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Conceptual Model for plastics Waste Management in Developing Countries – A Review

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Abstract

Plastics waste management is crucial in developing countries such as Sri Lanka. The mass of plastics waste has been increasing yearly due to the rise in plastics demand. Mismanagement of plastics waste is an alarming issue that creates critical environmental and health problems. Although plastics waste management methods, including recycling, pyrolysis and incineration, are available, sorting plastics waste is a challenging part of the process. This literature review mainly focuses on the available plastics waste separation techniques and the conceptual model for plastics waste management in developing countries. The results of the literature review show that plastics waste sorting techniques can be categorized as manual, dry, wet, and combined separation techniques. The conceptual model suggests inventing plastics waste parks in Pradeshiya Sabha areas and carrying out the separation of plastics from other waste and the separation of plastics according to the plastics type. Normally, manual and combined separation techniques can be used for this separation process. In addition, public awareness and legal framework are very important to build up a sustainable waste management system in a country. The proposed conceptual model can be applied to smaller administrative boundaries of the country with suitable separation techniques. To reduce usage of plastics, efforts must be made by citizens to study the usage of renewable raw materials to create innovative goods using current technological advancements. Additionally, daily usage of plastics should be minimised, which aids in the improvement of healthy environmental conditions.

Keywords: Plastics waste, Sorting, Recycling, Energy, Separation techniques

Introduction

Plastics have become indispensable and versatile materials in various sectors, such as healthcare, packaging, electronics, automotive, building and construction, due to their remarkable properties that enhance human lifestyles (Sharuddin et al., 2018). As the world population continues to grow, the demand for plastics has increased accordingly. Unfortunately, this has also led to a rise in plastics waste accumulation in the environment, mainly due to the disposal of single-use plastics. Consequently, plastics have also become a significant component of Municipal Solid Waste (MSW).

The per capita consumption rate of plastics is high in developed countries compared to developing countries. Figure 1 shows the per capita consumption of plastics in selected developed and developing countries (Masud et al., 2019; Hossain et al., 2020).

The plastics waste generation rate mainly depends on the socio-economic and geographical features of different countries. According to Figure 1, plastics waste generating rate is higher in developed countries than in developing countries. However, plastics waste management is at a very low level in developing countries due to the dearth of infrastructure, technology, and methodology for managing plastics waste appropriately.

Significance of the study

As a developing country, Sri Lanka is struggling with municipal waste collection and management mainly in urban areas. This situation has become a critical level during covid pandemic outbreak times. According to the literature, 7000 metric tons of solid waste are generated per day in Sri Lanka. Nearly 60% of solid waste from this amount is generated from the Western Province due to the high population density (Fernando, 2019). According to the Environmental Foundation Limited (EFL) in Sri Lanka, one person generates an average of 0.4-1.0 kg of waste per day, and only half of them is collected by the municipal councils for different waste management practices.

Objectives

The primary objective of the review is to comprehensive data collection on plastics waste composition, environmental pollution of plastics wastes, bioplastics as an alternative for the plastics, current status of plastics waste management of Sri Lanka and the world, gap identification in plastics waste management, strategies of plastics waste management, with more emphasis on plastics waste separation techniques, and finally to develop a conceptual plastics waste management model for developing countries.

The comprehensive review provides information on 68 related latest published reviewed articles and localised reports addressing the persistent issue of plastics waste in Sri Lanka. It aims to explain the current situation surrounding this problem while searching into potential methodologies for the effective separation of plastics waste within local administrative systems. In addition, this review information was used to suggest a conceptual model with plastics waste management with plastics waste separation techniques, specifically fitted for implementation in developing countries.

Review of Past Literature

Plastics waste composition

According to the data from Sri Lanka customs, Sri Lanka annually imports 500,000 metric tons of primary forms, finished and intermediate products for the plastics industry. A considerable amount of plastics raw materials and finished products are released as post-consumer plastics waste to the environment. It has been reported that, in Sri Lanka, one million sachet packets including jam, sauce and shampoo, are disposed of in

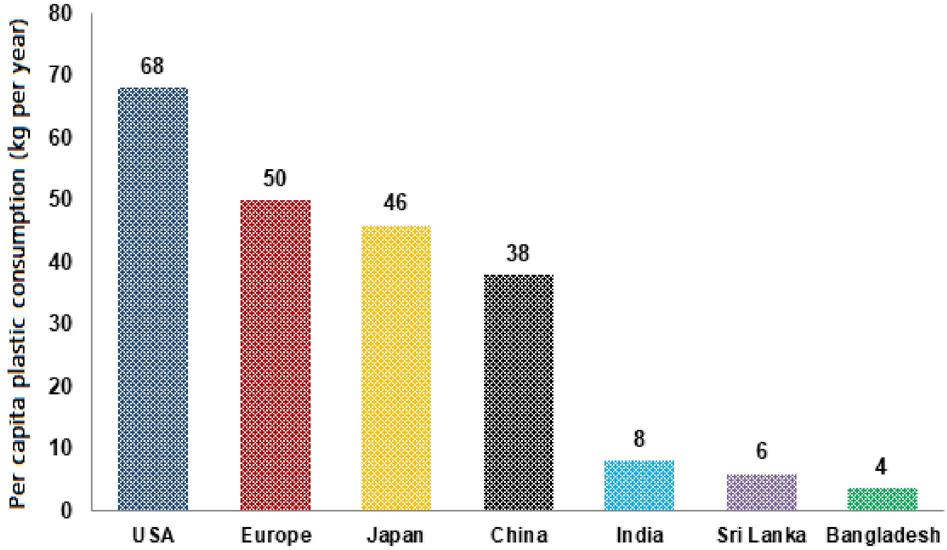


Figure 1. Plastics waste generation rate in developed and developing countries (Masud et al., 2019; Hossain et al., 2020.

open dumps every month. Furthermore, 20 million yogurt cups, 15 million lunch sheets, and 20 million grocery bags are dumped daily according to the survey results conducted by the Central Environmental Authority (CEA) in 2013 (Shantha, 2019; Karunarathna et al., 2020). According to the data from CEA in 2014, polyethylene and plastics have taken place 6% of the amount from the total waste in the solid waste composition as shown in Figure 2. The United Nations Centre for regional development report in 2019 shows that the plastics waste proportion of the solid waste is 10% in Sri Lanka (Samarasinghe et al., 2021). A case study of plastics waste sorting methods which was conducted in 2020 by the Department of Zoology and Environmental Management at the University of Kelaniya has analysed the waste disposal practices in Colombo and Kandy municipalities which are the areas of the highest population density in Sri Lanka. It has been reported that the most abundant waste plastics types in both areas are low-density polyethylene (LDPE), polyethylene terephthalate (PET), and polystyrene (PS) plastics.

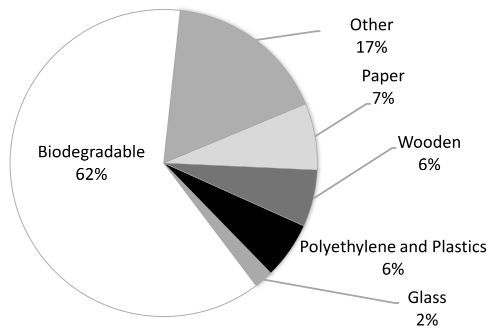


Figure 2. Waste composition in Sri Lanka. *Source*: Central Environmental Authority (2014).

In addition, a clear difference in the composition of urban and rural plastics waste can be identified by considering the number of different types of plastics waste. In 2016, a national survey conducted by the Japan International Cooperation Agency (JICA) showed that the amount of plastics waste from the total solid waste was 10% and 5% of urban and rural municipal solid waste, respectively, as shown in Figure 3 (Karunarathna et al., 2020). The percentage of soft plastics amount is higher than that of the hard plastics amount in both urban and rural solid waste streams (Karunarathna et al., 2020; Alahakoon and Karunarathna, 2020). The high amount of soft plastics waste commonly contains single used post-consumer packaging waste such as polyethylene bags, shopping bags, and lunch sheets.

Besides that, a case study conducted in Kandy Municipal Council (KMC), seven local authorities in Western Province, and Akkaraipattu Municipal Council (AMC), indicates that the total post-consumer plastics waste generated is estimated as 12.0, 54.4, and 4.8 tons per day, respectively (Alahakoon and Karunarathna, 2020) It is reported that the recycling of this plastics waste is carried out only in KMC and Western Province. The majority of plastics waste is discarded into open dumps. The estimated plastics waste per day in open dump areas in KMC, Western Province, and AMC is 7.23, 43.13 and 1.35 tons, respectively.

