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SUSTAINABLE SOLID WASTE MANAGEMENT IN DEVELOPING COUNTRIES: CONVERTING URBAN WOOD, GARDEN, FOOD, AND CARDBOARD WASTE INTO BIOCHAR USING PYROLYSIS

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Abstract

Effective municipal solid waste (MSW) management presents a critical challenge globally, exacerbated by rapid urbanisation, population growth, and shifting consumption patterns. This review paper focuses on the sustainable management of food, wood, garden, and cardboard waste (FW, GWW, and CW) in developing countries, with a particular emphasis on Sri Lanka. The review highlights the urgent need for innovative solutions due to the inefficiencies of current waste management practices, which primarily involve open dumping and limited composting and recycling. This review aims to evaluate the potential of pyrolysis technology in converting these waste streams into Biochar, a valuable by-product with numerous environmental, agricultural, and industrial applications. The methodology involved a comprehensive literature review using resources like Google Scholar and Science Direct, focusing on the application of Pyrolysis for transforming waste into Biochar. Key findings indicate that Pyrolysis offers a viable solution by converting waste into Biochar, which has beneficial applications in agriculture and environmental management. Pyrolysis techniques are noted for their potential to reduce methane emissions, improve soil fertility, and enhance waste-to-energy conversion. The review recommends enhancing waste segregation and collection infrastructure, promoting sustainable waste management techniques, increasing public awareness, and investing in research and development. Policy support and public-private partnerships are also essential for improving waste management practices. Future research should explore circular economy principles, the long-term impacts of current practices, and advanced waste processing technologies. Implementing these recommendations can significantly advance MSW management, mitigate environmental pollution, and promote public health, fostering more sustainable urban environments.

Keywords: Biochar, Biomass (Food and garden waste), Corrugated Cardboard, Municipal solid waste (MSW), Pyrolysis

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Introduction

MSW management poses a significant socio-environmental and economic challenge globally(Maheshi et al., 2015). The issue has escalated due to shifting consumption trends, population density increases, unregulated urban growth, rapid industrial expansion, and population surges, which compel rural inhabitants to migrate to urban centres. These factors result in the generation of immense quantities of solid waste daily, contributing to environmental pollution and impacting the health of living organisms (Chhabra et al., 2016; Gunaruwan & Gunasekara, 2016). Thus, effective waste management has become a critical global task.

Among the various waste streams, FW, GWW, and CW present significant challenges in urban waste management. The Food and Agriculture Organization (FAO) estimates that about 1.3 billion tons of food are produced annually for human consumption, and roughly one-third of this food is wasted (Yeshanew et al., 2016). GWW, often seen as eco-friendly by-products, is becoming a significant concern due to its substantial contribution to urban waste. Additionally, the rise in cardboard consumption has led to increased production of CW. The projected increase in the global population is expected to double MSW generation, potentially reaching around 30 million tons per year by 2033. In the United States, paper products and corrugated cardboard boxes (CCB) constitute 38% of MSW, highlighting the significant proportion of paper and cardboard in waste streams of the Environmental Protection Agency (EPA) (Sotoudehnia et al., 2020).

The handling, storage, and collection of FW, GWW, and CW in urban areas pose considerable environmental and public health risks. Management costs are rising due to inadequate infrastructure and insufficient waste sorting by residents. These issues underscore the urgent need for effective waste management strategies. Disparities in waste management practices between developed and developing countries reveal the importance of technical knowledge and financial resources in addressing these challenges. Municipal authorities in major cities worldwide must prioritise effective waste management solutions to mitigate these issues.

With a population density of 333 people per square kilometre, Sri Lanka is experiencing rapid urban growth, expected to reach 30% of the total population by 2030. This urban expansion is driving a significant increase in waste generation, with an annual growth rate of 1.2%. Approximately 8,218.4 tons of waste are generated daily, with the Western Province accounting for over 60% of this amount (Dissanayaka & Vasanthapriyan, 2019). According to the Waste Management Authority and the Central Environmental Authority, only about half of this waste is collected. Perishable waste, including FW, GWW, and CW, constitutes the majority of the waste by weight. Specifically, FW makes up 56.5% of MSW, with an average daily generation of 3,955 tons (FAO, 2015). This represents 30% of the annual FW. Garden Waste (GW) and Wooden Waste (WW) comprise 18.2% and 6% of the total waste, respectively. Cardboard products, including boxes, wrappings, posters, and book covers, comprise 7.8% of the total waste (Mervin Dharmasiri, 2019).

In Sri Lanka, about 85% of MSW is managed through open dumping, with only 15% handled via composting and recycling, highlighting the need for more sustainable waste management practices. Urban areas face significant challenges, including high waste generation, difficulty finding suitable disposal sites, and limited land within municipal boundaries (Ruzaik, 2021). Historically, ample land availability made solid waste disposal less urgent, but current city governments struggle with land scarcity for garbage disposal. Many urban waste management costs are directed toward collection and transportation, overshadowing disposal and refinement expenses. Despite efforts, considerable amounts of FW, GWW, and CW are still disposed of through open dumping. Open burning of CW and GWW further exacerbates air, water, and soil pollution, posing significant environmental and health risks (Ruzaik, 2021). FW in Sri Lanka is often repurposed as animal feed, which integrates it into the food chain but faces challenges such as improper waste separation, contamination with plastics, high transportation costs, and disease risk. Only a small portion of FW, GWW, and CW is used for composting and biogas production, which are limited by their slow processes, extensive land requirements, and odour issues (Gabhane et al., 2020). Cardboard, a common waste product, is often mishandled due to inadequate sorting practices despite government efforts to improve waste separation and composting through a 2016 circular.

