

Review

Small-Scale Mechanical Recycling of Solid Plastic Wastes: A Review of PET, PEs, and PP

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Abstract: Mechanical recycling of solid plastic wastes on a small-scale level can be accomplished with the correct approaches. Thermoplastics are mostly considered for mechanical recycling because of their physical properties and ease of reprocessing. This paper reviews the mechanical reprocessing techniques of selected thermoplastics (polyethylene terephthalate and polyolefins) since they constitute a significant proportion of plastics used commercially. Furthermore, necessary considerations for effective operation of small-scale plants, including energy requirements of machinery and optimisation in order to improve efficiency and product quality, are discussed. A clearer understanding and addressing of the process-related challenges will lead to successful establishment and management of small-scale mechanical recycling facilities to benefit communities. Efficient small-scale mechanical reprocessing establishments have become essential in reducing the environmental impacts of solid plastic wastes and for energy conservation.

Keywords: plastics; energy; small-scale mechanical recycling; environment; extrusion; PET; PE; PP

1. Introduction

Plastic recycling, which can be defined as the recovery, reuse, and reprocessing of waste plastics for economic and environmental reasons, has attracted attention over recent decades [1]. Plastic solid wastes have increased remarkably since the initial industrial-scale production of plastics in the 1940s, and 6–12 million tonnes of plastics are added to oceans each year [2,3]. Currently, 14 million tonnes of microplastics are on the seafloor [4]. Recycling is often emphasized as a possible solution to the pollution caused by unmanaged plastics production and disposal [5–7]. Mechanical recycling of plastic waste remains a viable approach to the environmental menace of waste plastics disposal [8].

Plastics, which are a group of organic materials that may be synthetic or semi-synthetic, can be made into various products and used for different applications due to their favourable physical properties [9]. Generally, plastics can be categorised into two forms: thermoplastics and thermosets [10,11]. Thermosets refer to those plastics that are irreversibly polymerised and set upon heating, thereby making them impossible to be remoulded [12,13]. Conversely, thermoplastics are polymers composed of linear molecular chains, and these plastics react to heating and cooling [11,14,15]. Their bond, which varies from dipole–dipole interactions, hydrogen bonding, weak van der Waals forces to aromatic rings, allows unchallenging movement among each other [16]. Since their bonds are weak, they readily soften when heated, enabling them to be moulded and remoulded repeatedly over various temperature and pressure ranges while remaining relatively stable [17,18]. These thermoplastics account for the majority of polymers utilised commercially, with polyolefins constituting 80% of all plastic applications [18]. Polyolefins are types of plastics produced from the polymerisation of olefin or alkene molecular units (monomers)

[19]. The common polyolefins are polyethylenes (PEs), polypropylene (PP)– based polymers, and olefin elastomers [20]. Nevertheless, there are current advances in copolymerising and synthesising functional polyolefins as well as non-functionalised monomers with polar monomers to improve their properties and widen their applications [21,22].

In 2014, the major thermoplastics included PE, PP, polyvinyl chloride (PVC), polystyrene (PS), and other styrenics, polyethylene terephthalate (PET or PETE) and polybutylene terephthalate (PBT) blends. In the same year, these major plastics represented approximately 76% of the total global consumption of plastics [23]. The current plastic resin identification coding system was developed in 2013 by the American Society for Testing and Materials (ASTM) to maintain a uniform coding standard for plastic manufacturing and recycling after revising the initial codes developed by the Society of the Plastics Industry (SPI) in 1988 [24]. A list of the plastics identification codes is given in Figure 1.















Resin Identification Number	Resin	Resin Identification Code - Option A	Resin Identification Code - Option B
1	Poly(ethylene terephthalate)	 PETE	 PET
2	High density polyethylene	 HDPE	 PE-HD
3	Poly(vinyl chloride)	 V	 PVC
4	Low density polypropylene	 LDPE	 PE-LD
5	Polypropylene	 PP	 PP
6	Polystyrene	 PS	 PS
7	Other resins	 OTHER	 0

Figure 1. Resin identification codes. Source [25, 26]. .

While most thermoplastics with resin identification codes 1–7 can be recycled, it would be beneficial for small-scale recyclers to focus on specific solid thermoplastic wastes with resin numbers 1 (PET), 2 (high-density PE [HDPE]), 4 (low-density PE [LDPE]), and 5 (PP), since they account for the bulk amount of materials utilised for packaging [1]. These solid thermoplastics are more durable than those with other identification codes and retain their properties despite reheating or remoulding [16]. Consequently, this project focused on the listed solid plastics (PET, HDPE, LDPE, and PP) as they are already ubiquitous and constitute an environmental challenge.[27].