Environmental pollution of plastics waste

Mismanagement of plastics waste adversely affects the terrestrial environment. In Sri Lanka, the most common waste disposing methods are open dumping on empty land, compost generating, and burning plastics and polythene in the open fire (Maheshi et al., 2015; Arachchige et al., 2019). It contains both biodegradable waste and non-biodegradable waste in open dumpsites as the waste separation is still not improved in the country. Continuous discarding of solid waste into the open areas aids in generating enormous garbage mountains in several districts in the country. Plastics waste has become ubiquitous in disposal sites and the surroundings due to their non-biodegradable nature and persistence in the natural environment. Therefore, plastics waste is a major burden in environmental pollution.

Dumping of plastics waste or landfilling of plastics waste with other solid waste can lead to toxic chemicals being released into the environment which raise harmful effects on the natural environment and public health. Plastics materials contain toxic chemicals such as phthalates, poly-fluorinated chemicals, bisphenol A (BPA), brominated flame retardants and heavy metals (eg: Pb, Sb, Cr, Co, Hg, Zn, Ni, Cu), and release or migrate into the soil after discarding in open dumpsites and landfills (Maheshi et al., 2015; Okunola et al., 2019; Rafey and Siddiqui, 2023). These hazardous chemicals percolate through the soil into the water table and accelerate ground and surface water pollution. Moreover, these hazardous chemicals lead to infertility in lands and cause less agricultural productivity (Maheshi et al., 2015). In addition, open dumpsites are a negative aesthetic factor in cities creating an unpleasant environment in adjacent areas. Also, wild animals near open dump areas happen to eat plastics waste by mistake with remaining food waste, and their lives ending in fatalities (Conlon, 2021). Further, blockage in sewage systems in urban areas causes huge problems including sudden flooding even with light precipitation due to inappropriate plastics waste disposal. These plastics waste materials provide facilities for the breeding of mosquitos after precipitation and spread diseases such as Dengue (Ayomoh et al., 2008; Conlon, 2021). On the other hand, the open burning of plastics waste emits hazardous pollutants, such as heavy metals (eg: Hg, Cu, Cr, Co, Pb), dioxins, polychlorinated biphenyls (PCBs) and furans, causing damage to the respiratory system in both humans and animals (Verma et al., 2016; Okunola et al., 2019; Alam et al., 2019).

Plastics waste in open dumps close to wetlands, marshes, beaches and coastal areas, and direct removal to rivers and waterways harm marine organisms and habitats of marine animals. Sri Lanka has been ranked the fifth among 20 countries for releasing

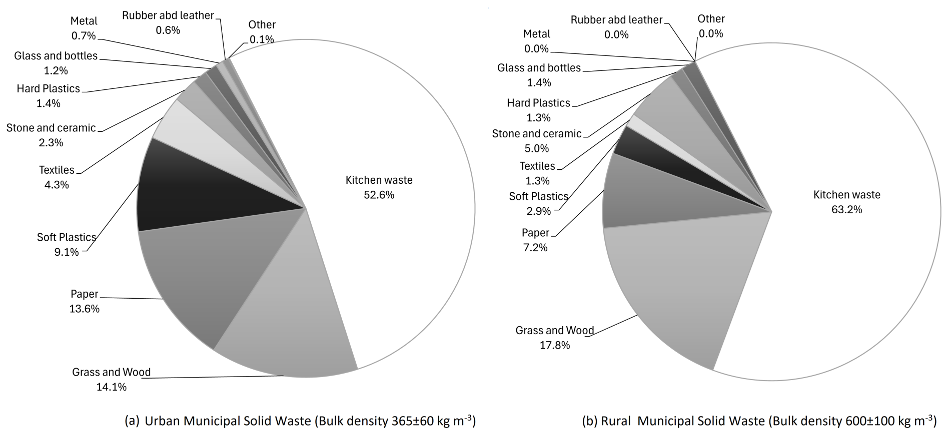


Figure 3. Composition of municipal solid waste in (a) urban and (b) rural areas of Sri Lanka (Karunarathna et al., 2020; JICA, 2016).

plastics waste into the ocean (Jambeck et al., 2015). It has been estimated that the weight of plastics waste in the ocean would increase more than the weight of live fish in the ocean by 2050 (Geyer et al., 2017). Reports have revealed that more than 260 species of marine organisms suffered from plastics debris in the ocean by getting entangled in abandoned or discarded fishing equipment (Okunola et al., 2019). Many plastics waste materials do not decompose in the ocean due to the lack of degradation conditions, such as the absence of UV light, low temperature, lack of oxygen, and absence of microorganisms (Streit-Bianchi et al., 2020). Despite the degradation, plastics waste materials follow through the fragmentation process and produce microplastics (< 5 mm) (Gallo et al., 2018; Streit-Bianchi et al., 2020). Microplastics debris can contain additives that would be included in the animal and human tissues through the food chain resulting in toxicity to organisms including carcinogenesis and endocrine disruptions in humans (Talsness et al., 2009; Cole et al., 2011; Jambeck et al., 2015).

Current status of plastics waste management in Sri Lanka

The Sri Lankan government has attempted to build up a sustainable management system for the past two decades. Some policies and programmes such as the ‘Pilisaru programme’ which was initiated by CEA in 2008 to gain “Waste-free Lanka in 2018” although it has not been achieved (Okunola et al., 2019; Basnayake et al., 2020). The local government is the lowest political structure in Sri Lanka which has three organizational units as local government bodies including the Municipal Council, the Urban Council, and Pradesheya Sabha responsible for the sustainable waste management system in the country.

Currently, in Sri Lanka, local authorities handle several disposal sites, and the main solid waste disposal methods are open dumping and landfilling (Arachchige et al., 2019). Industrial waste is identified as hazardous waste and the Holcim Geo-cycle Company has the legal permission to conduct the treatments on hazardous waste. In addition, the medical waste generated from hospitals is treated using incinerator facilities with the partnership of private companies (JICA, 2016). Although some programmes on waste to energy have been established since

2008, the Kerawalpitiya incineration plant remains the sole operational facility to date.

There is no proper waste segregation method when considering the plastics waste management system in Sri Lanka. At present, about 86% of the waste is dumped in the open and about 6% of it is converted into compost and about 4% is recycled (MoE, 2021). Plastics waste is also placed in open dump areas such as Kolonnawa, Bluemendhal, Kerawalpitiya wetlands and the coastline, with the other municipal solid waste. Some waste collectors and recycling companies are collecting segregated plastics waste by using the door-to-door collection method. About 300 waste collectors have been registered in CEA for collecting waste plastics including high-density polyethylene (HDPE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polyethylene terephthalate (PET), polypropylene (PP), polycarbonate (PC), high impact polystyrene (HIPS), acrylonitrile butadiene styrene (ABS) and polyvinylchloride (PVC). Most of these waste plastics are crushed and exported or sold as it is to recycling companies. Some of these waste plastics including ABS, PC and PVC are used to produce shoe soles, Vesak lanterns, trays for plant nurseries, etc. The waste PVC and PP are used to produce pipes for agricultural purposes and flowerpots for plant nurseries. However, this plastics waste collection routine is not sufficient to reduce the plastics waste problem in the country.

Established policies for plastics waste reduction in Sri Lanka

In 2006, a gazette notification was published on the prohibition of the manufacture of polyethylene or any polyethylene product of 20 μm microns or below in thickness to be used in Sri Lanka, and prohibition of the sale or use of these specific products (Shantha, 2019). In 2017, a gazette notification was published to prohibit the manufacture of food containers, plates, cups and spoons from expanded polystyrene. In addition, it also prohibited the sale, offer for sale, offer free of charge, exhibition, or use of food containers, plates, cups and spoons that are manufactured from expanded polystyrene within the country (Shantha, 2019). Another gazette notification was published in 2017 to prohibit open burning or cause to allow or permit the open burning of refuse or other combustible matters inclusive of plastics (Shantha, 2019).

The recently established policies were the prohibition of the manufacture of PET and PVC material for packaging agrochemical process, the prohibition of the manufacture sachets having less than or equal to a net volume of 20 mL, the prohibition of the manufacture of inflatable toys and cotton buds with the plastics stem (Shantha, 2019).