Sanitary landfilling, the predominant waste disposal method in Sri Lanka, functions as a biological reactor where microorganisms decompose organic waste into less toxic compounds. However, inadequate landfill management can contaminate soil and groundwater, gas emissions, and leachate production, necessitating costly and knowledgeable management practices. Reports indicate that 60% of organic waste at the Kaduwela recycling centre is rejected due to limited facilities (Gabhane et al., 2020). Incineration, though a modern technique for energy recovery, faces challenges with residual ash and inefficient energy utilisation. Researchers are exploring gasification, which involves partial combustion of GWW to produce CO_2 and CO for further combustion. Despite its potential, gasification yields are low, and slag disposal remains problematic (Gabhane et al., 2020). These conventional and thermal methods contribute significantly to greenhouse gas emissions, exacerbating global warming and environmental issues. Therefore, sustainable waste management solutions are critical. Biochar production from FW, GWW, and CW is gaining attention for its potential to address these challenges. Biochar, a carbon-rich by-product formed through high-temperature Pyrolysis or gasification, offers environmental benefits, including improved soil fertility and water purification, with production rates enhanced by modern thermochemical techniques(Gabhane et al., 2020).

This review explores the use of thermochemical Pyrolysis to convert FW, GWW, and CW into Biochar, a versatile and sustainable product. This method aims to minimise methane emissions and CO_2 release, supporting environmental health while offering economic benefits through rapid processing and valuable by-products. Biochar production enhances soil fertility, promotes seed growth, improves plant health, absorbs toxins, and aids in water purification (Sipra et al., 2018).

Methodology

To conduct this review, a comprehensive literature search was performed using web-based resources, including Google, Google Scholar, and Science Direct. The primary focus was on the sustainable management of FW, GWW, and CW in Sri Lanka, emphasising thermochemical-based pyrolysis methods for solid waste management in developing countries.

The literature search was restricted to publications from the past ten years (2014-2024) to ensure the review is focused on the most recent research and developments in the field. Keywords such as "pyrolysis," "Sri Lanka," "municipal solid waste (MSW)," "food waste," "garden and wood waste," "cardboard waste," "biochar," and "waste-to-energy" were employed to identify pertinent sources. The inclusion criteria for this review encompassed scientific reviews, journals, articles, and research papers relevant to the application of Pyrolysis in transforming urban FW, GWW, and CW into Biochar.

Discussion

Global Scenario of MSW

The global surge in MSW generation is driven by factors such as population growth, urbanisation, industrial expansion, and improved health and sanitation standards. This rise in waste poses significant challenges across various domains. Research shows that global MSW generation exceeds 10 billion tons annually and is expected to reach 14.8 billion tons by 2025. MSW encompasses unwanted or inert materials produced from residential, industrial, or commercial activities (Dissanayaka DMSH & Department, 2019).

Both individual and governmental decisions on consumption and waste management profoundly impact community health, productivity, and cleanliness. Poor waste management leads to numerous environmental and social issues, including ocean contamination, blocked drainage causing flooding, disease transmission through vector breeding, respiratory problems from airborne particles due to waste burning, harm to wildlife ingesting waste, and adverse economic effects such as decreased tourism. The unmanaged waste resulting from decades of economic growth calls for urgent action at all societal levels. Developing countries account for about 56% of global MSW (Chhabra et al., 2016; Dissanayaka & Vasanthapriyan, 2019).

Global Patterns in MSW Generation and Composition

The global generation and composition of MSW reveal significant trends that reflect the ongoing urbanisation and economic development across various regions. As urban areas expand, the production of MSW—a by-product of modern urban life—has been rising at an unprecedented rate. MSW comprises diverse materials, including organic waste (food scraps and yard trimmings), paper, plastics, glass, metals, textiles, e-waste, and rubber. This waste is managed and regulated by local or state authorities (*Trends in Solid Waste Management*, n.d.). A decade ago, urban populations of around 2.9 billion produced approximately 0.68 billion metric tons of MSW annually at an average rate of 0.64 kg per person per day. With urban populations nearing 3 billion, the annual generation has soared to 1.3 billion metric tons, averaging 1.2 kg per person daily. Projections suggest that 2025 urban residents will number 4.3 billion, producing 2.2 billion metric tons of MSW annually, or 1.42 kg per person per day (Saja et al., 2021).

The volume and nature of MSW are influenced by socioeconomic factors, including income levels and economic activities. Higher-income countries produce less organic waste (32%) and more dry recyclables (51%), like plastics, paper, and metals. Conversely, middle- and low-income countries generate more organic waste (53% and 57%, respectively) and fewer recyclables (20% in low-income regions). This correlation between economic status and waste composition is evident globally, with organic waste forming a significant portion of the MSW in lower-income regions. At the same time, developed areas generate higher proportions of recyclable materials (Dissanayaka & Vasanthapriyan, 2019). Urban lifestyles, characterised by increased consumption and reduced time for household activities, further exacerbate waste generation. As cities grow and economies evolve, managing MSW sustainably becomes increasingly complex, necessitating innovative and efficient waste management strategies.

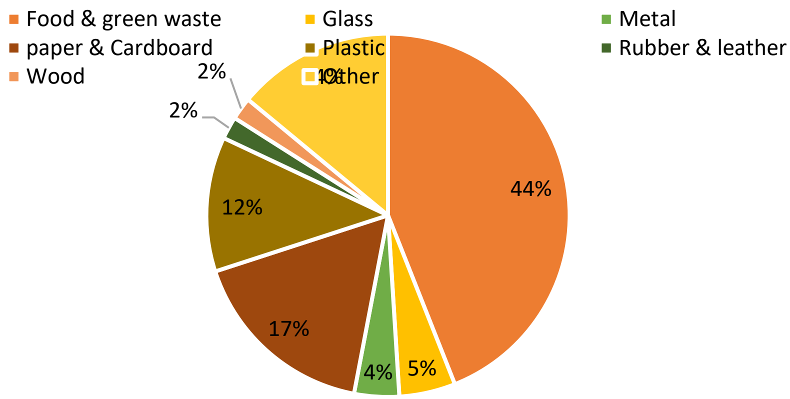

Fig. 1 - Global waste composition by percentage (*Trends in Solid Waste Management*, n.d.)

Comparative MSW Management Practices Worldwide.