This review targeted small-scale approaches to reprocessing the selected waste plastics, particularly rigid plastics, and converting them into resources. Generally, breakable plastics are referred to as rigid plastics, and include cups, pails, food containers, lids, and milk bottles [28]. These rigid plastics can also be described as self-supporting and most often have wall thicknesses > 0.25 mm; however, their rigidity and flexibility levels can vary based on the production method [29]. Small-scale recycling presents an impactful approach to recycling since, industrially, it is less expensive to source and manufacture plastics with new raw materials than to recycle [30]. Considering that plastics are mainly manufactured from fossil fuels – oil and natural gas [31], the raw materials costs decrease as oil production increases. Generally, current recycling strategies are insufficient to manage the volume of plastic wastes already in circulation, and the volume of these waste streams is projected to increase [32]. Therefore, innovative ideas and methodologies, such as small-scale mechanical recycling, are required to tackle the growing plastic waste problem.

2. Background

2.1. Scale of the Plastic Waste Problem

The unsustainable use of plastics in contemporary society has awakened the need for combating pollution problems in the environment and ecosystems [33]. Since most plastics are durable, moisture-resistant, and relatively inexpensive, the avid attraction to use and consume plastic-made goods in our daily lives cannot be ignored. However, most of these plastics accumulate as debris in landfills and rivers due to inadequate disposal systems, while some end up in oceans and beaches [34–36]. Galovic [3] estimated that 6–12 million tonnes of plastics are added to oceans each year. This will equate to 1 tonne of plastics for every 3 tonnes of fish in the ocean by the year 2025 [37]. Plastics also contribute to greenhouse gas emissions, such as carbon dioxide (CO₂), into the atmosphere due to inefficient manufacturing processes, poor lifecycle design, and unsustainable disposal systems such as incineration, with the potential for 56 GT of carbon emissions from plastic production by 2050 [38].

Moreover, many researchers have documented the reality of plastic wastes in the marine environment [39–41]. Borrelle et al. [42], as supported by Jambeck et al. [39], posited that 4.4–12.7 million tonnes of waste plastics are added to oceans every year, and Lamb et al. [43] maintained that 11.1 billion plastic items are entangled on coral reefs across the Asia–Pacific region; a figure that is predicted to increase 40% by 2025. Recycling these plastics prevents the accumulation of plastic wastes from the sources, even though the specific quantity of deposits in the ocean from terrestrial sources is unknown. However, it is known that plastics in waterways will eventually cause harm to marine organisms and may provide a habitat for pathogens to reproduce [42–48]. A large quantity of the plastics in oceans consists of microplastics (< 5 mm), which are mainly fragments broken from larger objects, as well as resin pellets and powders [49]. They are referred to as primary microplastics when they emanate from pellets of resins [50] or cleaning and cosmetic products [51]. On the other hand, they are termed secondary microplastics when they are derived from meso (5–25 mm) or macroplastics (> 25 mm) that may result from weathering on land or in water [52].

Considerable effort has been made in encouraging the reduction of plastic production and reuse; however, it has to be weighed on a scale of costs and benefits, particularly considering the implications of not having such plastics available in the food packaging industry [53]. Therefore, recycling presents an option for reducing waste [54], second only to source reduction and prevention [30].

2.2. Small-Scale Plastics Recycling

The increasing demands for utilising plastic products in packaging and the awakened environmental concerns remain the significant drivers of plastic recycling, and investment costs and profit difficulties also lead to the challenges of attracting large-scale investors [55,56]. Currently, there are no agreed data on the appropriate capacity that constitutes small-scale recycling. For instance, Beston (Henan) Machinery Company designed basic small-scale plastic recycling plants to accommodate flows of 6–20 t/d [57]. In contrast, some small-scale recyclers generate maximums of 1 t/d, reducing to 60% of that capacity considering machine breakdowns and the type of products developed [58]. For this paper, flows < 10 t/d were considered small scale.

There are many ways that plastics can be recycled and reprocessed [59,60], including primary, secondary, tertiary, and quaternary recycling [10,34], which are discussed below.

Primary recycling, also referred to as the closed-loop process, involves the mechanical recycling of plastics that are neither contaminated nor dissimilar in quality, thereby resulting in uniformity of the produced end-products [60]. This method is mainly used within the initial manufacturing of virgin plastics as recycled plastics are highly unlikely to meet such original quality standards [61].