Existing plastics waste management methods - worldwide

Recycling plastics waste is the most common practice in many developing countries. In most countries, solid waste management rules are applicable to plastics waste as well. This includes the regulation of different types of plastics waste, such as single-use plastics bags, microbeads and packaging material. On the other hand, proper municipal solid waste disposal mechanisms have been implemented in developed countries, and hence, plastics are collected for recycling, landfilling, or incineration (Huysman et al., 2017; Bryant et al., 2018; Brouwer et al., 2018). In developing countries, as proper municipal solid waste management scheme has not been implemented, plastics are collected by informal garbage collectors and ended up in open dumps (Dijkstra et al., 2020). According to the results of the life cycle impact assessment in different treatments of waste plastics, it has been reported that mechanical recycling show a lower impact on environmental pollution than those of landfilling, incineration, and energy conversion methods (Chen et al., 2020). Nowadays, the concept of the valorization of waste has been more emphasised than the traditional waste management methods. This is known as the circular economy which is supported by scientific inventions in recycling and reprocessing of plastics. According to this concept, disposal of plastics is treated as a resource rather than waste (Dijkstra et al., 2020). Therefore, developed countries are paying more attention to the recycling of plastics waste before subjecting plastics waste to other disposal methods. Table 1 shows the waste management methods and policies for resource recovery that have been implemented in developed countries (Chen et al., 2021).

Segregation of waste is a promising method as it reduces the amount of waste ended up in open dumps and landfilling while increasing the amount of recyclable waste (Sukholthaman and Sharp, 2016). Public participation is very important in this step and their contribution of waste separation helps to reduce most of the problems in waste collection, transportation, intermediate treatment, and disposal process (Sukholthaman and Sharp, 2016).

In Japan, Kamikatsu village residents use a system that allows them to separate household waste into 34 categories (Sidjabat and Ilmi, 2020; Garcia-Rubio, 2020). This environmental initiative aims to reduce the amount of waste that ends up in incinerators which could harm the food supply and the environment due to the emission of greenhouse and hazardous gases. The separated waste is then transferred to recycling centres. This town has been achieved a recycling rate of 80% after many residents get used to the routine of washing, sorting, and transporting trash to the recycling centres and aims to recycle 100% in near future (Garcia-Rubio, 2020).

Sweden has introduced one of the most successful waste management systems in the European Union (Sidjabat and Ilmi, 2020; Garcia-Rubio, 2020; Milios et al., 2018). Citizens are aware of the importance of separating waste properly. This procedure is carried out through the separation of waste into different coloured bags according to their type. Then, further separation process is carried out as recyclable and non-recyclable waste in various waste separation plants that are situated throughout the country. Recyclable waste is formed into new materials and non-recyclable materials are burned in plants to generate electricity under the process of "waste-to-energy".

Bhattacharya et al. (2018) have reported a model for recycled plastics waste in India. In this model, after the plastics waste is collected, it is separated, cleaned, shredded, and pelletized at the recycling process plant. Then, the recycled granules are developed into value-added products with high performance based on the research and developments with the aid of government support. It has been suggested that recycled plastics granules can be used to manufacture furniture, fire-retardant plastics, incorporate in road laying, low-end products such as flowerpots, dust bins, and toys as well as production of fuel oil. Besides, Ragaert et al. (2020) have developed a new product called "Greentile" from the materials of sink fraction obtained from the float-sink sorting of mixed post-consumer packaging waste which has been sent to the incineration before.

Arachchige et al. (2019) have proposed a waste management model to address the solid waste problem in Sri Lanka. Accordingly, a clustering process has been suggested, according to the total waste generation in sub-district units, including Pradeshiya Sabha level or District Units. The proposed model categorizes waste into three types: Type S, with total waste less than 30 tons per day; Type M, with total waste ranging from 30 to 100 tons per day; and Type L, with total waste higher than 100 tons per day. The authors recommend implementing

Table 1. List of countries and their respective plastics waste management methods for resource recovery (Chen et al., 2021).

Country	Policy	Method of resource recovery
Denmark	Denmark Without Waste II	Recycling
Germany	German Closed Cycle Management Act	Circular economy
Japan	Waste Management and Public Cleansing Law	Recycling at source and recycling fee
Sweden	Swedish Environmental Code	Waste to energy
USA (San Francisco)	Mandatory Recycling and Composting Ordinance	Composting and recycling at source

composting and recycling for Type S cluster areas, while employing waste-to-energy and landfilling methods for Type M and L areas. The study emphasizes the importance of proper management processes by local governments to implement the proposed model effectively. Furthermore, citizens are encouraged to segregate household waste correctly, using colour-coded bags: green for biodegradable waste, blue for cardboard and paper, orange for plastics and polyethylene, and yellow for hazardous waste.

Alternative for plastics: Biodegradable plastics

Biodegradable plastics are a better solution for reducing the plastics waste problem due to their fast degradability, as conventional petroleum-derived plastics take more than a hundred years to fully decompose (Ebnesajjad, 2013). It is not imperative to biodegradable plastics are always synthesised from biomaterials. On the other hand, plastics that are synthesised from biomaterials are not always biodegradable (Rujnić-Sokele and Pilipović, 2017). It can be identified as four main categories of plastics according to the biobased materials and biodegradability properties (Rujnić-Sokele and Pilipović, 2017; Alaerts et al., 2018; Onen Cinar et al., 2020). They are:

i. Biobased-not biodegradable bioplastics:

- bio-polyethylene
- bio-polypropylene
- bio-polyamide
- cellulose-acetate
- bio-polyisoprene
- bio-polyethyleneterephthalate

ii. Biobased-biodegradable bioplastics:

- polylactic acid (PLA)
- polyhydroxyalkanoate (PHA)
- thermoplastics starch
- cellulose-regenerates

iii. Fossil based-not biodegradable conventional plastics:

- high-density polyethylene (HDPE)
- low-density polyethylene (LDPE)
- polypropylene (PP)
- polystyrene (PS)
- polyvinylchloride (PVC)
- ethylenevinylalcohol (EVOH)

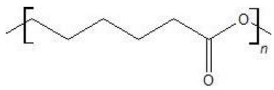
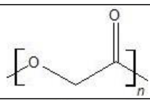
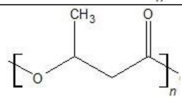
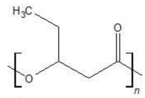
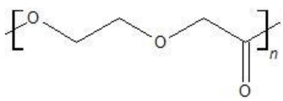
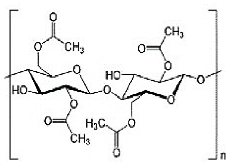
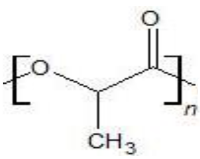
iv. Fossil based-biodegradable bioplastics:

- co-polyester
- polybutyleneadipate terephthalate (PBAT)
- polycaprolactone (PCL)
- polybutylenesuccinate (PBS)

The biodegradability of plastics depends on several parameters, such as raw materials of plastics, chemical composition, structure of the final product, and plastics decomposing environment (Rujnić-Sokele and Pilipović, 2017). Table 2 gives the details of some common biodegradable polymers in the market and their applications.

Although biodegradable plastics have the potential to decompose in a short period, these plastics simply cannot be discarded into the terrestrial environment after the

Table 2. Common biodegradable polymers that are available in the market (Ebnesajjad, 2013).

Polymer	Chemical Composition	Applications	Biodegradability
Ɛ-Polycaprolactone (PCL)		Sutures, contraceptive implants, paints, and metal protection films	> 12 months
Polyglycolide or polyglycolic acid (PGA)		Sutures	> 3 months
Polyhydroxyalkanoate: polyhydroxy butyrate (PHB) and polyhydroxy valerate (PHV)	 (PHB)  (PHV)	Compost bags, consumer packaging, agriculture films	3 – 12 months
Polydioxanone (PDO)		Sutures	< 7 months
Cellulose acetate		Cigarette filters, textiles, spectacle frames, film media, wound dressings, toothbrush	< 24 months (Depends on acetate content)
Polylactic acid (PLA)		Spunbond fabrics, pure and natural diapers, casings, Fibre electronics covers, cloths, fibre fills, film overwraps, PLA bottles, foodservice ware	

end-of-life. The biodegradation rate of these biodegradable plastics depends on disposal methods and vital particular conditions including temperature, the presence of light, the presence of oxygen, presence of specific microorganisms (Rujnić-Sokele and Pilipović, 2017; Agarwal, 2020). The disposing methods, such as reuse, recycling, energy recovery and composting, can be identified as the main disposal options of biodegradable plastics (Rujnić-Sokele and Pilipović, 2017; Gioia et al., 2021).

Compostable plastics undergo decomposition of the polymer by microorganisms and convert it into carbon dioxide, water, mineral salts, and biomass without affecting any toxic side effects to the natural environment (Rujnić-Sokele and Pilipović, 2017; Agarwal, 2020; Gioia et al., 2021). The following four criteria should be achieved by bioplastics to fulfill the compostable ability (Rujnić-Sokele and Pilipović, 2017; Agarwal, 2020).

i. Bioplastics material should contain 50% organic matter and not exceed the standard limitations of the heavy metal amounts in the chemical structure.

ii. Biodegradation or the conversion of organic carbon into carbon dioxide of the bioplastics material should be able to undergo 90% of decomposing percentage within six months at controlled composting conditions.

iii. The bioplastics material should disintegrate within 12 weeks and fragments should not be detectable visually or should be smaller than 2 mm under the controlled composting conditions.

iv. After the degradation of the bioplastics material, residue products should not cause any toxic effect to the natural environment.

