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Types of Automated Recycling Machines for Plastic Waste Management in Promoting Sustainability: a Short Review

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The growing problem of plastic trash has spurred research into creative ways to reduce environmental damage and promote sustainability. Plastic is not only derived from non-renewable resources, but it also doesn't biodegrade in most cases. The most widely recycled plastics are polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), and polypropylene (PP). This study emphasises the need for automated recycling technology in sustainably managing plastic waste. Different plastic recycling machines serve a variety of functions and processes thus this review aims for four types of machines which are shredders, granulators, extruders, and compression to be studied. Shredders shred large plastic objects into smaller parts, granulators grind plastic waste into pellets or granules, extruders shape melted plastic into continuous forms, and compression moulding machines create solid plastic goods from heated and compressed plastic. Depending on the form of plastic and the recycling method employed, recycling waste plastic may offer a variety of viable goods and promote the circular economy concept. The study also examines the challenges of implementing this technology, such as investment costs, machine performance, energy efficiency, material properties, technological limitations, and infrastructural requirements. It is clear from a comparison of these four recycling machine types that shredders and granulators have a lot to offer in terms of lower greenhouse gas emissions and energy efficiency. However, in order to produce high-quality recycled products, extruders and compression moulding equipment are essential. Thus, an integrated strategy that capitalises on each machine type's advantages can improve plastic waste recycling's overall efficacy and support both environmental sustainability and financial viability. By leveraging technological advancements, these machines have the capacity to alleviate the global plastic pollution problem and bring civilisation closer to a more sustainable future.

1. Introduction

The third most common type of waste produced worldwide is plastic, and the amount of plastic waste produced overall rises in tandem with increases in the world's population and per capita consumption. The nation's waste management system faces several significant issues as a result of these factors (Chen et al., 2021). To lessen waste management and pollution problems, there is an increasing need for affordable, environmentally friendly materials. "Sustainable consumption" was defined as "consumption that meets basic needs while minimizing the use of natural resources, toxic materials, waste emissions, and environmental pollutants throughout the product or service's life cycle," while also "bringing a higher quality of life and greater use of services (Moshood et al., 2022). A significant amount of plastic manufactured annually is used to create packaging that is thrown away after a year of usage or other short-lived goods such as plastic packaging. Although plastics have been recycled since the 1970s, the amount recycled varies depending on the type and application of plastic and the location. Over the past few decades, the recycling of packaging materials has rapidly expanded in some

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countries. Before recycling, plastic waste is usually sorted through a sequence of separation steps because it can't be mixed together to be recycled (Hopewell, 2009). A tiny symbol of three arrows creating a triangle with a number in the centre is embossed on a lot of plastic containers and it indicates the type of resin from which it is made (Latkin, 2022). From Table 1, the recycling code number 1 is the most commonly recycled plastics which are water bottles from polyethylene Terephthalate (PET). While for recycling number two, is High Density Polyethylene (HDPE) which is commonly used for milk cartons and shampoo bottles, and number 5 which is Polypropylene (PP) is commonly used for margarine tubs and ready-meal trays. This green number code is the common recycled thermoplastic because it has easily been processed, contains minor amounts of foreign materials, reheated and remould again. Approximately 12 % of used plastic gets recycled worldwide. While a greater portion 25 % is burned, the majority with roughly 60 % ends up as litter on land, in rivers and oceans, in landfills, and poorly managed dumps (Lange, 2021). Polystyrene (PS) Low-density polyethylene (LDPE) and Polystyrene (PS) are not common plastics to be recycled. Even though Low-density polyethylene (LDPE) depicts the highest waste producers, the processable is difficult, as other plastics such as PVC and Polystyrene (PS) are uncommon plastic to be recycled (Wong et al., 2022).