Secondary recycling can be defined as mechanical recycling of plastics that results in the downgrading of the polymer quality, and is achieved through several processes such

as pelletising, shredding, extrusion, and remoulding [10]. Secondary and primary recycling are related since they involve recycling plastic material through mechanical means [10]. Moreover, Hopewell et al. [34] maintained that primary and secondary recycling classification could be based on context. For example, if a recovered plastic that could not be fitted into the original purpose is used to make a new product that would have otherwise consumed virgin polymers, it can be viewed as primary recycling. In contrast, for the remainder of the paper, it is referred to as secondary recycling if the recovered plastics were applied in making products that would not usually involve virgin polymers.

Tertiary recycling, also known as feedstock recycling, refers to the chemical recycling process whereby polymers are broken down into monomers, shorter oligomers, and component materials which may then be utilised in several applications [62,63]. Tertiary recycling can be considered as closing the loop since it theoretically leads to unrestricted recovery of materials for reuse [10,18]. However, this recycling method mainly involves sophisticated processes and must be conducted in controlled environments such as gasification facilities [64].

Quaternary recycling, also defined as valorisation by Hopewell et al. [34], involves the processing method of incinerating plastics to recover energy [15,60]. This method is considered a last resort when the other recycling methods are not convenient and can lead to environmental pollution and toxic gas emissions [2,65,66].

Amongst these four plastic recycling methods, secondary recycling appears to be attainable on a small-scale level, considering the benefits of simplicity and proven practicality [18,67]. The method is gaining global attention and creating revolutionary recyclers who trade in empty plastic containers at recycling centres in exchange for currency [68]. On the other hand, committed organisations such as Precious Plastic and Plastic Collective are creating networks and engaging communities to embrace and implement mechanical recycling and reprocessing of thermoplastics [69,70]. The small-scale mechanical recycling of thermoplastics focuses on PET, which is a common thermoplastic polymer resin that belongs to the polyester family of polymers, and polyolefins (HDPE, LDPE, and PP), which are formed by polymerisation of olefin monomer units, due to their ease of recycling and reprocessing [30]. Grigore [11] pointed out that PP, HDPE, and LDPE possess greater mechanical impact resistance than other thermoplastics. However, the challenge of a mechanical recycler lies in ensuring purity and minimal degradation of the polymers during the process [2,71]. As stated previously, recycling ordinarily involves large-scale infrastructure and significant cost investment. However, with the overwhelming amount of plastics in circulation and the possibility of generating income [71] and creating a circular economy through mechanical recycling [30,72], developing small-scale plastic recycling stations presents a viable opportunity. Researchers have classified plastics recycling [15,34,60,62,63], and identified mechanical recycling as the most feasible option for small-scale operations [18,67].

3. Mechanical Recycling Processes

3.1. Separation and Sorting into Polymer Resin Types – Processes

3.1.1. Introduction to polymer separation

When polymer materials arrive at a recycling station, they need to be separated into respective resin classifications for proper identification, processing, and quality control. It is also necessary to separate the different plastic types to achieve adequate purity, as it is vital to obtain high purities of > 99% for recycling [73]. Therefore, resin categorisation remains a critical sorting approach for the plastic recycling industry [74]. Solid plastic wastes can be separated in various ways including: manual sorting, the application of machines (automatic sorting), or a combination of both, with each method presenting peculiar considerations and trade-offs [75]. A sketch of the plastic resin separation and sorting process is provided in below Figure 2.

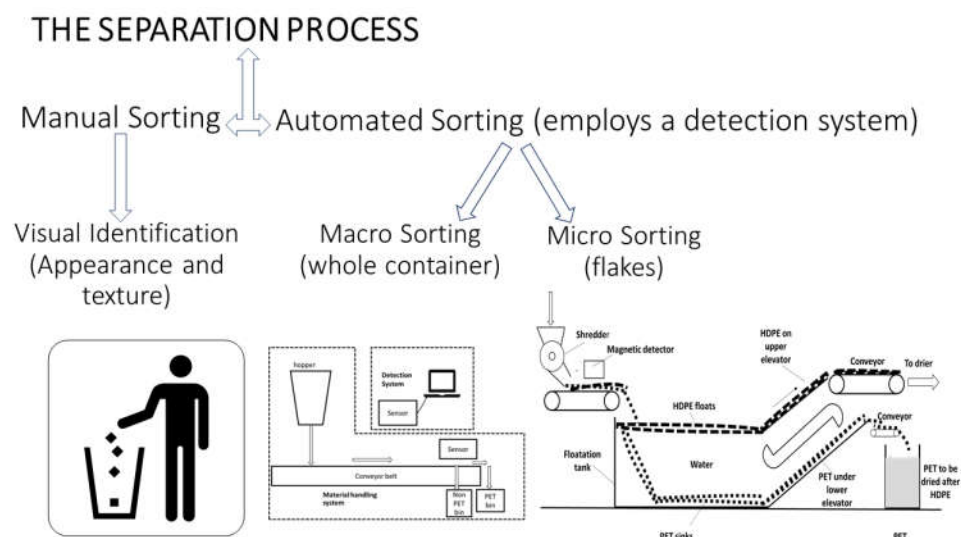


Figure 2. Plastic resin separation/sorting process. Adapted from [74,76]. PET - polyethylene terephthalate, HDPE – high-density polyethylene.