There are bioplastics materials that do not fulfill the above criteria of compostable standards (e.g., bio-PET, bio-PP, bio-PE). These bioplastics that are not conformed to the criteria of compostable ability should undergo conventional plastics waste disposal methods, such as recycling and energy recovery. Compostable bioplastics are widely used as bags for food waste collection and agricultural mulch films where the separation of organic matter and plastics is problematic. Most of the biodegradable plastics are decomposed completely under industrial composting conditions. Therefore, all biodegradable plastics material may not be suitable for home-composting conditions that contain natural environmental conditions. The biodegradability of plastics materials is achieved by taking advantage of their natural characteristics. This process only succeeds if the correct conditions are encountered.

Strategies of plastics waste management

Plastics waste recycling

Compared to incineration and landfilling, recycling of plastics waste is more eco-friendly and is an acceptable method of disposal. Basically, recycling is divided into two categories: mechanical and chemical (Hopewell et al., 2009; Faraca and Astrup, 2019). The former refers to the process of converting non-biodegradable plastics into useful products, while the latter includes various methods to break down plastics into their basic components, which can then be repurposed. Some chemical recycling methods involve re-heating, while others may use chemical reactions or solvents without re-heating (Hopewell et al., 2009). Instead of chemical recycling, mechanical recycling is an eco-friendlier method. It saves energy and produces less pollution.

Plastics are classified into seven types according to the materials used in its production. This classification supports identifying the plastics materials in the mechanical recycling process. Table 3 shows the types of plastics, common use and the products that could obtain after the recycling process (Okunola et al., 2019).

Although these recycling waste management principles reduce plastics consumption, there must be a proper sorting system to handle the amount of post-consumer plastics waste that is inevitably generated.

Upcycling of waste plastics

Generally, plastics only downcycles, losing significant strength once it is melted, whereas upcycling is the new concept of converting the waste plastics into something more valuable (Chanda, 2018; Faraca and Astrup, 2019).

Carbon is the major component of plastics, and therefore, waste plastics can provide a

Table 3. Types of plastics and their common industrial applications.

Recycling code	Types of plastics	Applications	Recycled materials
1	Polyethylene terephthalate (PET)	Soft drinks, water bottles, containers, salad dressing, biscuit trays, and salad domes.	Pillow and sleeping bag filling, clothing, soft drink bottles, carpeting, building insulation
2	High-density polyethylene (HDPE)	Shopping bags, freezer bags, buckets, shampoo, milk bottles, ice cream containers, juice bottles, chemical and detergent bottles, rigid agricultural pipe, crates.	Recycling bins, compost bins
3	Polyvinyl chloride (PVC)	Cosmetic container, plumbing pipes and fittings, electrical conduct, blister packs, wall cladding, roof sheeting, bottles, garden hose, Shoe soles, cable sheathing, blood bags and tubing.	Compost bin
4	Low-density polyethylene (LDPE)	Refuse bags, irrigation tubings, mulch film, cling wrap, garbage bags, squeeze bottles.	Bin liners, pallet sheets
5	Polypropylene (PP)	Microwave dishes, lunch boxes, packaging tape, garden furniture, kettles, bottles and ice cream tubs, potato chip bags, straws	Pegs, bins, pipes, pallet sheets
6	Polystyrene (PS)	CD cases, plastic cutlery, imitation glassware, low-cost brittle toys, video cases/foamed polystyrene cups, protective packaging, building and food insulation	Recycle bin
7	Other	Miscellaneous plastics (laminates, multilayered materials, composites), automotive and appliance components, computers, electronics, cooler bottles, packaging	Recycle bin

carbon source for carbon-based value-added products, such as light hydrocarbons, carbon black/activated carbon, carbon fibres, carbon nanotubes, and graphene (Chanda, 2018). Converting waste plastics into such value-added products is a good example of upcycling.

Pyrolysis of plastics waste

In the process of pyrolysis, organic polymer chains are converted into liquid oil, gases, and char products at high temperatures

(300-900 °C) in the absence of an oxygen environment through thermal decomposition (Miandad et al., 2016). In addition, when a suitable catalyst is used, the quality of the liquid oil yield can be improved, and the process temperature can be reduced. It is reported that the pyrolysis process can convert plastics into 78-84 wt.% of liquid oil (Miandad et al., 2016). This liquid oil, obtained from the plastics pyrolysis process, has the potential to be used as an alternative to fuel oil. The most common plastics waste types used for the pyrolysis process are LDPE, HDPE, PP and PS. In addition, PVC plastics is not heavily employed for the pyrolysis process as the reaction vessel may corrode due to the emission of hydrochloride gas during the pyrolysis process (Miandad et al., 2016).

Plastics waste incineration

Plastics waste that contains a high amount of impurities and recycled materials is more cost-effective by being applied to the incineration process (Hahladakis and Iacovidou, 2019). Therefore, plastics waste, such as composite materials, multilayered materials and low-quality recycled materials, that cannot be recycled again can be used for this process. Plastics waste materials contain a higher calorific value and a lower moisture content when compared to organic waste materials. Therefore, plastics waste is a suitable material for incineration and recovers energy from direct combustion. In this process, It is produced electricity, steam, or heat from the direct combustion of plastics waste as a raw material (Arachchige et al., 2019). In Sri Lanka, the surface moisture of plastics waste increases due to rainy seasons. Therefore, the moisture removal pre-heating process would be required before the incineration process of plastics waste in order to reduce the energy of the combustion process (Arachchige et al., 2019).

Currently, in Sri Lanka, an incineration power plant is being established in Colombo municipal area to generate electricity with fresh municipal solid waste with the partnership of Western Power Company Pvt. Ltd. in Muthurajawela. It has been estimated to convert 700 metric tons of solid waste into electricity by operating approximately 7,500 hours a year and providing 9.7 MW of power to the Ceylon Electricity Board. However, hazardous gas emissions can occur due to the incineration process, and it should be promoted the reduction, reuse, and recycling of plastics waste in society.

Plastics waste disposal in landfills

Nowadays, in many countries, one of the most often used approaches for disposing of municipal solid waste is landfilling (Aljaradin and Persson, 2012; Sabour et al., 2020). There are advantages as well as disadvantages to disposing of plastics waste in landfills. Compared to recycling and energy recovery processes, landfilling requires lower investment to the initiation, and labour-intensive is low. However, environmental problems are high in landfills mainly due to the production of greenhouse gases (CO_2 and methane). To avoid this problem, modern landfills are required control systems to collect landfill gases and leachates (Chanda, 2018).

Gap identification of plastics waste management in Sri Lanka

Currently, the Municipal Councils of Sri Lanka have collected only the waste that is segregated as biodegradable waste, cardboard or paper, and plastics. The municipal councils have scheduled particular days in a week for the collection of mentioned segregated waste. Although this segregated waste is collected on different days, the disposal of this waste takes place in an open dump. The main problem is that the rest of this plastics waste becomes dirty due to contamination of the remaining food and soil. There is no proper separation method of this waste plastics according to the types of polymers in the plastics composition to be carried out in the recycling process as well as the other energy recovery processes.

In addition, problems can be identified as allocated funding for waste management programs is not sufficient for the maintenance of garbage collecting and transporting vehicles. Inadequate waste collection vehicles and irregularity of waste collection persuade burning and illegal dumping of solid waste in society. Even if waste is separated as non-biodegradable or plastics, paper, and cardboard, organic and hazardous waste, all categories ended up in the same transporting vehicle during the collection, and mixed solid waste is disposed to the dumping sites at the end. Furthermore, the amount of defined garbage bins for waste categories are not sufficient in public areas. The lack of policies and a strong legal framework promotes the incorrect waste disposal practice in public areas. On the other hand, recycling facilities are centred only for urban areas (Alahakoon and Karunarathna, 2020). The negative attitude of the people about waste management, lack of participation, high rate of population growth in urban areas, and space limitations are the other reasons for the increase in the municipal solid waste problem (Fernando, 2019).

In addition, the main factors of improper waste management in Sri Lanka can be categorized as financial issues, political issues, technical issues, and socio-cultural issues. Several programs for solid waste management have been proposed and initiated in the past two decades to obtain a proper waste management system in Sri Lanka. The main reason for the failure of these waste management programmes seems to be the poor implementation and the lack of teamwork of both government authorities and society.

