse gas and pollutants from MSW treatments in the world (Lu et al. 2020)

Waste to Energy

Due to economic and industrial growth, the country needs more electric power. Therefore, reducing the volume of waste and at the same time generation of power out of it can be achieved by municipal waste to energy plants. There is one waste to energy (WTE) plant in the country, establish within the sturdy areas in 2021 with the capacity of disposing of 600 tons MSW volume disposal per day (this is further referred to in Fig 5). WTE is a widely practiced technology for MSW management in most developed countries, Environmental Protection Agency has stated that WTE technologies are clean reliable sources of renewable energy with less environmental impact than any other source of energy (Anoop et al. 2016).

The main drawback of WTE plants is pollutant emissions in general and in WP Sri Lanka W2E plants face a problem of final disposal of bottom ashes which is coming out of the system. but the plant is still not in full operation. In this study, however, energy waste is not considered a material recovery option. Meanwhile, incineration and landfilling are not considered the recovery option. Another study stated that recycling has high industrial potential and complementary pathways for closing the loop on most of the waste categories and is vastly preferable to energy recovery and landfilling (Ragaert et al. 2017).

RDF for Co-processing

RDF is organic matter containing a high calorific fraction of processed MSW (paper, plastic, textiles, wood, rubber, and others) compatible with conventional fossil fuels or biomass with respect to calorific value. The use of RDF as a source of energy is an integral part of waste management and it is regulated by EU regulations (EU Parliament Directive 2008/98/EC on waste). RDF is becoming more and more attractive as an energy source as the necessity to increase the proportion of alternative energy use is becoming harder (Porshnov et al. 2018)

14 tons per day of volume is co-processed from the study area. There is a possibility to increase this volume further with proper waste segregation at the source.

Sanitary Land Filling

One small-scale landfill is operating in the study area with a capacity of 19 tons per day. The majority of MSW in the respective local authority area is disposed of in a landfill. There is a large-scale project to develop the divert large volumes to sanitary landfill situated over 100 km from the study area for disposal waste generation in a high populated area under study scope. However, this is currently not functioning.

Waste Burning and Burying at the Household Level (HH)

The results of the study highlight the need for further research on unaccounted and unidentified material flows involved in household-level burying and burning. This causes more harm to the environment and human beings.

Table 2: Waste composting percentages (as a percentage of total waste generation of the province).

Province	Composting % of total waste generation
Western	13.05%
Central	12.68%
North- Western	5.67%
Southern	18.17%
Northern	10.50%
Eastern	2.31%
North Central	7.36%
Sabaragamuwa	9.71%
Uva	14.51%

Common waste management practices found included open burning, burying, reusing, disposing of plastics in backyard pit, mixed waste disposal in the backyard, selling, and recycling. Most rural households in the world are still using traditional methods of managing waste, even though recommended waste management practices such as reusing and recycling were found in some households (Nxumalo et al. 2020).

Study results show that the most of waste is burnt at the household level in North Central, North Western, Northern, Southern, Uva, and Saboragamuwa as per Table 3. This may lead to inadequate waste collection and a lack of awareness by the local authorities to the public.

CONCLUSION

Municipal Solid Waste is the largest waste volume generation source in the country. However, this material has a huge potential in terms of waste recycling and reuse. An analysis of scientific literature discloses that the majority of municipal solid waste is burned or buried. Therefore, this study reflects on the importance of research in unaccounted and unidentified material flows involved in household-level burying and burning. Moreover, given that a large portion of collected waste is directed to open dumps, further study is required to evaluate the recycling potential of this element of waste.

A major factor that influences the rate of generated waste per year and the percentage composition of each physical waste stream is the socio-economic level. Moreover, the organic stream of the waste and the rate of recycling volumes depends largely on the income levels of the society.

Overall results show per capita per day of waste generation in Sri Lanka stood at 0.43kg, whereas, the Western province represents that 0.56 kg due to the high population area with the highest rate of urbanization. However, the global average per capita per day of waste generation stood at 2.22 kg (USEPA 2021). The material and energy recovery represent 31% and 33% respectively in the study area from total collected waste. 36% of the material finally ended up in open dumpsites even after collection. Further research needs to be done on material and energy recovery potential identification in dumping waste, as this can convert to valuable results with proper management practices with available resources.

Table 3: Waste burning and burying percentages out of total generation in respective provinces.

Province	Waste burning % of the total waste generation of the respective province	Waste burying % of the total waste generation of the respective province
Western	27.16%	11.85%
Central	42.84%	26.73%
North- Western	61.26%	25.66%
Southern	48.63%	51.23%
Northern	56.98%	19.12%
Eastern	38.55%	20.22%
North Central	66.43%	20.45%
Sabaragamuwa	43.20%	39.72%
Uva	48.43%	28.58%

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