The manual sorting approach involves identifying and separating specific resins based on appearance and texture, as indicated in Figure 2. On the other hand, the automated sorting system requires a detection system for both macro and micro-sorting. For the macro-sorting shown in Figure 2, whole containers pass through the hopper and are transported by the conveyor belt to the bin, where they are separated into respective resins through sensor systems. Micro-sorting requires a flotation system in addition to the detection system for the resin separation, as shown in Figure 2 above. These processes are further detailed below.

3.1.2. Automated sorting

Automated sorting can be classified into direct sorting, which uses material properties to separate polymers into various designations, and indirect sorting, which employs a detection system that automatically sorts inputs into designated units [77]. However, such systems are usually combined with municipally generated solid wastes that comprise numerous other materials [78], which may not be comparable with the kind of plastic waste produced for a small-scale recycling project. Plastics arriving at the recycling station are expected to conform to the level of separation determined by the supplier. However, reliability of such separations may not be trusted as they may not have been conducted by professionally trained individuals.

The plastics sorting method can depend on the type of materials available [10]. The type of technology usually applied in automated plastics sorting involves spectroscopy and X-ray [79,80]. Briefly, the equipment that utilises spectroscopy radiates a light that is reflected by the different plastics with a distinctive wavelength, wherein a sensor reads and interprets those wavelengths to the processing unit for separation into various categories or separation bins, while the x-ray technology is utilised in analysing plastics at the rudimentary scale thereby enabling operators to be able to detect specific constituents like chloride in PVC and some bromide additives [81]. However, the complexity of plastic products, including different colours (such as black, with reduced reflection) and materials bearing other resin parts, make spectroscopy (especially near-Infrared [NIR] technology) ineffective [82].

Furthermore, the automated sorting process may be categorised based on sizing. Sizing can be graded into macro-sorting (i.e., separation of whole containers) or micro-sorting (i.e., separation of shredded plastic flakes) [28,72]. Wahab et al. [74] designed a system for macro-sorting PETE, which worked on an intelligent detection system comparable to an NIR system that separates plastics into PETE and non-PETE units (shown in Figure 2).

In the design, the plastics move via a hopper connected to a conveyor belt, which is linked with an ejector with sensors that detect PETE and actuate plastic flows into the separate PETE and non-PETE bins that are attached. These sensors also transmit signals to a computer for monitoring purposes.

The micro-sorting system from Pringle and Baker [76] (also shown in Figure 2) works on an advanced detection whereby shredded plastics are linked to a floatation system of water and conveyors wherein the PETE flows through a lower elevator into a separate bin, and the less dense plastic resins flow through the upper elevator to continue through the separation process. However, both macro and micro systems have limitations. For instance, in the macro-sorting system, the final classification of plastic resins accuracy was approximately 95%, which is still not perfect for PETE recycling and is inferior to the float-sink method of micro-sorting, which has 98% accuracy [83]. The micro-sorting system is also accompanied with water management challenges since water is utilised, and the fate of the water and water quality must be considered. Furthermore, the flakes need to be dried before further processing since the shredded resins become wet during the float process.

Another drawback of the automated sorting system regarding spectroscopy is the inability of the system to recognise additives such as bromine [81]. Finally, while the automated system of separating plastics remains an explorable option in recycling, small-scale enterprises may be limited by its high-cost requirements. Hence, there is a need to invent and devise a reliable, accurate, and cost-effective automated or semi-automated method of sorting plastics on a small-scale level.

3.1.3. Manual Sorting

The manual sorting system of plastic separation requires trained operators to visually identify and separate plastics based on resin classifications. Personnel expertise plays a significant role in assessing the process [84]. However, manual sorting remains a part of most recycling facilities, even though automatic processing could be conducted in future [34]. This is important considering the complexity of waste plastics. For instance, bumpers bars are predominantly composed of PP in Europe, with inlays of metals such as iron and aluminium, PVC, sheet moulding compounds or PE, and paint, which should be manually removed to prevent contamination and incompatibility [79]. Therefore, the types of plastic waste streams can also affect the necessary sorting technique. In addition, the manual sorting system may not be favourable for large-scale plastic recycling operations given the increased labour costs involved [85].