Conceptual model for plastics waste management

When considering the current situation in Sri Lanka, mixed plastics waste can be identified as dry mixed plastics waste and contaminated mixed plastics waste. A certain percentage of the dry mixed plastics waste is collected by recycling centres and separated for the recycling process. The contaminated mixed plastics waste is collected by the municipal councils and a higher amount of them dispose of open dumps. This model is developed for the segregation of general contaminated mixed plastics waste that generates from households, institutional, commercial, industrial, hospitals, and other areas. The schematic presentation of the conceptual model is shown in Figure 4.

Waste disposal areas in local authorities and municipal councils can be converted into waste parks as the areas doing pretreatments for the mixed plastics waste. These waste parks should be divided into Waste Park Section 1 and Waste Park Section 2. The mixed municipal solid waste generated from public areas is collected by the local authorities and transported to the Waste Park Section 1. The separated waste at the source from households and institutional areas should hand over the plastics waste into Waste Park Section 2. It can be introduced to a buying and selling system to promote source separation of plastics waste among the citizens.

The cleaning process can be carried out in the Waste Park Section 2. Then shredding and separation can be done after the cleaning process. There are several techniques for the separation of plastics waste and recyclable and non-recyclable plastics can be separated for further process. After separating recyclable and non-recyclable plastics they can be distributed to the recycling companies and disposal areas.

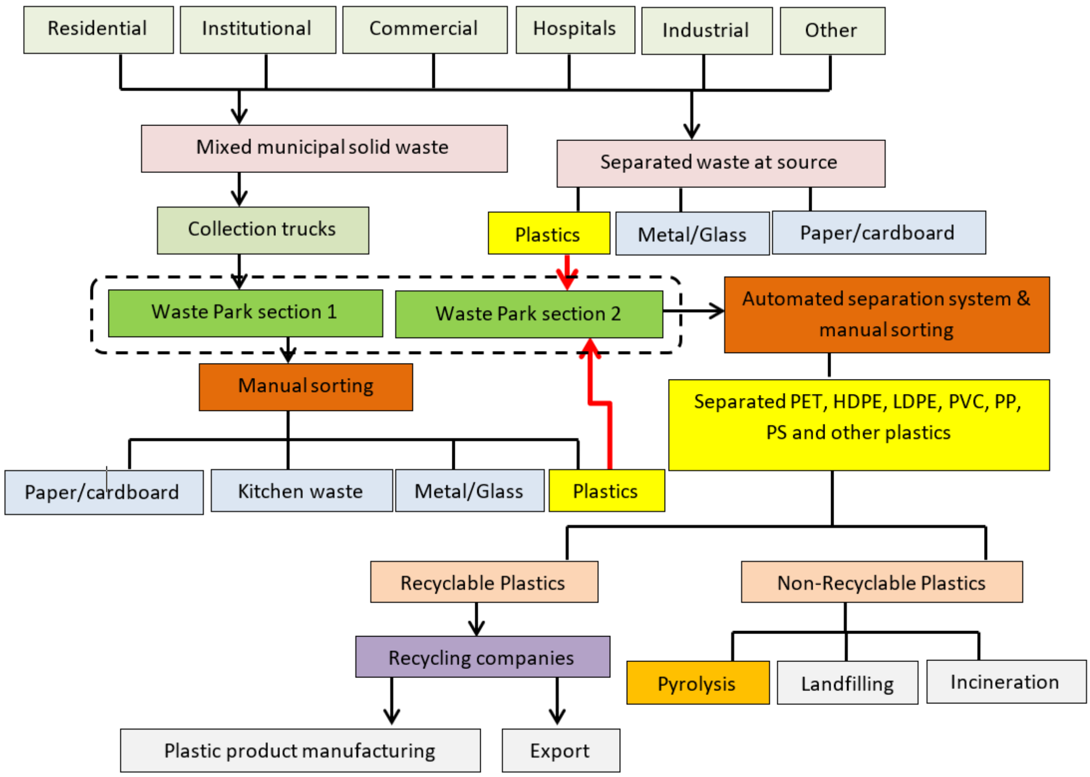


Figure 4. Schematic presentation of the conceptual waste management model.

Separation techniques for plastics waste

The current plastics waste management problem in Sri Lanka is the separation of plastics waste according to the different types of polymers in the plastics compositions. Because recycling of plastics is mainly limited to rigid packaging materials such as PET bottles or other pure PP or PE containers (Araujo-Andrade et al., 2021). There are several methods to separate plastics from other waste as well as plastics. Figure 5 shows the classification of several methods in plastics waste separation (Ruj et al., 2015).

Manual sorting

Waste plastics are classified according to their shape, appearance, colour, and brand using manpower in this sorting system (Sutar and Salunkhe, 2015). It is a simple method based on the material identification code and does not require an advanced instrument handling technique. In addition, errors can occur due to the lack of proper knowledge about plastics types in this sorting method. Manual sorting can be effective for small-scale operations or for initial sorting before more advanced separation techniques are applied. However, it is labour-intensive, time-consuming, and may have limitations in terms of accuracy and efficiency compared to automated sorting methods. However, manual sorting cannot be applied to separate plastics that are made from composite materials, such as fibre-reinforced plastics and multi-layered structures (Araujo-Andrade et al., 2021). Nonetheless, manual sorting remains an important part of plastics waste management, especially in regions or facilities where automated systems are not available or

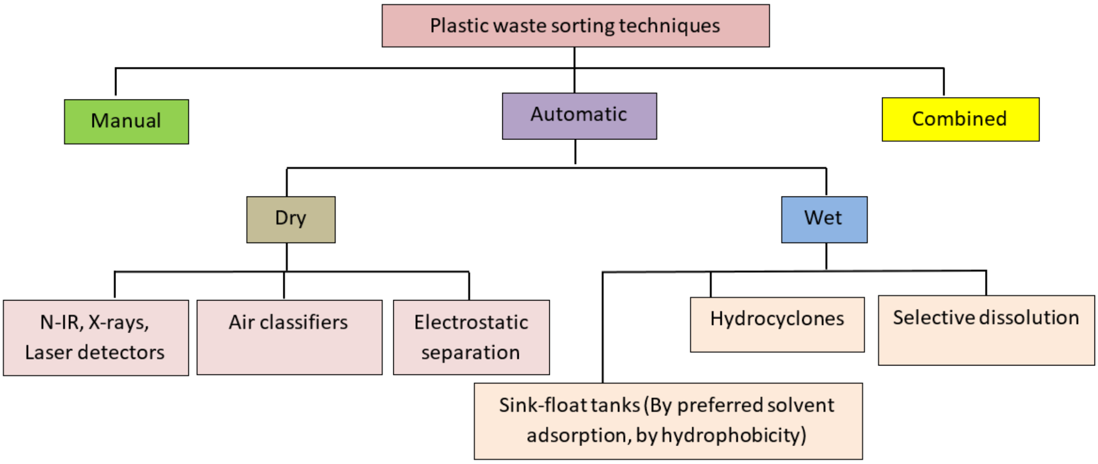


Figure 5. Classification of the plastics sorting methods (Ruj et al., 2015).

economically feasible.

Automatic separation

Automatic separation of plastics waste can be further classified as dry sorting techniques and wet sorting techniques.

Dry separation

Cleaning of plastics waste can be carried out using a dry or wet process according to the quality of the collected waste samples. When compared to the wet cleaning process, dry cleaning with air has more advantages as it avoids excessive energy consumption for the post-separation drying process. It can be separated from dirt and dust in the waste plastics materials using proper equipment such as screen units and air stream separators (Jank et al., 2015; Chanda, 2018).

Dirt and dust particles that adhere to the plastics materials due to the electrostatic charge can be removed using a screen unit and air separator, respectively. In the screen unit, mixed plastics such as various types of composite materials follow the size reduction before the dry-separation (Hansen et al., 2007; Jank et al., 2015). In the air stream separators, lighter materials have been carried upward by the air stream to discharge and heavy materials have been carried downward. The cascade separators that separate fibres and insulation film or foam and soft film and the fluidized air bed separators that separate the rubber from rigid thermoplastics or aluminum from plastics are the commercially available air stream separator units (Chanda, 2018).

Air classifier

Air classifiers are used to distinguish heavy plastics materials from light plastics materials using airflow as a medium (Serranti and Bonifazi, 2019). Furthermore, this technique can be used as a cleaning process of contaminants such as dust, sand, glass powder, and wooden materials in the main plastics waste stream. This technique has a simple working principle; that is, the heavy materials are blown down with the speed of the air stream, and the light materials are blown up as shown in Figure 6. (Shapiro and Galperin, 2005; Gundupalli et al., 2017). In practice, plastics waste such as packaging materials and foils can be separated primarily from automotive parts, electrical and electronic devices through air classifiers.