Table 1: Cycling code and estimations of plastic waste generation in Malaysia in 2016 (Wong et al., 2022)

Plastic name	PET	HDPE	PVC	LDPE	PP	PS	Other
Cycling code	01	02	03	04	05	06	07
Waste mass (t)	188,366	293,485	32,721	323,370	112,645	113,245	6,231

It is essential to decrease plastic production and consumption while simultaneously increasing recycling to lessen plastic pollution. Recycling offers ways to cut down on the amount of oil used, carbon dioxide emissions, and waste that needs to be disposed of. Compared to traditional methods, automated recycling operations can cut energy intensity by 25 % and carbon footprints by up to 30 %/t of recycled plastic (Hopewell, 2009). The expense of various chemical recycling processes is a drawback in comparison to mechanical recycling. When direct mechanical crush methods are utilised for recovery, physical methods do not alter the chemical structures and properties of the plastics (Karmakar, 2022). Recycling for consumers can be challenging because state and country recycling policies vary greatly, thus a multipronged strategy that targets consumer knowledge of recycling methods and recyclable materials is necessary (Latkin et al., 2022). Many thorough evaluations that summarize the latest developments in plastic recycling have been carried out. However, reviewing the chemical recycling for the three main polymers PET, PE, and PP was the focus of many researchers (Fan et al., 2022). This research aims to assess the sustainability and efficiency of different automated recycling methods for plastic waste management, including shredders, granulators, extruders, and compression moulding machines by discussing the process or concept of recycling, its environmental impact, and performance. The review is based on literature review and priority was given to recent studies published within the last decade.

2. Recycling machine

2.1 Shredder machine

A "shredder" is a machine that is capable of breaking plastics into small pieces of various sizes before another machine can transform them into useful items. The shredder machine that is currently on the market has a somewhat similar concept design and it can be referred to in Figure 1 below. It was discovered that the axle shaft and the blades, which are essential components of the shredding machines, directly impact the shredding performance. Two-shaft shredders are helpful because of their large capacity. Both the high purchase price and the hefty maintenance costs are undesirable (Buckshumiyan, 2023). The geometry and orientation of the blades that were fitted into the single or double shafts and how successfully it does that task relies on its shear and impact strength were found to determine its yields. There have been numerous documented designs for small to medium-sized machines (Wong et al., 2022). Suliman and Johar (2022) successfully developed a shredding machine for plastic recycling with approximately 20 kg/d of production. The six essential components of the shredding machine used in this study to recycle plastic are the motor, worm gearbox, shredder box, hopper, sieve, and structure. The component that directed the waste plastic into the shredder box is called the hopper and the shredding operation was carried out in the shredder box. The rotation required to rotate the blade shaft is provided by the motor with an output torque of 300 Nm. The time taken off the plastic shredder to shred plastic waste was recorded to determine the efficiency of the plastic shredder. From the result, within 737.3 s of shredding time, 2.5 kg of waste PET was used and the output weight of the shredded plastic was 2.31 kg. After calculation, the shredding rate is 0.0034 kg/s and the shredding efficiency is 0.92. Raji et al. (2020) developed a shredder machine with a new blade design to accommodate an average of 50 kg of waste plastic for processing. This machine was observed only suitable for domestic plastics of smaller units. The blades do not have a specific number of edges; instead, each blade is equipped with PV-form teeth. These blades were installed on a double shaft capable of rotating in either direction, and the efficiency has been further reduced due to the increase in shaft rotation speed. The machine was observed to have low efficiency for the LDPE. This may be due to the poor flexural strength and flexural modulus of the LDPE. The machine performance for HDPE, PVC and PET is satisfactorily above 90 % meanwhile for LDPE is only 60 %. This may be considered fairly efficient for a medium-scale production process of the shredding machine.