Generally, the simplicity of the manual sorting process makes it an attractive approach for consideration [86]. It can result in improved separation precision compared to the automatic system; nevertheless, that may come with the disadvantage of reduced throughput volume [87]. The Clean Washington Center [88] argued that the best practices for manual sorting of plastics, such as in PETE recycling, lie in the ability of the operator to identify and separate containers from a stream of mixed plastics. Simple methods are established for physically identifying plastics [89]. The Welding Institute [90] listed distinguishing physical properties of targeted hard plastics such as translucency or opacity, feel, texture, and the ability to bend, scratch, crumble, flake, or cut easily. Although most plastic products are currently denoted with their resin classification numbers, it remains still crucial to create a standardised and optimised manual sorting system for small-scale industries, considering that some recycling facilities may be based in remote communities. Since identifying the various resin categories in a mix of plastics is complex as additives to the polymers can alter the complexity, it may also be necessary to combine various forms of manual separation [76].

Another manually applied sorting technique of separating plastics is conducting a float test using water at room temperature (298 K) [90,91]. When using water as a working fluid at a density of 1.0 g/mL and testing against densities of PETE (1.38–1.39 g/mL), HDPE (0.95–0.97 g/mL), LDPE (0.92–0.94 g/mL), and PP (0.90–0.91 g/mL), it is observable that

PETE will sink whereas other plastic types will float [92]. That means that PETE will be easily separated, and the challenge will lie in correctly identifying the other polymers.

In carrying out manual sorting of plastics, finding a balance in the suitable options is essential as the manual system of sorting polymers is widely engaged in various material recovery facilities due to the low technology involved [93]. Moreover, in making products through small-scale recycling facilities, creating an organised methodology for the manual sorting of plastics can be helpful. Since small-scale mechanical recycling should aim to minimise energy consumption and costs in creating a circular economy, making an economic decision for a manual sorting system is essential. However, there is no generalised tool to develop and standardise the manual sorting method.

3.2. Decontamination/Cleaning

Plastics selected for recycling will have to suit acceptable purity levels for the recycling process to proceed. Decontamination remains crucial in recycling plastics, as most plastics, particularly polyolefins (PEs and PP), are utilised for many food packaging applications [94]. Some establishments have developed specific cleaning procedures for recycled plastics, including washing and decontaminating PETE flakes using water [95]. It was shown that the density of PETE in water presented a valuable good cleaning advantage compared to polyolefins [95]. However, in another project on the PETE washing process, Krehula et al. [96] demonstrated that washing PETE bottles in sodium hydroxide (NaOH) at 75 °C for approximately 15 min provided improved purity compared to washing in water alone, and with minimal polymer degradation.

In general, plastic containers used for toxic materials such as pesticides are not accepted as inputs in material recycling [97]. Picuno et al. [98] maintained that agrochemical containers could be recycled after undergoing a triple rinsing process and further washing using extraction solutions such as methanol and acetone. Hossain and Mozumder [99] posit that washing PETE flakes with 3.0% NaOH and 0.5% detergent at 90 °C produced acceptably clean input. Nevertheless, Welle [100] proved that the purity of post-consumer PETE could be advanced to up to 99.9% in the Flake To Resin (FTR®) concept, which investigated artificially contaminated flakes with model contaminants. However, oligomers typically used for the polymerisation of virgin PET were added to the remolten polymers during extrusion in that process, and these additives may have contributed further to the improved quality.

The method of Kronos (Thailand) Co. Ltd. [95] appears to be more sustainable for the procedures described above since it uses water as its washing liquid; however, the process involves passing flakes through several processes such as pre-treatment, caustic washing, and hot post-washing. Hence, this may require a sizable cost investment in machinery, procurement, storage, and material handling. The other methods mentioned above involved chemical usage in their cleaning process, which, in turn, creates an additional challenge in handling chemical waste disposal and environmental pollution.

Similarly, some researchers have also observed that the cleanliness of PEs increased with the addition of NaOH [101,102]. Groh [94], as supported by Palkopoulou et al. [103], maintained that due to the non-identical physical properties of PET and polyolefins, such as decreased thermal stability of the latter, polyolefins exhibit lesser absorption resistance to pollutants within their polymeric material and require decontamination at an elevated scale. Comparatively, in work carried out on PP decontamination during extrusion, the level of decontamination changed with varying extrusion methods, time, temperature, and simulants [104]. There is no standardised cleaning system for PEs, PPs, and PETEs for recycling. As previously stated micro-sorting of plastics achieved an accuracy of approximately 98% [83,105]; however, inputs to plastic recycling need to have purity > 99% [73]. Even though the current technologies for the decontamination and cleaning of PETEs are also used for polyolefins, Palkopoulou et al. [103] argued that the appropriate system should consider the characterisation of the input materials, its critical parameters such as temperature, pressure, and residence time in the process, as well as a possible control test

for polyolefins. This literature review on the current cleaning and decontamination techniques of PETE and polyolefins showed that the process continues to be developed, and that certainty remains a challenge in the absence of a standardised approach for small-scale systems.