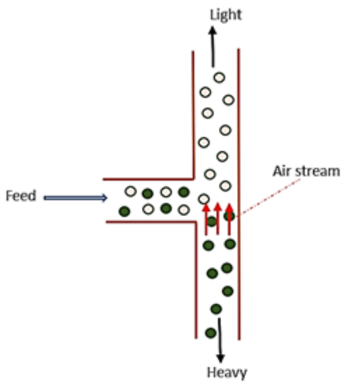


Figure 6. Schematic representation of an air classifier (Serranti and Bonifazi, 2019).

Triboelectrostatic separation

The triboelectrostatic separation method is a strongly suitable method for plastics waste separation due to the maintenance of the original properties of the plastics, such as high efficiency, low cost, and the low impact of environmental pollution (Li et al., 2015). Dielectric properties in plastics particles are used in this separation. plastics waste particles are rubbing together to induce different electrical charges and separation is carried out inside an electric field that contains positive and negative electrodes (Al-Salem et al., 2009). The triboelectric charging sequence in plastics can be aligned as positively charged plastics to negatively charged plastics; (+) ABS-PP-PC-PET-PS-PE-PVC-PTFE (-) (Dodbiba et al., 2002; Serranti and Bonifazi, 2019). Furthermore, when two plastics materials in this sequence are rubbed against each other, the material closest to the positive end is charged positively and the material closest to the negative end is charged negatively. The main disadvantages in the electrostatic separation of plastics waste can be identified as follows: The plastics waste stream should be dry and clean because water and dirt particles on the surface of the waste plastics would not provide specific electrical properties to the plastics (Wu et al., 2013). In addition, the additives and fillers in the plastics would prevent the surface charging of the plastics (Wu et al., 2013; Li et al., 2015).

Spectroscopic separation

Spectroscopic separation is carried out based on optical spectroscopies such as the Fourier-transform infrared spectroscopy (FTIR), near-infrared spectroscopy (NIRS), Raman spectroscopy (RS), and X-ray and laser spectroscopic techniques. When exposed to a specific optical wavelength, the plastics material reflects an ideal spectrum for each type of plastics. According to the spectral fingerprints of the chemical composition of plastics, it has been able to differentiate into plastics types (Araujo-Andrade et al., 2021).

The FTIR is present in the mid-infrared (MIR) region which provides a wide spectral range (4000-400 cm-1) for molecules to vibrate at specific wavelengths by absorbing infrared radiation. The most common plastics used in the packaging process such as PET, polyamide, polylactic acid, HDPE, PVC, LDPE, PP, and PS can separate through the MIR spectroscopy analysis (Jung et al., 2018). The main advantage of this method is coloured and black plastics that have included carbon black or fibre materials can be identified due to the MIR range poses beyond the visible range. Recently, the MIR spectroscopy system is with a combination of hyperspectral cameras that are working on the MIR range can provide chemical imaging based on molecular information of the sample. It is more reliable to separate black plastics into specific plastics using hyperspectral cameras with MIR spectroscopy technology (Araujo-Andrade et al., 2021).

In addition, plastics with minor changes in the structure, such as PP, PS, polyamide, PE, acrylonitrile, ABS, PET, polycarbonate, PVC, polyurethane and polyvinylidene chloride, can be separated due to the high sensitivity of detection using Raman spectroscopic analysis (Araujo-Andrade et al., 2021). However, the detection of acrylonitrile specifically may present challenges. This is because acrylonitrile, a monomer in some plastics like ABS, has a strong CN stretch vibration that may overlap with other signals in the spectrum, making it harder to distinguish depending on the spectral resolution and the specific matrix in which it's embedded. Furthermore, Raman spectroscopy and near-infrared spectroscopy (NIRS) cannot be used to separate black plastics since these techniques operate in the visible to near-infrared region, where black materials absorb most of the light, reducing the effectiveness of the detection (Brouwer et al., 2018). The laser and X-ray spectroscopic techniques are commercially used to identify and separate organic and inorganic materials in plastics such as flame retardants or inorganic fillers (Araujo-Andrade et al., 2021). Table 4 summarizes the commercially available optical techniques and their functionality in plastics identification.

Wet separating techniques

Sink-float separation: The plastics materials are separated according to their density in a suitable separation solution medium in the density separation method. Herein, plastics that are lower density than that of the medium solution come to the surface whereas plastics that are higher density than that of the medium solution sink in the bottom. The olefinic materials including HDPE, LDPE, and PP can separate from PET, PVC, PS, and ABS plastics from the flotation section when using water as the medium solution in the float-sink tank (Pongstabodee et al., 2008). In addition, different medium solutions are required for individual separation of both flotation and sink plastics materials. Composite plastics materials that incorporate fillers in the processing and hollow shape plastics cannot be separated using this density separation technique. This technique can mainly be used to separate polyolefin fractions from post-consumer plastics. Although, waste fractions should undergo pre-separation and screening steps to avoid impurities as organic and wooden waste (Bauer et al., 2018).

Hydrocycloning: Hydrocycloning is a density separation technique. It uses centrifugal forces and fluid resistance to separate particles with distinct properties (Hansen et al., 2007; Yuan et al., 2015). First, the size of plastics particles should be reduced and introduced into the inlet in a perpendicular direction. Afterward, materials are rotated within the vessel and eventually created a vortex. The centrifugal force moves heavy materials outward and could be collected from the bottom of the chamber as shown in Figure 7. The light materials move into the centre of the vortex and can be collected from the upper part of the chamber. It has been reported that low-density particles are difficult to separate from the cyclone chamber due to the particle moves away by the underflow stream (Yuan et al., 2015). This separation method requires relatively complex instruments and needs to have exact characteristic control of the plastics such as polymer to fluid ratio, particle size, and particle morphology (Serranti and Bonifazi, 2019).

Selective dissolution: The selective dissolution and reprecipitation methods are used to separate target polymers from multilayered materials. Different organic solvents, such as toluene, tetrahydrofuran and xylene, are used to dissolve the first polymer of multilayered plastics material in the solvent whereas second polymers and additives remain as residues. The dissolved polymer can reprecipitate after separating through filtration of the remaining residues (Kaiser et al., 2017).

This method has been applied to the recycling of waste plastics packaging, electrical and electronic equipment (Knappich et al., 2017), and construction materials (Kaiser et al., 2017). The advantages of this method are that high-quality material can be

Table 4. Summary of commercially available optical techniques in plastics identification (Araujo-Andrade et al., 2021).

Spectroscopic techniques	Price (from cheap US$ to expensive US$$$$$)	Typical device spectral range	Compatibility with black plastics	Handheld option	Imaging option	Quantitative processing	Safety concerns	Typical penetration depth/range
Near-infrared spectroscopy	US$	900-2500 nm	No	Yes	No	Yes	No	< 4.0 nm
Near-infrared hyperspectral imaging	US$$$	900-1700 nm	No	No	Yes	Yes	No	< 4.0 nm
FTIR spectroscopy	US$$-US$$$	4000-400 cm^{-1}	Yes	Yes	Yes	Yes	No	0.5-2.0 µm
Mid-infrared hyperspectral imaging	US$$$$	3500-2400 cm^{-1}	Yes	No	Yes	Yes	No	µm
Raman spectroscopy	US$$-US$$$$	2800-200 cm^{-1}	No	Yes	Yes	Yes	Yes	µm (wavelength dependent)
Laser-induced breakdown spectroscopy	US$$	200-1000 nm	Yes	Yes	Yes	Yes	Yes	µm-mm
X-ray fluorescence spectroscopy	US$$-US$$$$	X-ray source range: 5-80 keV	No	Yes	Yes	Yes	Yes	cm

obtained from the precipitated polymer and no complex sorting techniques are required. The main drawbacks are that the high solvent cost and energy required drying process of recovered polymers (Kaiser et al., 2017).

Other automated separation techniques

Other automated sorting techniques employ various properties of the waste material including magnetic susceptibility, electrical conductivity and density for heavy media separation by applying external fields like magnetic, eddy current and gravity respectively (Gundupalli et al., 2017; Araujo-Andrade et al., 2021). Auxiliary separation techniques are used to clean the plastics waste stream from other materials such as ferrous metals including stainless steel, nickel alloys, and non-ferrous metals including aluminum and copper (Serranti and Bonifazi, 2019). Magnets are used to separate ferrous metal whereas eddy current-based separators are used to separate non-ferrous metals (Serranti and Bonifazi, 2019).