MSW management practices differ significantly worldwide due to variations in waste volume, composition, and economic conditions. While emerging technologies are often promoted as ideal solutions, effective waste management requires a broader perspective beyond technological advancements. Globally, a substantial portion of MSW is either dumped or landfilled; approximately 37% is dumped, and 8% is landfilled with gas collection systems. About 31% of waste is diverted from open disposal sites, 19% recycled or composted, and 11% incinerated for final disposal. Waste management in high- and upper-middle-income countries often includes controlled landfills and advanced treatment facilities.

In contrast, low-income countries predominantly rely on open dumping, with 93% of waste disposed of this way compared to just 2% in high-income countries. Regions such as the Middle East, North Africa, Sub-Saharan Africa, and South Asia dispose of more than half of their waste through open dumping. High- and middle-income countries typically use landfills for 54% of their waste, but in high-income countries, this practice accounts for only 39%, with 36% of waste recycled or composted and 22% incinerated. Incineration is common in high-capacity, high-income, and landlocked countries (*Trends in Solid Waste Management*, n.d.).

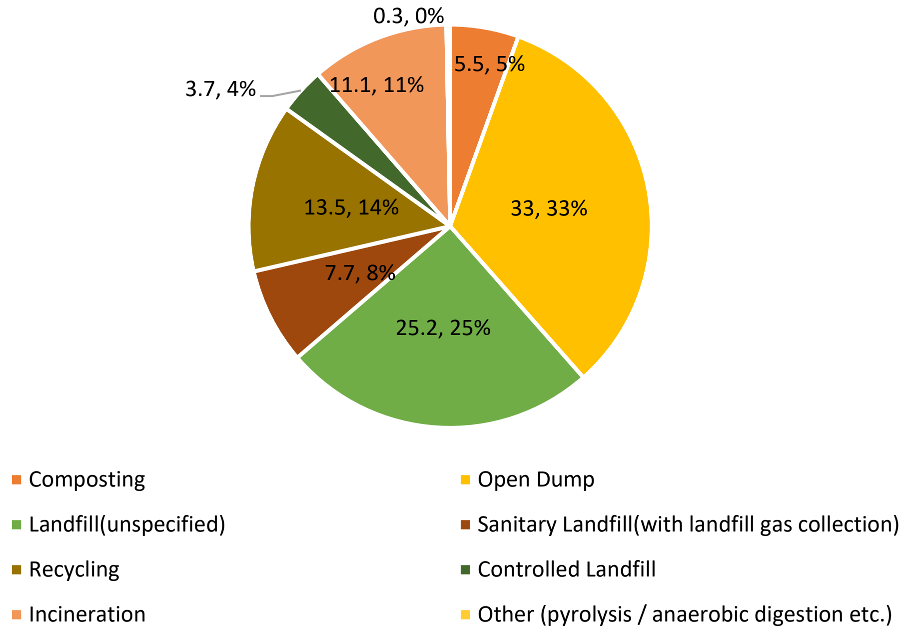

Fig. 2- Global treatment and disposal of waste by percentage (*Trends in Solid Waste Management*, n.d.)

Impact of a Lack of MSW Management

The lack of proper MSW management has significant environmental, social, and economic impacts. Environmentally, FW, GWW, and CW in landfills produce substantial amounts of methane, a greenhouse gas far more potent than carbon dioxide. Greenhouse gases such as methane, carbon dioxide, and chlorofluorocarbons contribute to global warming and climate change by absorbing infrared radiation and heating the Earth's atmosphere. Additionally, around 70% of water use occurs in agricultural areas, and improper management of FW, GWW, and CW threatens freshwater and groundwater resources (Sharma & Jain, 2020). The distribution and disposal processes of these wastes also have significant environmental impacts, as they require large amounts of fuel, leading to long-term emissions from exhaust gases and further exacerbating environmental degradation.

Open dumping of MSW contaminates water bodies and creates stagnant water, increasing the spread of vector-borne diseases such as dengue. Landfills cause soil pollution and infertility. In 2016, MSW generated an estimated 1.6 billion tons of CO_2 equivalent greenhouse gas emissions, accounting for 5% of global emissions. This was primarily due to waste disposal in open dumps and landfills without gas collection systems. Without improved waste management practices, annual solid waste emissions are projected to increase to 2.38 billion tons of CO_2 by 2050 (*Trends in Solid Waste Management*, n.d.). Improper management of MSW also leads to the emission of additional greenhouse gases, contributing to climate change. The accumulation of MSW degrades the food chain, destroys biodiversity by harming animals, significantly increases marine pollution, harms marine wildlife, and reduces ocean resources. Improper waste management practices, such as burning plastics and other MSW, result in the emission of toxic gases like dioxin and methane, which have severe health impacts, including respiratory diseases and cancers. This highlights the urgent need for improved waste management strategies to mitigate the adverse environmental and health consequences associated with FW, GWW, and CW.

The improper management of FW, GWW, and CW has significant social impacts. These types of waste contribute to public health issues, as FW attracts pests and promotes the spread of diseases, adversely affecting the quality of life in communities. Unmanaged GWW can lead to increased fire hazards, while CW, when not properly recycled, contributes to urban blight and decreases the aesthetic appeal of neighbourhoods. Moreover, accumulating these wastes can obstruct drainage systems, leading to flooding and breeding grounds for disease vectors such as mosquitoes, which spread illnesses like malaria and dengue fever. The social burden of dealing with these health issues disproportionately affects low-income communities, where waste management systems are often inadequate.

Economically, the impacts of waste management are significant. The costs for collecting, transporting, and disposing of FW, GWW, and CW strain municipal budgets, particularly in developing areas. Inefficient waste systems lead to higher operational costs and missed economic opportunities. For example, FW in landfills produces methane, a greenhouse gas that requires costly environmental mitigation. Conversely, recycling and composting GWW and CW can create jobs and generate revenue by converting waste into valuable resources. Proper waste management can also boost city attractiveness, enhancing tourism and local business. Without effective systems, the economic burden of waste mismanagement continues to rise, affecting both public finances and the private sector.

MSW in Sri Lanka Context.