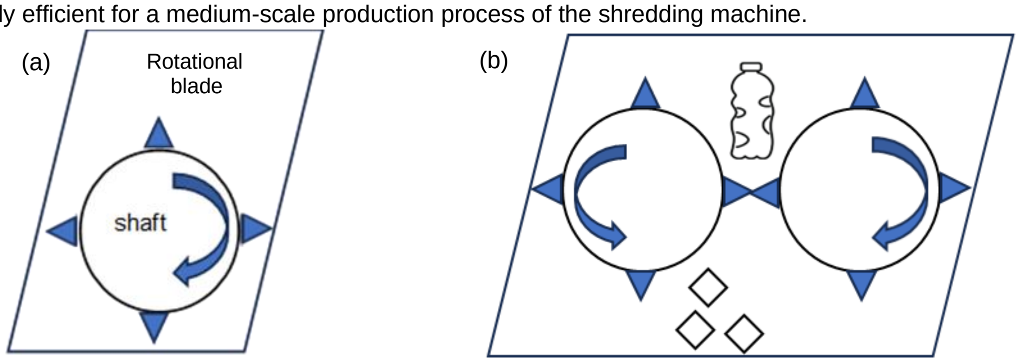

Figure 1: Diagram for (a) single shaft shredder and (b) two shaft shredders

Buckshumiyan et al. (2023) focused their study on developing a shredding machine for recycling plastic machines for HDPE, PVC, PET, and PP. The study revealed that shredding plastic at three different motor speeds resulted in an average particle size of 5.07 mm² and a success rate of 53.6 %. Its best performance occurred when shredding PVC at a machine speed of 1806.7 rpm In 3 minutes, the machine can shred the bottle, and 95 % of the content is reusable. The machine had a low specific mechanical energy of 392 kJ/kg, and it could handle a maximum load of 19 kg/h. The shredder performed admirably, shredding 52.8 % of the PVC in 2 minutes at a machine speed of 1290.5 rpm and producing particles with an average size of 6.29 mm^2. The average particle size of PET is 12.23 mm^2, however, HDPE is shredded 48 % of the time and typically results in an average particle size of 13 mm^2. At a speed of 1003.7 rpm, 53.3 % of the PVC material was shredded into pieces with an average size of 7.51 mm^2 and it was completed in 2 min. At this speed, the machine's specific mechanical energy for PVC was 1 % lower than at 1806.7 rpm. At a throughput of 31.67 kg/hr, the machine's recovery efficiency was 95 %, 1 % higher than at a speed of 1290.5 rpm. Again, the device shredded 52.3 % of HDPE in 4 minutes, with an average particle size of 4.58 mm^2 and an 83 % recovery rate.

2.2 Extrusion machine

Extrusion is a process used for creating a product from continuous pipes and profiles to films and sheets by forcing a raw material through a die. The machine operates by using a rotating screw within a cylindrical barrel to push the material forward. As the material moves through the barrel, it undergoes mixing, heating, and shaping, depending on the specific requirements of the process. To achieve optimum performance and product quality, extrusion machines need to have precise control over temperature, pressure, screw speed, and design. There are two types of screw extruders: single screw and multiscrew. The most common reasons single screw extruders are used are their affordability, ease of use, robustness, and dependability. Twin screw extruders are more effective than single screw extruders at achieving uniform mixing of various materials, including liquids, additives, and fillers. Figure 2 depicts the basic concept of an extrusion machine. The plastic waste can be fed into an extrusion machine only after it has been converted into uniform pellets or granules. The screw's rotating action transfers the contents from the feed hopper into the feed mouth. The solid polymer is transformed into a melt and forced out of the die by the thermal heat from the barrel and the mechanical shear from the screw. The increase in pressure due to a decrease in volume causes the input material to be conveyed along the length of the rotating screw. The extrusion head has a die nozzle with the orifice shaped according to the required extrudate geometry. It requires substantial energy to melt and reshape plastics, particularly those with high melting points, resulting in higher greenhouse gas emissions (Shrivastava, 2018).