Materials can be separated before the size reduction or after the size reduction according to the resin type and the colour in the automated separating techniques. In most of the recycling industries automated separating techniques are used to separate

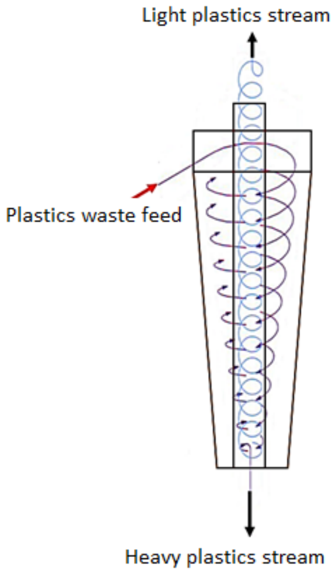


Figure 7. Schematic presentation of plastics hydro-cyclone separator (Serranti and Bonifazi, 2019).

look-alike post-consumer bottles such as non-pigmented PVC and PET bottles (Chanda, 2018).

Sustainable plastics waste management-Public awareness and legal framework

Plastics waste management cannot be sustainable without the support of society. Therefore, public awareness and the legal framework on plastics waste management are very important. Several researchers have identified factors that affect the implementation of waste management systems in a country such as participation of the citizen, the sufficiency of resources, people's awareness and training, staff awareness and training, availability of the market, support from the political leadership, and contribution of the society and the business community (Fernando, 2019; Basnayake et al., 2020).

In terms of plastics waste management, public awareness about the plastics types, characteristics, and application is very important. As in many developing countries, a lack of commitment to sustainable waste management practices from the public can also be observed in Sri Lanka. Waste segregation at the household level is also practised at a minimum level. Even though they are segregated, collectors dump all waste into one collection chamber installed on the garbage collecting vehicles. Therefore, knowledge about plastics types and recyclable codes should be included in the education system in Sri Lanka. Public awareness programs should be implemented at the school level with the priority of the local authorities. For that, the government can get the support of the private sector. It can implement the separation of plastics waste according to their type among the society by advertising through media channels. Also, introduction of TV-series and movies about the importance of plastics waste management and the separation process as a community can be done to increase the positive attitude towards the source separation of plastics waste. In addition, staff awareness about the plastics types is also important in the waste collection and separation section in municipal councils. Award systems can also be implemented to motivate the workers who have the correct knowledge about the plastics separation process.

On the other hand, the established policies should be maintained in a proper legal framework. People and manufacturing companies both should be able to act beneath the policies when it comes to disposing of plastics waste and manufacturing plastics products, respectively. Political leadership and the ministries that are responsible for waste management should stop the blaming game and properly handle and sustain the waste management plans.

Conclusion and Recommendations

Plastics waste management is a challenging problem in Sri Lanka as a developing country.

However, this can be done by establishing a proper plan, policies, and engagement of citizens. The conceptual model suggests the post-separation of plastics waste in a waste park that was established in the smaller administrative boundary of the country as Pradeshiya Sabha. For that, a combination of plastics waste separation techniques can be used. At the same time, source separation of plastics waste according to the plastics-type must be encouraged at the domestic level. Then the source-separated plastics waste was handed over to the waste parks near the area. These waste parks can be used as intermediate sorted plastics waste distribution points for further processes such as recycling, pyrolysis, and incineration. Legal framework and public awareness are recommended as an essential part of this process.

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References

Agarwal, S. (2020), Biodegradable polymers: Present opportunities and challenges in providing a microplastic-free environment, *Macromolecular Chemistry and Physics* **221**(6), 2000017.

Al-Salem, S., Lettieri, P. and Baeyens, J. (2009), Recycling and recovery routes of plastic solid waste (PSW): A review, *Waste Management* **29**(10), 2625–2643.

Alaerts, L., Augustinus, M. and Van Acker, K. (2018), Impact of bio-based plastics on current recycling of plastics, *Sustainability* **10**(5), 1487.

Alahakoon, Y. and Karunarathna, A. (2020), Modelling of post-consumer plastic flow in municipal solid waste stream: A case study in few major local authorities of Sri Lanka, *in* 'Urban Mining and Sustainable Waste Management', pp. 219–230.

Alam, O., Yang, L. and Yanchun, X. (2019), Determination of the selected heavy metal and metalloid contents in various types of plastic bags, *Journal of Environmental Health Science and Engineering* **17**(1), 161–170.

Aljaradin, M. and Persson, K. (2012), Environmental impact of municipal solid waste landfills in semi-arid climates - Case study – Jordan, *The Open Waste Management Journal* **5**(1).

Arachchige, U. S. P. R., Peiris, H., Heshanka, S., Udakumbura, M. and Nishantha, P. (2019), Proposed model for solid waste management in Sri Lanka, *International Journal of Scientific & Technology Research* **8**(12).

Araujo-Andrade, C., Bugnicourt, E., Philippet, L., Rodriguez-Turienzo, L., Nettleton, D., Hoffmann, L. and Schlummer, M. (2021), Review on the photonic techniques suitable for automatic monitoring of the composition of multi-materials wastes in view of their posterior recycling, *Waste Management & Research: The Journal for a Sustainable Circular Economy* **39**(5), 631–651.

Ayomoh, M., Oke, S., Adedeji, W. and Charles-Owaba, O. (2008), An approach to tackling the environmental and health impacts of municipal solid waste disposal in developing countries, *Journal of Environmental Management* **88**(1), 108–114.

Basnayake, B. F. A., Ariyawansha, R. T. K. and Karunarathna, A. K. (2020), Compendium of principles applied and technologies developed for managing municipal solid wastes in Sri Lanka, *in* R. P. De Silva, G. Pushpakumara, P. Prasada and J. Weerahewa, eds, 'Agricultural Research for Sustainable Food Systems in Sri Lanka: Volume 2: A Pursuit for Advancements', Springer, Singapore, pp. 475–507.

Bauer, M., Lehner, M., Schwabl, D., Flachberger, H., Kranzinger, L., Pomberger, R. and Hofer, W. (2018), Sink–float density separation of post-consumer plastics for feedstock recycling, *Journal of Material Cycles and Waste Management* **20**(3), 1781–1791.

Bhattacharya, R. R. N. S., Chandrasekhar, K., Roy, P. and Khan, A. (2018), Challenges and opportunities: plastic waste management in India, *South Asian Born-Digital NGO Reports Collection Project* .

Brouwer, M. T., Thoden Van Velzen, E. U., Augustinus, A., Soethoudt, H., De Meester, S. and Ragaert, K. (2018), Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy, *Waste Management* **71**, 62–85.

Bryant, S. T., Straker, K. and Wrigley, C. (2018), The typologies of power: Energy utility business models in an increasingly renewable sector, *Journal of Cleaner Production* **195**, 1032–1046.

Chanda, M. (2018), *Plastics Technology Handbook*, 5 edn, CRC Press, New York.

Chen, H. L., Nath, T. K., Chong, S., Foo, V., Gibbins, C. and Lechner, A. M. (2021), 'The plastic waste problem in Malaysia: management, recycling and disposal of local and global plastic waste'.

Chen, W.-Q., Ciacci, L., Sun, N.-N. and Yoshioka, T. (2020), Sustainable cycles and management of plastics: A brief review of RCR publications in 2019 and early 2020, *Resources, Conservation and Recycling* **159**, 104822.

Cole, M., Lindeque, P., Halsband, C. and Galloway, T. S. (2011), Microplastics as contaminants in the marine environment: A review, *Marine Pollution Bulletin* **62**(12), 2588–2597.

Conlon, K. (2021), A social systems approach to sustainable waste management: leverage points for plastic reduction in Colombo, Sri Lanka, *International Journal of Sustainable Development & World Ecology* **28**(6), 562–580.

Dijkstra, H., Van Beukering, P. and Brouwer, R. (2020), Business models and sustainable plastic management: A systematic review of the literature, *Journal of Cleaner Production* **258**, 120967.

Dodbiba, G., Shibayama, A., Miyazaki, T. and Fujita, T. (2002), Electrostatic separation of the shredded plastic mixtures using a tribo-cyclone, *Physical Separation in Science and Engineering* **11**(1-2), 63–92.

Ebnesajjad, S. (2013), Handbook of biopolymers and biodegradable plastics: properties, processing and applications.

Faraca, G. and Astrup, T. (2019), Plastic waste from recycling centres: Characterisation and evaluation of plastic recyclability, *Waste Management* **95**, 388–398.

Fernando, R. L. S. (2019), Solid waste management of local governments in the Western Province of Sri Lanka: An implementation analysis, *Waste Management* **84**, 194–203.

Gallo, F., Fossi, C., Weber, R., Santillo, D., Sousa, J., Ingram, I., Nadal, A. and Romano, D. (2018), Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures, *Environmental Sciences Europe* **30**(1), 13.

Garcia-Rubio, P. (2020), '5 Recycling Lessons From Different Countries in the World'.
URL: *https://www.bbvaopenmind.com/*

Geyer, R., Jambeck, J. R. and Law, K. L. (2017), Production, use, and fate of all plastics ever made, *Science Advances* **3**(7), e1700782.