Sri Lanka, a developing country, generates 7 billion tons of solid waste daily, of which more than 60% comes from the Western Province (Dissanayaka et al., 2019) (Dissanayaka & Vasanthapriyan, 2019). According to the Waste Management Authority and the Central Environmental Authority, Sri Lanka produces 7000 MT of solid waste daily, but only half of it is collected by local authorities. There are 335 local authorities responsible for MSW in Sri Lanka. The collected waste comprises 59.2% FW, 18.2% GW, 6% WW, and 5.4% plastic waste (Mervin Dharmasiri, 2019). In addition, cardboard and paper account for 3.20% and 2.30%, respectively, as shown in Fig 3.

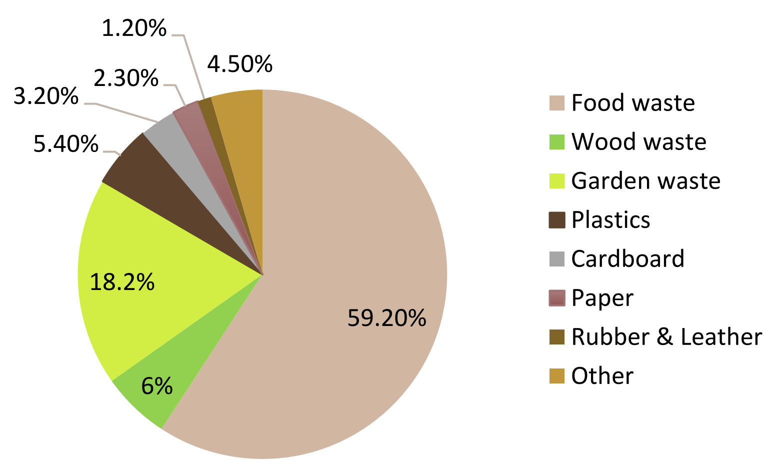

Fig. 3 - Composition of MSW in Sri Lanka, showing the percentage of different waste types in the total waste stream (Menikpura et al., 2012).

In Sri Lanka, approximately 85% of MSW is openly dumped, with the remaining 15% allocated for composting (10%) and recycling (5%). Waste not collected by municipal councils is often disposed of inappropriately, including dumping on streets, in water bodies and backyards, open dumping, or burning (Mervin Dharmasiri, 2019).

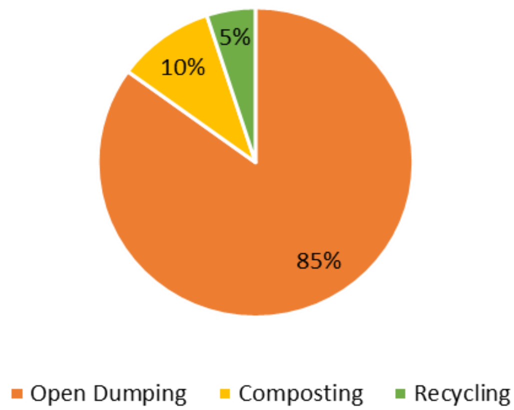

Fig. 4- Treatment and Disposal of Waste in Sri Lanka, showing the percentage of waste managed through different methods (Mervin Dharmasiri, 2019).

Policy and Regulatory Framework for Waste Management in Sri Lanka

Waste management in Sri Lanka is challenged by open dumping and incineration, a legacy of inadequate investment and fragmented waste management systems (Wang et al., 2021). These practices harm the environment and obstruct sustainable solutions like Pyrolysis. The Sri Lankan government has implemented policies, notably the National Solid Waste Management Policy 2007, focusing on waste reduction, recycling, and safe disposal. While the government recognises the benefits of waste-to-energy technologies such as Pyrolysis, adopting these practices is hindered by a lack of strict regulations and comprehensive frameworks. Strengthening regulatory measures and investing in advanced technologies could enhance waste management, reduce environmental impacts, and promote using Pyrolysis effectively to transform urban waste into Biochar.

FW Generation and Management Strategies in Sri Lanka

In Sri Lanka, the responsibility for waste collection and disposal is primarily managed by local authorities, including municipal and urban or local councils (Pradeshiya Sabha). Approximately 80% of the organic waste generated is short-term biodegradable FW, amounting to an estimated 353 tonnes per day, constituting half of the total waste produced. Although initiatives for source segregation at the household level were introduced in Colombo in late 2017, a substantial portion of FW (around 146 tonnes per day) is already segregated for recycling processes. However, the Colombo Municipal Council (MC) has yet to fully implement a comprehensive waste management strategy. The Central Environment Authority has initiated the "National Pilisaru" waste management strategy, emphasising waste reduction, reuse, and recycling (3Rs). New regulations and laws are being established to enforce the segregation of organic waste at the household and institutional levels, creating opportunities for resource recovery and green businesses. The Colombo MC is spearheading this effort through an integrated waste management plan in collaboration with the private sector to actualise the 3Rs concept. Techniques such as price reductions on fruits and vegetables by supermarket chains before weekends and at the end of their shelf life are employed to minimise FW generation. The primary methods for controlling FW in Sri Lanka include composting, landfilling, open dumping, and biogas generation (FAO, 2018).

GWW Generation and Management Strategies in Sri Lanka

GWW, categorised as green waste, includes untreated wood items, unrefined wood products like tree stumps and limbs, and vegetation from home gardening activities such as lawn clippings and pruning (Haryanto et al., 2021). This type of waste is generated from various sources, including construction, furniture making, demolition activities, and home gardening. In Sri Lanka, approximately 85% of GWW is disposed of in open dumps without pre-treatment, cover, or compression. This disposal method poses significant environmental risks, as the exposed waste can adversely affect human society and the environment. Often, this waste is dumped in ecologically sensitive areas such as wetlands, beaches, water bodies, residential areas, or near public institutions. Open burning of GWW is also common in urban areas, contributing to environmental and public health hazards. The smoke emitted from burning pollutes the air, soil, groundwater, rivers, and streams, endangering the environment and the community (Maheshi et al., 2015).

CCW Generation and Management Strategies in Sri Lanka.