3.3. Shredding and Size Determination

Guidance on the appropriate size dimensions of a polymer shred is dependent on equipment capabilities [106]. However, El-Haggar [107] insisted that keeping plastic shred proportions smaller leads to more structuring of shapes, particularly for pelletising, which engenders broader and soaring requests for plastic shreds. In support of the notion of shredding to achieve much smaller sizes, Cruz-Estrada et al. [108], in their study of wood-plastic composites as building materials, used a screen plate with 4 mm in diameter holes to create HDPE working materials after granulating. Similarly, Khait [109] posited that the products size should vary from flakes (2–3 mm), fluff (1–2 mm), to various particle size powders that can comprise ultrafine powders < 200 μm . These powdered materials are advantageous in plastics processing because they can be blended easily with other materials and additives if required and can be used for different applications, such as powder coating, rotational moulding, and compounding [109]. Nevertheless, generated pellets of varying grades of plastics may also be utilised to produce various products [110], as they can be sold to other companies to be used as feedstock [111].

On the other hand, Maisel et al. [112] maintained that waste electrical and electronic equipment shred particle sizes of 10–20 mm are optimal for improving the sorting effectiveness and recyclability of the polymers and reducing wastes due to powders. Shredded polymers can also be further reduced in size to 5–10 mm [107]. That implies that the applicable sorting method may affect determination of the shred sizes. Even though it is advisable for a small-scale project to consider manual and macro-sorting rather than micro (flake) sorting because of its simplicity and affordability, the quality implications of generating smaller-sized shreds should also be considered.

Finally, it appears that finer particle sizes and powders produce superior results in mixing and generating products with higher strength and uniformity. For instance, in work carried out using 0.85 and 2.00-mm-sized HDPE and calcium carbonate (CaCO_3) as an additive, it was found that 0.85-mm HDPE shreds provided the highest mechanical strength [113]. Hence, the certainty of the target products to be made may also influence the sizing of shreds. For example, various polymer blends can be utilised in producing different products, such as in wood-plastic composites [114]. Hanna [115] suggested a separate chamber where the material is mixed and conveyed to an extrusion chamber through a tube.

In conclusion, as the mesh or screen on the shredder influence the dimensions of shreds, it will be necessary to target shredding machinery with mesh hole sizes that fall within the desired diameters. A key point of future work is to extrude different shred sizes and monitor their physical, chemical, and mechanical properties to determine and recommend the optimum shred size.

4. Considerations for Effective Operation

4.1. Energy Demands of Machinery

From the outset, small-scale mechanical recycling should aim to create a system that is environmentally friendly, consumes minimal energy, and simple maintenance. Zheng and Suh [116] maintained that the strategic implementation of renewable energy with recycling in line with control procedures could effectively contribute to keeping carbon emissions in check such that the 2050 emission level would be similar to that of 2015. Carbon emissions from plastics that contribute to global climate change do not only come from incineration and disposal of plastics, but also arise from the plastic production pro-

cesses [39]. The University of California [117] reported that the processing lifespan of plastics, such as landfilling, incineration, recycling, and composting in some instances, cause CO₂ emissions, and that these discharges amounted to almost 1.8 billion tonnes in 2015.

An existing goal of small-scale recycling is to devise a process that would utilise less energy by reducing the carbon footprint. It is important to consider renewable energy options in powering production machinery, as recycling may consume more energy than creating virgin products due to the additional processes such as decontamination [118]. Extrusion remains at the centre of the energy consumption for the mechanical recycling option chosen, even though other auxiliary processes can be added [119]. Deng et al. [120] stated that extrusion remains one of the most critical and vital stages in the thermoplastic manufacturing process. Hence, the power requirements of an extruder are an essential aspect of analysis [121]. A comparison of the energy efficiency of extruders is displayed in Table 1.

Table 1. Comparison of energy consumption and losses during extruding.

Opinions on Energy of Extruders
1. Frankland [122] stated that extruder power requirements are equal to the output rate multiplied by the specific heat of resin, temperature rise in barrel, and heat losses of up to 35%, plus an additional 20% safety factor.
2. Plastics Institute of America [123] maintained that > 40% of the energy provided to small-scale extruders is unaccounted for and not effectively utilised via the same drive, convection, radiation, and conduction, leading to efficiency reduction.
3. Deng et al. [120] posited that extruders may incur total system energy losses of approximately 15–20% since they do not operate at optimal settings for the majority of the time.