Gioia, C., Giacobazzi, G., Vannini, M., Totaro, G., Sisti, L., Colonna, M., Marchese, P. and Celli, A. (2021), End of life of biodegradable plastics: Composting versus re/upcycling, *ChemSusChem* **14**(19), 4167–4175.

Gundupalli, S. P., Hait, S. and Thakur, A. (2017), A review on automated sorting of source-separated municipal solid waste for recycling, *Waste Management* **60**, 56–74.

Hahladakis, J. N. and Iacovidou, E. (2019), An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste (PCPW): Focus on recycling, *Journal of Hazardous Materials* **380**, 120887.

Hansen, T. L., Jansen, J. L. C., Davidsson, and Christensen, T. H. (2007), Effects of pre-treatment technologies on quantity and quality of source-sorted municipal organic waste for biogas recovery, *Waste Management* **27**(3), 398–405.

Hopewell, J., Dvorak, R. and Kosior, E. (2009), Plastics recycling: challenges and opportunities, *Philosophical Transactions of the Royal Society B: Biological Sciences* **364**(1526), 2115–2126.

Hossain, S., Rahman, M. A., Ahmed Chowdhury, M. and Kumar Mohonta, S. (2020), Plastic pollution in Bangladesh: A review on current status emphasizing the impacts on environment and public health, *Environmental Engineering Research* **26**(6), 200535–0.

Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J. and De Meester, S. (2017), Performance indicators for a circular economy: A case study on post-industrial plastic waste, *Resources, Conservation and Recycling* **120**, 46–54.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R. and Law, K. L. (2015), Plastic waste inputs from land into the ocean, *Science* **347**(6223), 768–771.

Jank, A., Müller, W., Schneider, I., Gerke, F. and Bockreis, A. (2015), Waste separation press (wsp): A mechanical pretreatment option for organic waste from source separation, *Waste Management* **39**, 71–77.

JICA (2016), Data collection survey on solid waste management in Democratic Socialist Republic of Sri Lanka, Technical report, Japan International Cooperation Agency (JICA).

Jung, M. R., Horgen, F. D., Orski, S. V., Rodriguez C., V., Beers, K. L., Balazs, G. H., Jones, T. T., Work, T. M., Brignac, K. C., Royer, S.-J., Hyrenbach, K. D., Jensen, B. A. and Lynch, J. M. (2018), Validation of ATR FT-IR to identify polymers of plastic marine debris, including those ingested by marine organisms, *Marine Pollution Bulletin* **127**, 704–716.

Kaiser, K., Schmid, M. and Schlummer, M. (2017), Recycling of polymer-based multilayer packaging: A review, *Recycling* **3**(1), 1.

Karunarathna, A., Rajapaksha, T., Gamagedara, Y., Kadera, S. and Vidanage, N. (2020), Towards sustainable operation and management of centralized composting in Sri Lanka, Technical report, The Institute for Global Environmental Strategies.

Knappich, F., Hartl, F., Schlummer, M. and Mäurer, A. (2017), Complete recycling of composite material comprising polybutylene terephthalate and copper, *Recycling* **2**(2), 9.

Li, J., Wu, G. and Xu, Z. (2015), Tribo-charging properties of waste plastic granules in process of tribo-electrostatic separation, *Waste Management* **35**, 36–41.

Maheshi, D., Steven, V. P. and Karel, V. A. (2015), Environmental and economic assessment of ‘open waste dump’ mining in Sri Lanka, *Resources, Conservation and Recycling* **102**, 67–79.

Masud, M. H., Akram, W., Ahmed, A., Ananno, A. A., Mourshed, M., Hasan, M. and Joardder, M. U. H. (2019), Towards the effective E-waste management in Bangladesh: a review, *Environmental Science and Pollution Research* **26**(2), 1250–1276.

Miandad, R., Barakat, M., Aburiazaiza, A. S., Rehan, M. and Nizami, A. (2016), Catalytic pyrolysis of plastic waste: A review, *Process Safety and Environmental Protection* **102**, 822–838.

Milios, L., Esmailzadeh Davani, A. and Yu, Y. (2018), Sustainability impact assessment of increased plastic recycling and future pathways of plastic waste management in Sweden, *Recycling* **3**(3), 33.

MoE (2021), National action plan on plastics waste management 2021-2030, Technical report, Ministry of Environment, Colombo.

Okunola, Alabi, Kehinde I, O., Oluwaseun, A. and Olufiropo E, A. (2019), Public and environmental health effects of plastic wastes disposal: A Review, *Journal of Toxicology and Risk Assessment* **5**(2).

Onen Cinar, S., Chong, Z. K., Kucuker, M. A., Wieczorek, N., Cengiz, U. and Kuchta, K. (2020), Bioplastic production from microalgae: A review, *International Journal of Environmental Research and Public Health* **17**(11), 3842.

Pongstabodee, S., Kunachitpimol, N. and Damronglerd, S. (2008), Combination of three-stage sink–float method and selective flotation technique for separation of mixed post-consumer plastic waste, *Waste Management* **28**(3), 475–483.

Rafey, A. and Siddiqui, F. Z. (2023), A review of plastic waste management in India – challenges and opportunities, *International Journal of Environmental Analytical Chemistry* **103**(16), 3971–3987.

Ragaert, K., Huysveld, S., Vyncke, G., Hubo, S., Veelaert, L., Dewulf, J. and Du Bois, E. (2020), Design from recycling: A complex mixed plastic waste case study, *Resources, Conservation and Recycling* **155**, 104646.

Ruj, B., Pandey, V., Jash, P. and Srivastava, V. (2015), Sorting of plastic waste for effective recycling, *International Journal of Applied Science and Engineering Research* **4**, 564–571.

Rujnić-Sokele, M. and Pilipović, A. (2017), Challenges and opportunities of biodegradable plastics: A mini review, *Waste Management & Research: The Journal for a Sustainable Circular Economy* **35**(2), 132–140.

Sabour, M. R., Alam, E. and Hatami, A. M. (2020), Global trends and status in landfilling research: a systematic analysis, *Journal of Material Cycles and Waste Management* **22**(3), 711–723.

Samarasinghe, K., Pawan Kumar, S. and Visvanathan, C. (2021), Evaluation of circular economy potential of plastic waste in Sri Lanka, *Environmental Quality Management* **31**(1), 99–107.

Serranti, S. and Bonifazi, G. (2019), Techniques for separation of plastic wastes, *Use of Recycled Plastics in Eco-efficient Concrete* .

Shantha, A. (2019), Cost benefit analysis for the national post consumer plastic waste management project, Technical report, Central Environment Authority.

Shapiro, M. and Galperin, V. (2005), Air classification of solid particles: a review, *Chemical Engineering and Processing: Process Intensification* **44**(2), 279–285.

Sharuddin, S. D. A., Abnisa, F., Daud, W. M. A. W. and Aroua, M. K. (2018), Pyrolysis of plastic waste for liquid fuel production as prospective energy resource, *IOP Conference Series: Materials Science and Engineering* **334**, 012001.

Sidjabat, F. M. and Ilmi, A. (2020), Kamikatsu japan's ecovillage conceptual framework for environmental management (case study: Lake Ciburuy, West Java, Indonesia), *Journal of Physics: Conference Series* **1625**(1), 012063.

Streit-Bianchi, M., Cimadevila, M. and Trettnak, W., eds (2020), *Mare Plasticum - The Plastic Sea: Combatting Plastic Pollution Through Science and Art*, Springer International Publishing, Cham.

Sukholthaman, P. and Sharp, A. (2016), A system dynamics model to evaluate effects of source separation of municipal solid waste management: A case of Bangkok, Thailand, *Waste Management* **52**, 50–61.

Sutar, A. and Salunkhe, H. (2015), Waste plastic separation - a comparative feasible study - IJIRCT, *International Journal of Innovative Research and Creative Technology* **1**(3), 320–322.

Talsness, C. E., Andrade, A. J. M., Kuriyama, S. N., Taylor, J. A. and Vom Saal, F. S. (2009), Components of plastic: experimental studies in animals and relevance for human health, *Philosophical Transactions of the Royal Society B: Biological Sciences* **364**(1526), 2079–2096.

Verma, R., Vinoda, K., Papireddy, M. and Gowda, A. (2016), Toxic pollutants from plastic waste- A review, *Procedia Environmental Sciences* **35**, 701–708.

Wu, G., Li, J. and Xu, Z. (2013), Triboelectrostatic separation for granular plastic waste recycling: A review, *Waste Management* **33**(3), 585–597.

Yuan, H., Fu, S., Tan, W., He, J. and Wu, K. (2015), Study on the hydrocyclonic separation of waste plastics with different density, *Waste Management* **45**, 108–111.