Eboh et al. (2021) focus on the fabrication of extruder machines for the production of printed material for three-dimensional (3D) printers from waste polyethylene terephthalate (PET) plastics. It describes the fabrication process, including temperature control and energy efficiency evaluation. Studies have focused on designing and constructing single screw-type extruders using band heaters and screws to melt and move PET plastics into a die to produce continuous filament. Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) are typically used as base components for 3D printers, and the research design process involves three prototypes with optimised properties. Furthermore, research has focused on upcycling recycled PET with additives for extrusion into uniform filaments with desirable thermal and mechanical properties, which are ideal for material-extrusion additive manufacturing (MEX-AM) technology. In addition, research focusing on the thermal and mechanical behaviour of recycled PET resulting from extrusion and 3D printing has been carried out to improve the conditions for processing and sustainability by repurposing PET waste in fused filament fabrication (FFF) techniques. The equipment has an energy efficiency of 75.2 % and is capable of processing approximately 1 kg of plastic in 30 min. Modifications such as reactive extrusion using chain extenders were proposed to enhance the melt flow properties of recycled PET for 3D printing. Kumar et al. (2021) researched to increase production by building a Double Screw Extrusion Machine for PET plastic waste recycling, that produced encouraging outcomes in terms of melt yield for filament applications. With the engine DC power supply set to 6 V, a ceramic heater raises the barrel chamber's temperature to between 230 and 250 °C while a motor turns the screw rod clockwise at a low speed. The PET flakes as it passes through the screw rod get heated and melted which then finally get extruded from the nozzle. A filament with dimensions between 2 and 2.5 mm is needed for the 3D printer, and the machine successfully produces a continuous filament between the specifications that is free of air bubbles and roughness.

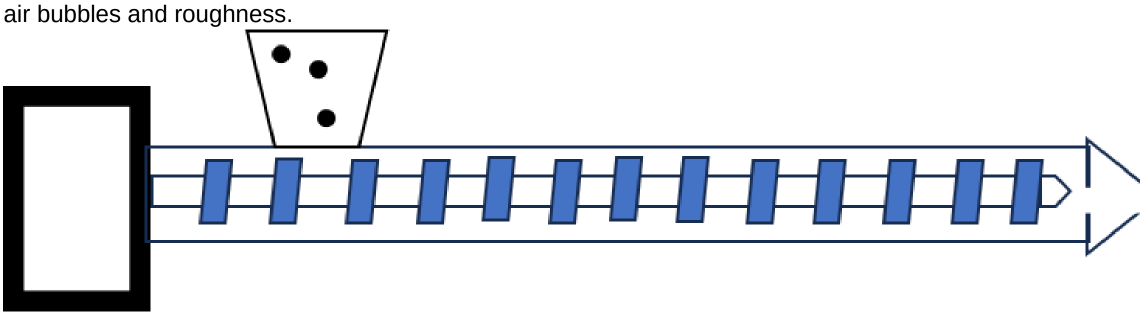

Figure 2: Diagram for a single screw type of extrusion machine

2.3 Compression machine

Compression moulding is a relatively simple process involving pressing or squeezing a deformable material charge between two halves of a heated mould. Not for the purpose of reducing the size of waste materials, compression moulding is an industrial procedure used to shape plastic into specialised goods or components. As shown in Figure 3, the inserted material is forced to take on the shape of the mould by applying heat and pressure, closing the mould with a top plug and allowing it to cool and solidify. For the plastic to become malleable and flow into the mould cavity with ease, it must be heated to its melting point or above. To guarantee complete melting without overheating, which might harm the material, the temperature must be carefully regulated and it demands exact control over temperature, pressure, feedstock quality, and mould condition (Greene et al., 2021). Waste plastic can be compressed and used in a variety of heavy industries such as for construction material. To produce bricks, tiles, and concrete, plastic waste is used as a binder, aggregate, fine aggregate, modifier, or substitute. Rosmanizan and Nor (2021) has&fabricated a plastic compressor machine to develop colourful solid paving bricks for walkways from plastic waste. One brick can be produced in 1 h by using 450 g of shredded plastic waste at 250 °C. Other authors conducted a comparison between conventional hollow concrete blocks, which measure 200 × 200 × 400 mm and are bought from the market, and concrete blocks of the same size that had plastic bottles implanted in them. After 28 d, the average weight of the conventional hollow blocks was 20.08 kg, and their compressive strength was 6.38 MPa. In contrast, the plastic bottle block weighed 24.85 kg and had a compressive strength of 10.03 MPa. The results show that recycling plastic bottles for use in concrete block masonry not only solves the issue of finding new uses for plastic trash but also enhances the strength and weight characteristics of the brickwork (Lamba et al., 2021).
The design by Xevgenos et al. (2015) presented an innovative miniature waste compressor that was designed and developed for municipal solid waste at a household level. The design of the system was in line with the Waste Framework Directive (2008/98/EC), as it allowed for the compression of municipal solid waste, namely: plastic (PET and HDPE), paper (cardboard and Tetrapak), and metal (aluminium and tin cans). It has been determined through the use of a software tool (LS-DYNA) that the optimum compression ratio per waste stream

is greater than 3:1. This helps to reduce the energy requirements of the recycling system, with the goal of limiting it to less than 1 kWh daily. This target was successfully achieved.