There is no overall agreement on the energy losses associated with an extruder. These energy losses can occur in different phases of the process when electrical energy is converted to thermal or mechanical energy, with the drive system consuming the bulk of the energy supplied [124]. Hence, the values cannot be precisely measured as a whole but are linked to separate elements such as the machine parameters, the type of material being processed, as well as the operator's expertise [125].

Therefore, developing a highly efficient system and reducing energy losses in machinery, overall production processes, and lifespan is necessary to avoid the negative multiplier effect on the environment. The ImpEE Project [126] argued that energy consumption during bioplastics production is higher than that for PET and PE production. However, another point remains that even if these biologically produced plastics utilise more energy during production, the overall energy usage in the product lifespan may be favourable [127]. Overall, the challenge for small-scale recyclers lies in developing a processing and recycling facility that minimises energy dissipation and optimises output efficiency.

4.2. Comparison of Capacity and Sizes of Extruders

A general trend is that extruders with larger barrels and a higher mass flow rate or output rate require more power [124]. A search in Alibaba – the Chinese e-commerce hub [128], also supports that position. The search terms included single-screw plastic extruders with screw length-to-diameter (L/D) ratios ranging from 25:1–33:1.

An example of a single-screw extruder showing a comparison of size, capacity, and average power rating is displayed in Figure 3.

The output rate of the extruders increased variably from approximately 15% to 200%, while the barrel sizes enlarged at the rate of approximately 27% to approximately 154%. These resulted in an average power increment of 185 kW among the samples [129].

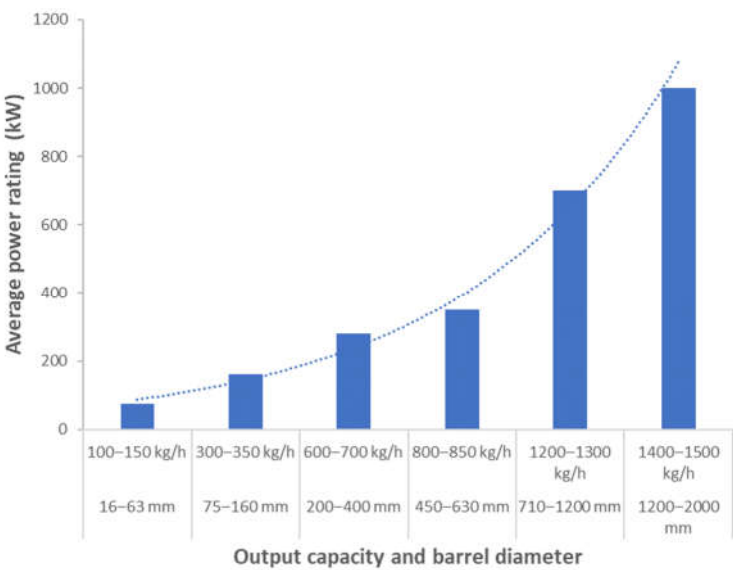


Figure 3. Comparison of single-screw extruders advertised in Alibaba in 2021. Source [129].

In considering the choice of an extruder, it is essential to appraise the cost requirements against usage. If the extruder barrel is larger than necessary, it can lead to additional heat-up time, causing additional energy losses since the barrel size is proportional to the heated area. This dissipation can result in adverse working conditions [130].

The single-screw extruders are the most popularly used in industry [131,132]. They are widely deployed for their affordability, straightforward designs, ruggedness, and reliability [133]. Nevertheless, twin or multi-screw extruders may have the following advantages: higher conveying capacity at low speed; ability to handle different materials with low motor power requirements; desirable and controlled pumping rate over a significant range of parameters; lesser heat during operation; reduced residence time in the extruder; and better mixing as well as pumping ability that is not reduced by backflow [134].

There are different types of extruders in the industry, as classified in Table 2.

Table 2. Extruder types. Source [135].

Extruder classification based on design mechanisms
1. Continuous with single-screws (single as well as multi-stage) or multi-screws (dual-screw, etc.)
2. Continuous disk/drum which utilise drag melt actions or elastic melt actions
3. Discontinuous that utilise ram and reciprocating actions

However, in choosing suitable single-screw extruders, available options should be accounted for. They include mixers such as the Maddock (Leroy) and Pin, extruder classes such as the vented extruder, and screw options such as the barrier and wave screws [136]. The various advantages and disadvantages of the available single-screw extruder options are categorised in Table 3.