Nearly 60% of MSW in Sri Lanka is biodegradable, including CCB, which constitutes about 3.2% of the total MSW generation. CCB is widely used for packaging purposes, especially for food delivery in urban and suburban areas. While some amount of CCB is reused and recycled, the lack of public knowledge and practice in sorting waste materials hinders effective recycling efforts(Mervin Dharmasiri, 2019). Often, cardboard packaging is not kept clean and undamaged, undermining the reuse and recycling processes. Incineration of CCB is also practised, but it does not produce added-value products, merely reducing the quantity of MSW. Since most CCB waste is produced in households, there is a need for more efficient household-level waste management strategies. Given that CCB is highly lignocellulose, it can be managed at the household level to produce Biochar, which offers agricultural, environmental, and economic benefits. Implementing such a management procedure could enhance the value derived from CCB waste while reducing its environmental impact.

Conventional Waste Treatment Approaches

MSW management in Sri Lanka employs traditional and emerging biological treatment methods. Composting, a primary method, involves the aerobic decomposition of organic waste by microorganisms, yielding compost that enriches soil organic matter and acts as an eco-friendly alternative to chemical fertilisers (Sipra et al., 2018). However, the process is hindered by slow degradation rates, significant land and time requirements, and unpleasant odours. Another prevalent method is sanitary landfilling, where waste is compacted in layers within engineered sites to minimise environmental and health risks by facilitating decomposition and capturing toxic gases (Hasan et al., 2021). Despite its efficacy in reducing waste volume and preventing landslides, landfilling poses pollution risks, notably from methane emissions that can contaminate groundwater and pose fire hazards.

Additionally, a unique approach in Sri Lanka involves converting FW and GW into animal feed, a practice beneficial for its low environmental impact and integration into the food chain. Inspired by successful implementations in East Asia and Europe, this method could significantly reduce greenhouse gas emissions and land use associated with conventional livestock feed production (Salemdeeb et al., 2017). However, it faces challenges such as regulatory restrictions due to disease control concerns, the necessity for effective waste separation to avoid contamination and high transportation costs (Weligama et al., 2021). Thus, while biological treatment methods for MSW in Sri Lanka offer sustainable benefits, they also present notable drawbacks that require comprehensive management and policy solutions for effective waste management.

Energy Recovery from Waste

An alternative and practical approach for managing FW, GWW, and CW is through energy extraction. Research indicates that extracting energy from urban waste is economically viable and sustainable (Hasan et al., 2021). Energy recovery can be achieved through various processes such as combustion, incineration, gasification, and Pyrolysis (Sipra et al., 2018). These processes convert waste into useful energy sources, such as thermal power or fuel, which can be utilised for electricity generation or as fuel, thereby contributing to the overall energy mix. This method not only aids in waste disposal but also transforms GWW into valuable energy resources, providing a dual benefit of waste reduction and energy production(Hasan et al., 2021).

Thermal Waste Treatment Techniques

Thermal treatment methods, such as combustion (incineration), gasification, Pyrolysis, and torrefaction, are also employed for waste management (Sipra et al., 2018). Incineration, a widely used technology, reduces landfill needs and recovers energy from combustible waste (Chhabra et al., 2016). Operating at high temperatures (850 to 1200 ºC) with excess oxygen, incineration can generate approximately 500 to 600 kilowatts per ton of MSW. However, it produces toxic gases (NOx, SOx) and ash, which are challenging to manage. Gasification, requiring less oxygen than incineration, is a partial combustion process producing H_2 and CO for secondary combustion. Despite its benefits, gasification faces challenges such as low gas yields, slag removal issues, high transportation costs, complex gas purification, and potential heavy metals and organic pollutants leaching. Both biological and thermal methods emit significant greenhouse gases, contributing to global warming and climate change(Hasan et al., 2021). Pyrolysis, gaining interest in biochar production, decomposes organic matter without oxygen and converts waste into biogas, condensable gases, tar, and char without leaving residual waste. This zero-waste technology produces Biochar, a valuable energy source and soil amendment, with applications dating back over 2500 years (Gabhane et al., 2020; Sipra et al., 2018).

Pyrolysis: A Revolutionary Approach in Waste Management

Pyrolysis, a thermal decomposition process conducted in the absence of oxygen, transforms waste materials into solid (Biochar), liquid (bio-oil), and gas (bio syngas) products (Tripathi et al., 2016). The yield and characteristics of these products are highly dependent on the operational conditions of the process. Biochar, one of the critical outputs of Pyrolysis, has notable applications in soil enhancement, improving water retention and nutrient content (Hasan et al., 2021). Pyrolysis is versatile and can process a wide range of feedstocks, including FW, textiles, plastics, paper, and woody biomass.

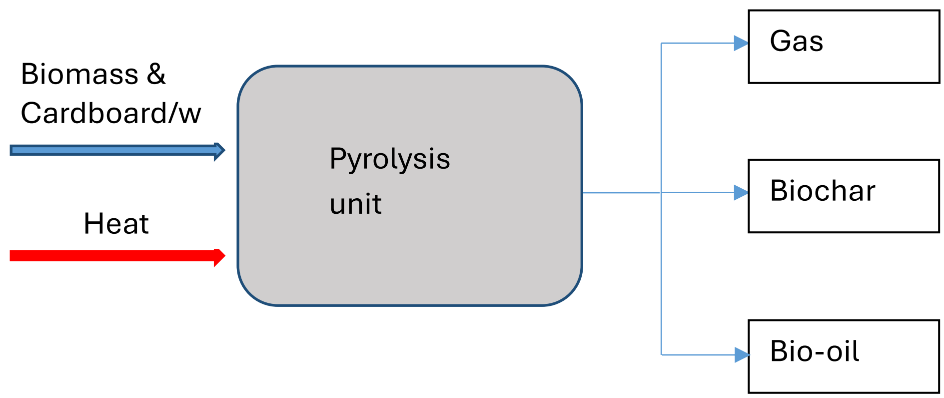

Fig 5. Basic pyrolysis process (Elkhalifa et al., 2019).