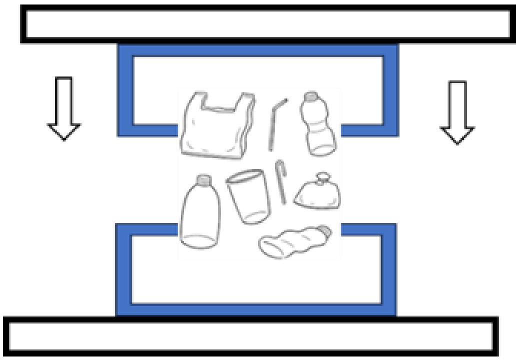

Figure 3: Diagram of compression moulding machine to squeeze recycled plastic waste into a new shape

2.4 Granulators Machine

Plastic granulating machines are industrial crushing equipment used to reduce plastic materials. It is mostly used to grind plastic into consistently sized pieces that can be recycled or converted into new plastic shapes (Imaekhai et al., 2018). Granulators, unlike shredders and even grinders, may reduce materials to 0.2 mm or smaller. These small sizes are made feasible by the open-rotor designs of granulators, which allows for the processing of lighter materials as opposed to the closed-rotor operation of shredders and grinders. The open-rotor functionality of granulators also means more air space is present facilitating product agitation and cooling (Calovini et al., 2021).

The design attributes of granulating equipment might differ, but they are all driven by the same fundamental concept. In a study by Imaekhai (2018), research was carried out to develop a more compact and economical iteration of the machine using readily available local materials. The goal was to maintain optimal performance, reduce vibration, and improve shear efficiency in order to achieve a uniform granule size. The machine consists of the hopper, the grinding chamber with the shaft and cutting blades, and a discharge unit. It is powered by a 5.5 horsepower motor, operates at 3,000 rpm, and can process 1 kg of recycled plastic per hour at 75 % efficiency. The machine operates on the principle of shearing; power is transmitted via a transmission coupler from the motor to the granulating shaft. To make the inflow plastics small enough to go past the discharge screen, they are granulated until they reach the target size.

It has been shown by numerous research teams and businesses that post-consumer waste plastic, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), HDPE, PS, PP, PET, and LDPE, may be recycled into 3D printing filaments. The study by Ravindran et al. (2019) successfully demonstrates the designs, build, and testing of an open-source waste plastic granulator for its ability to convert post-consumer waste, 3D printed products, and 3D printer waste into polymer feedstock for recyclebots of fused particle/granule printers. With components that cost less than USD 2,000, the device can be constructed from open-source blueprints. The power consumption of the device ranges from 380 to 404 watts for PET and PLA, which are the most commonly used post-consumer plastic waste and 3D printer plastic, respectively. The final particles and the distribution of particle sizes show that most of the particles are fines with total areas less than 10 mm^2 and were found to be appropriate for use in both recycle-bots and direct material extrusion 3D printers. Granulators produce fewer greenhouse emissions since this process is technically simple and does not need heating, pressure or reshaping plastic. The basic energy of recycling machines dominates the energy demand of the granulators where larger machines perform better at greater processing rates, while smaller machines are more energy-efficient at lower processing rates. This is driven by the power requirements of the drive motors (Shuaib and Mativenga, 2016).

3. Conclusion and Future Direction

In summary, even though automated recycling technology presents promising benefits for controlling plastic trash, more study and development are needed to solve current issues and improve the effectiveness, affordability, and scalability of these systems. Compression and extrusion recycling machines require substantial energy to melt and reshape plastics, particularly those with high melting points, resulting in higher greenhouse gas emissions. Addressing material compatibility, energy efficiency and infrastructural challenges will be crucial to enhance the management of plastic trash globally and facilitate environmental sustainability.

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