Compared to other thermal conversion technologies, Pyrolysis offers significant advantages. Its primary benefit is optimising the process for different desired outcomes. For instance, slow Pyrolysis is ideal for maximising biochar production, while fast Pyrolysis is suited for higher yields of bio-oil (Sipra et al., 2018). Additionally, Pyrolysis can handle various types of biomass, whether dry, wet, complex, or soft. It can also treat industrial wastes such as sewage sludge with minimal difficulty, and in some cases, pre-treatment can enhance efficiency. Another advantage of Pyrolysis is its flexibility in both operating conditions and feedstock types. The products of Pyrolysis are environmentally friendly, producing low levels of sulphur and nitrogen oxide (NOx) gases. This helps reduce greenhouse gas emissions, creating a cleaner atmosphere (Weligama et al., 2021). This adaptability and environmental benefit make Pyrolysis a promising technology for sustainable waste management.

Table 1- Advantages and disadvantages of waste management methods

Waste management	Advantages	Disadvantages	References
Open Burning	✓ Reduces the volume of waste quickly ✓ Low initial setup cost ✓ It can be implemented in areas with limited access to waste management infrastructure.	✓ Produces ash that needs to be managed and disposed of properly ✓ Releases toxic gases and particulate matter into the air, contributing to air pollution ✓ Health hazards to nearby populations due to inhalation of harmful emissions ✓ Incomplete combustion can lead to the release of harmful pollutants like dioxins and furans ✓ Contributes to climate change by emitting greenhouse gases such as CO_2 and methane ✓ Legal restrictions and regulations in many regions due to environmental and health concerns	(Maheshi et al., 2015; Prateep Na Talang & Sirivithayapakorn, 2021)
Open Dumping	✓ Simple and low-cost waste disposal method ✓ Requires minimal technological investment ✓ Can handle a wide variety of waste types ✓ Methane can be captured and used for energy generation in controlled settings ✓ Limited need for immediate processing of waste	✓ Potential for groundwater and soil contamination due to leachate ✓ Occupies large areas of land, leading to land degradation and loss of habitat ✓ releases methane, a potent greenhouse gas contributing to climate change ✓ Attraction of pests and vectors, leading to public health concerns ✓ Unpleasant odors and aesthetic issues ✓ Long-term management and monitoring required ✓ Risk of fire outbreaks	(Gabhane et al., 2020; Prateep Na Talang & Sirivithayapakorn, 2021)
Animal Feed	✓ The use of FW and GWW is favourable to the food chain system ✓ Low-level environmental impact by reducing methane emissions. ✓ Using FW and GW as pig feed could offer public health benefits.	✓ Difficulty in the separation of MSW into food and GWW. ✓ The probability of containing toxins material with food. ✓ Disease control concerns (correlation with foot-and-mouth disease).	(Salemdeeb et al., 2017) .

	✓ Economically beneficial for the food animal industry.	✓ FW and GW are not recycled into the protein component of cattle feed.	
Composting	✓ Low initial cost ✓ Organic fertiliser. ✓ It can be produced easily. ✓ Higher yields. ✓ Soil enhancement helps to retain moisture. ✓ Prevention of soil erosion.	✓ Emission of greenhouse gases (Methane, CO_2) ✓ The quality of compost depends on the ingredients. ✓ Long reaction time. ✓ Nutrient imbalance of the soil. ✓ Diseases can be spread. ✓ Environment issues such as odours and dust.	(*26 Important Pros & Cons Of Composting - E&C*, n.d.).
Sanitary Landfilling	✓ Provide energy sources ✓ Keep hazardous waste segregated ✓ Non-recyclable waste is allowed ✓ Modern landfills can be eco-friendly ✓ It can be used as a temporary storage space	✓ Groundwater contamination ✓ Gas emission ✓ Leachate generation ✓ Land degradation ✓ Responsible for climate change ✓ Leads to emissions of greenhouse gases	(Ghose & Franchetti, 2018),(*Advantages and Disadvantages of Landfills - Conserve Energy (Future*, n.d.).
Incineration	✓ Reducing Landfills and open burning ✓ Well-established technology ✓ Significant reduction of the amount of MSW by weight and volume (70–80%) ✓ Efficient electricity generation ✓ Inexpensive extraction of heat energy ✓ Requires less time	✓ The production of dioxins and other persistent organic pollutants results in air pollution and hinders the extraction of valuable chemicals from the MSW. ✓ Releasing NOx ✓ Special care is needed to dispose of the produced fly ash safely. ✓ High capital and operating costs. ✓ Highly inefficient upon burning of high moisture content waste. ✓ Minimum energy extraction.	(*Various Advantages and Disadvantages of Waste Incineration - Conserve Energy Future*, n.d.)**,**(Fericelli, n.d.)**.**
Gasification	✓ Used for all kinds of wastes ✓ Technology can be expanded easily	✓ Production of tar. ✓ More significant capital costs and Higher operating costs.	(Yap & Nixon, 2015; Amit Kumar

		✓ Higher energy consumption. ✓ Corrosion of metal tubes during the reaction. ✓ Ashes are troublesome	Mishra, R N Singh, 2015)
Pyrolysis	✓ Up to 80% energy recovery rate. ✓ Less land requirement. ✓ A smaller amount of CO_2 and no methane emissions ✓ Better quality of solid residues; high calorific value products (38 MJ/kg) ✓ Production of a lesser volume of flue gases per kg of waste, thus reducing the flue gas treatment capital cost.		(Sotoudehnia et al., 2020; Hasan et al., 2021)

Practical Applications of Biochar Derived from MSW

There is a growing global interest in producing Biochar from MSW due to the pressing challenges in waste management. Biochar production via the pyrolysis method, conducted under limited oxygen conditions, is rapidly and economically beneficial. This method reduces methane emissions and releases only small amounts of CO_2, supporting ecosystem balance. The solid product of MSW pyrolysis, known as Biochar, offers numerous environmental benefits.

Biochar is a stable, carbon-rich material produced by heating plant matter at relatively low temperatures (<600°C) in low-oxygen conditions. It is a potent climate-mitigation material that can sequester carbon dioxide from the atmosphere due to its resistant nature, aiding long-term carbon storage. Biochar serves multiple purposes, including pollution prevention, enhancing soil fertility, and promoting sustainable agriculture (Dennis, 2019).

Derived from biomass such as crop residues, FW, GWW, and CW, Biochar is highly porous with a significant specific surface area. These properties make it an excellent soil amendment, improving soil structure, water retention, and nutrient content. Combining biochar production with densification processes can facilitate its handling and broader application in agricultural practices.

Overall, Biochar from MSW presents a sustainable solution for waste management and environmental protection, contributing to reduced greenhouse gas emissions and enhanced soil health.

Conclusions and Recommendations.

The review highlights MSW management's multifaceted challenges and opportunities, emphasising the urgency for sustainable solutions. Key findings reveal that FW, GWW, and CW are significant contributors to environmental pollution and health hazards due to inefficient waste management practices. The current strategies in Sri Lanka, which predominantly involve open dumping and limited composting and recycling, are insufficient to handle the escalating waste volumes projected to double by 2033. This review suggests effective pyrolysis techniques for FW, GWW, and CW to achieve biochar yields that meet the specifications of final applications. This Biochar can be used to make various sustainable environmental, agricultural, and industrial gains. As a soil additive, Biochar improves soil fertility and condition, reduces pollution, stores carbon, and has been employed in various environmental applications due to its unique characteristics. The physicochemical characteristics of Biochar, such as its surface area, micro-porosity, and pH, offer a way to maximise its effectiveness in intended uses. Future studies will use laboratory testing, employing KOH to increase the absorption efficiency of FW, GWW, and CW biochar to test its efficiency in removing copper from the soil.

Several key actions are recommended to enhance MSW management in Sri Lanka. First, implementing comprehensive source segregation policies at the household level and strengthening waste collection infrastructure is essential. Promoting sustainable waste management practices, such as biochar production from GWW, and expanding composting and biogas facilities are crucial. Public awareness campaigns should emphasise the importance of waste segregation alongside training programs for local authorities and waste management workers. Policy support, including stricter regulations and incentives for sustainable practices, is necessary. Investing in research for improved waste-to-energy technologies and fostering public-private partnerships to enhance waste management infrastructure are also recommended. Additionally, exploring circular economy principles and advanced waste sorting and recycling technologies can improve MSW management, reduce environmental pollution, and promote public health.

References

26 Important Pros & Cons Of Composting - E&C. (n.d.).

Advantages and Disadvantages of Landfills - Conserve Energy Future. (n.d.).

Amit Kumar Mishra, R N Singh, P. P. M. (2015). Effect of Biomass Gasification on Environment. *Transplantation*, *71*(2), 229–233. https://doi.org/10.1097/00007890-200101270-00010

Chhabra, V., Shastri, Y., & Bhattacharya, S. (2016). Kinetics of Pyrolysis of Mixed Municipal Solid Waste- A Review. *Procedia Environmental Sciences*, pp. *35*, 513–527. https://doi.org/10.1016/j.proenv.2016.07.036

Dissanayaka, D. M. S. H., & Vasanthapriyan, S. (2019). Forecast Municipal Solid Waste Generation in Sri Lanka. *2019 International Conference on Advancements in Computing, ICAC 2019*, 210–215. https://doi.org/10.1109/ICAC49085.2019.9103421

Dissanayaka D.M.S.H., V. S., & Department. (2019). IDENTIFY INFLUENTIAL VARIABLES THAT AFFECT MUNICIPAL SOLID WASTE GENERATION AND FORECAST MUNICIPAL SOLID WASTE GENERATION IN SRI LANKA. *Sustainability (Switzerland)*, *11*(1), 1–14. http://scioteca.caf.com/bitstream/handle/123456789/1091/RED2017-Eng-8ene.pdf?sequence=12&isAllowed=y%0Ahttp://dx.doi.org/10.1016/j.regsciurbeco.2008.06.005%0Ahttps://www.researchgate.net/publication/305320484_SISTEM_PEMBETUNGAN_TERPUSAT_STRATEGI_MELESTARI

Elkhalifa, S., Al-Ansari, T., Mackey, H. R., & McKay, G. (2019). Food waste to biochars through Pyrolysis: A review. In *Resources, Conservation and Recycling* (Vol. 144, pp. 310–320). Elsevier. https://doi.org/10.1016/j.resconrec.2019.01.024

FAO. (2015). City Region Food System Situational Analysis - Colombo, Sri Lanka. *Food and Agriculture Organization of the United Nations*. http://www.fao.org/3/a-bl821e.pdf

FAO. (2018). *Food Waste Management in City Region Food System*. 8. http://www.fao.org/publications/card/en/c/CA1109EN

Fericelli, P. D. (n.d.). *Engineering for a Smart Planet, Innovation, Information Technology and Computational Tools for Sustainable Development*.

Gabhane, J. W., Bhange, V. P., Patil, P. D., Bankar, S. T., & Kumar, S. (2020). Recent trends in biochar production methods and its application as a soil health conditioner: a review. *SN Applied Sciences*, *2*(7). https://doi.org/10.1007/s42452-020-3121-5

Ghose, S., & Franchetti, M. J. (2018). Economic aspects of food waste-to-energy system deployment. *Sustainable Food Waste-to-Energy Systems*, 203–229. https://doi.org/10.1016/B978-0-12-811157-4.00011-5

Glaser, B. (2007). Prehistorically modified soils of central Amazonia: A model for sustainable agriculture in the twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *362*(1478), 187–196. https://doi.org/10.1098/rstb.2006.1978

Gunaruwan, T. L., & Gunasekara, W. N. (2016). Management of Municipal Solid Waste in Sri Lanka: A Comparative Appraisal of the Economics of Composting. *NSBM Journal of Management*, *2*(1), 27. https://doi.org/10.4038/nsbmjm.v2i1.19

Haryanto, A., Hidayat, W., Hasanudin, U., Iryani, D. A., Kim, S., Lee, S., & Yoo, J. (2021). Valorisation of Indonesian wood wastes through Pyrolysis: A review. *Energies*, *14*(5), 1–25. https://doi.org/10.3390/en14051407

Hasan, M. M., Rasul, M. G., Khan, M. M. K., Ashwath, N., & Jahirul, M. I. (2021). Energy recovery from municipal solid waste using pyrolysis technology: A current status and developments review. *Renewable and Sustainable Energy Reviews*, *145*(September 2020), 111073. https://doi.org/10.1016/j.rser.2021.111073

Klinghoffer, N. B., & Castaldi, M. J. (2013). Gasification and Pyrolysis of municipal solid waste (MSW). In *Waste to Energy Conversion Technology*. https://doi.org/10.1533/9780857096364.2.146

Maheshi, D., Steven, V. P., & Karel, V. A. (2015). Environmental and economic assessment of "open waste dump" mining in Sri Lanka. *Resources, Conservation and Recycling*, pp. *102*, 67–79. https://doi.org/10.1016/j.resconrec.2015.07.004

Menikpura, S. N. M., Gheewala, S. H., & Bonnet, S. (2012). Sustainability assessment of municipal solid waste management in Sri Lanka: Problems and prospects. *Journal of Material Cycles and Waste Management*, *14*(3), 181–192. https://doi.org/10.1007/s10163-012-0055-z

Mervin Dharmasiri, L. (2019). Waste Management in Sri Lanka: Challenges and Opportunities Sri Lanka Journal of Advanced Social Studies Vol. 9 No. 1, 2019. *Sri Lanka Journal of Advanced Social Studies*, *9*.

O'Toole, A., Knoth de Zarruk, K., Steffens, M., & Rasse, D. P. (2013). Characterisation, Stability, and Plant Effects of Kiln-Produced Wheat Straw Biochar. *Journal of Environmental Quality*, *42*(2), 429–436. https://doi.org/10.2134/jeq2012.0163

Prateep Na Talang, R., & Sirivithayapakorn, S. (2021). Environmental and financial assessments of open burning, open dumping and integrated municipal solid waste disposal schemes among different income groups. *Journal of Cleaner Production*, *312*(May), 127761. https://doi.org/10.1016/j.jclepro.2021.127761

Ruzaik, F. (2021). Geographical Measurements to Resolve Issues Associated with Municipal Solid Waste Disposal Empirical Evidence from Wet and Intermediate Agro-ecological Zones of Sri Lanka. *International Journal of Research and Analytical Reviews (IJRAR) Www.Ijrar.Org*, *8*(1), 563–580. http://doi.one/10.1729/Journal.26082

Saja, A. M. A., Zimar, A. M. Z., & Junaideen, S. M. (2021). Municipal solid waste management practices and challenges in the southeastern coastal cities of Sri Lanka. *Sustainability (Switzerland)*, *13*(8). https://doi.org/10.3390/su13084556

Salemdeeb, R., zu Ermgassen, E. K. H. J., Kim, M. H., Balmford, A., & Al-Tabbaa, A. (2017). Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. *Journal of Cleaner Production*, *140*, 871–880. https://doi.org/10.1016/J.JCLEPRO.2016.05.049

Sharma, K. D., & Jain, S. (2020). Municipal solid waste generation, composition, and management: the global scenario. *Social Responsibility Journal*, *16*(6), 917–948. https://doi.org/10.1108/SRJ-06-2019-0210

Sipra, A. T., Gao, N., & Sarwar, H. (2018). Municipal solid waste (MSW) pyrolysis for bio-fuel production: A review of effects of MSW components and catalysts. *Fuel Processing Technology*, *175*(November 2017), 131–147. https://doi.org/10.1016/j.fuproc.2018.02.012

Sotoudehnia, F., Baba Rabiu, A., Alayat, A., & McDonald, A. G. (2020). Characterisation of bio-oil and Biochar from Pyrolysis of waste corrugated cardboard. *Journal of Analytical and Applied Pyrolysis*, p. *145*, 104722. https://doi.org/10.1016/j.jaap.2019.104722

Trends in Solid Waste Management. (n.d.). Retrieved October 5, 2021, from https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html

Tripathi, M., Sahu, J. N., & Ganesan, P. (2016). Effect of process parameters on production of Biochar from biomass waste through Pyrolysis: A review. *Renewable and Sustainable Energy Reviews*, *55*, 467–481. https://doi.org/10.1016/j.rser.2015.10.122

Various Advantages and Disadvantages of Waste Incineration - Conserve Energy Future. (n.d.).

Wang, K. C. M., Lee, K. E., & Mokhtar, M. (2021). Solid waste management in small tourism islands: An evolutionary governance approach. *Sustainability (Switzerland)*, *13*(11). https://doi.org/10.3390/su13115896

Wang, Y., He, T., Liu, K., Wu, J., & Fang, Y. (2012). From biomass to advanced bio-fuel by catalytic pyrolysis/hydro-processing: Hydrodeoxygenation of bio-oil derived from biomass catalytic pyrolysis. *Bioresource Technology*, *108*, 280–284. https://doi.org/10.1016/j.biortech.2011.12.132

Weligama Thuppahige, R. T., & Babel, S. (2021). Environmental impact assessment of organic fraction of municipal solid waste treatment by anaerobic digestion in Sri Lanka. *Waste Management and Research*. https://doi.org/10.1177/0734242X211013405

Yap, H. Y., & Nixon, J. D. (2015). A multi-criteria analysis of options for energy recovery from municipal solid waste in India and the UK. *Waste Management*, pp. *46*, 265–277. https://doi.org/10.1016/j.wasman.2015.08.002

Yeshanew, M. M., Frunzo, L., Pirozzi, F., Lens, P. N. L., & Esposito, G. (2016). Production of biohythane from food waste via an integrated system of continuously stirred tank and anaerobic fixed bed reactors. *Bioresource Technology*, *220*, 312–322. https://doi.org/10.1016/j.biortech.2016.08.078