It is crucial to consider the justification for these screw options when choosing the type of extruder screw. For instance, grooved-barrel screws with axial slots preceding the feed throat in the barrel that improves the feed rate of resin per turn are popular for HDPE recycling [137]. On the other hand, vented two-stage extruders are suitable for recycling of PET, polyamides, polyoxymethylene thermoplastics, etc., which absorb moisture readily from the environment as water vapour must be removed from these polymer extrudates to prevent the degradation of the final products [138]. Consequently, this may reduce the need for drying resins during the process.

Generally, an extruder functions as melting and pumping equipment, turning flakes or pellets into a uniform extrudate. Therefore, the heat created by the shear compressive actions of the screws, the heat conducted by the barrel from the heating bands and the length of the screws and barrels, are important considerations regarding the choice of extruders and materials [139].

In acknowledging the various advantages of single-screw extruders, it is also necessary to recognise their limitations. Common shortcomings such as difficulty in mixing and dispersing extremely fine particles – (i.e., mean particle size of $< 50\ \mu\text{m}$), can be tackled with recent advances in modified control and feed mechanisms [140]. Also, single screw compounding extruders with improved distributive and dispersive mixing similar to double screws and with increased pressure-generating capacity are being developed at reduced costs [141]. Therefore, small-scale production facilities can effectively utilise single-screw extruders with optional screw modifications.

Principally, a standard extruder should simultaneously fulfil the basic specifications of mass throughput, pressure build-up, and melt temperature [142]. Hence, the L/D ratio of an extruder screw should be reviewed before selecting the specific extruder. The extruder output is a relative measure of its length per diameter [132]. Vlachopoulos and Strutt [131] stated that the diameters of single-screw extruders usually vary between 25–250 mm with L/D ratios ranging from 20–36, with a normal running speed of 20–50 rpm, as well as a possibility that a 60-mm-diameter extruder can generate close to 200 kg/h.

Finally, for plastic recycling enterprises, decisions regarding the selection of extruders should also be based on the economics of cost and benefits: the cost of manufacturing the products (including power requirements) against the benefits of machinery size, output, and screw design.

Table 3. Merits and demerits of single-screw extruder options.

Single-screw option	Merits	Demerits
Leroy (Maddock) mixer	<div><div>✓</div><div>Assist in improving melt homogeneity [136]</div></div> <div><div>✓</div><div>Optimal mixing is generated when the mixing flight undercut of the Maddock mixer is < 1% of the barrel diameter [143]</div></div>	Mixing flight undercut of greater than 1% of the barrel diameter results in higher chances of resin degradation [143].
Pin mixing screw	<div><div>✓</div><div>Contains numerous lines of pins that interrupt the rotational flow pattern of resins to improve mixing, and this does not result in a remarkable shear intensity [144]</div></div>	A Maddock mixing section may also be required to improve thermal melt homogeneity after shearing [145].
Vented extruder	<div><div>✓</div><div>Extruder venting, also known as devolatisation, acts mainly, as the name suggests, to remove volatiles, moisture, air, and impurities during the extrusion process [146]</div></div> <div><div>✓</div><div>The high length per diameter (L/D) ratio and variable screw design of vented extruders provide a greater level of blending [145]</div></div>	Vent leakage and contamination are problems associated with the vented extruder [147].
Barrier screw	<div><div>✓</div><div>Improves melt quality and extruder output by controlling the polymer flight from the channel's pushing side and utilising an accompanying screw to separate the solid bed from the molten resin using offset barrier flights [131]</div></div> <div><div>✓</div><div>Additional control of molten polymer flow from the melt film to the melt pool leads to stable and increased output at reduced temperatures [136]</div></div> <div><div>✓</div><div>Compatible with the Maddock mixer [144]</div></div>	Conventional barrier screws are prone to shearing type mixing, which results in solid bed plugging; therefore, optimised barrier screw designs are needed to overcome it [148].
Wave screw	<div><div>✓</div><div>Wave screws work in deep cycling channels to improve mixing performance and melt homogeneity [137]</div></div> <div><div>✓</div><div>Improves the ability of a screw to melt resins as well as melt uniformity [136]</div></div>	Advanced designs of the wave screw, such as the double wave screw, may be needed for improved performance [136,149].

Even though there is a proposed formula for determining the power requirements of plastic extruders (output rate x specific heat of resin x temperature rise in barrel x heat

losses + an additional factor of safety) [122], the ultimate decision of selecting the correct extruder rests upon the expertise of the recycler in considering the parameters, as previously mentioned.

4.3. Moulding Machinery Selection

Moulding is another crucial process in determining the shape and form of the final product. The moulding process can be defined as a method of forming malleable materials – in this case, thermoplastics – into shapes of created parts in a mould, often with the aid of a plastic moulding machine [150,151]. Fibertech Inc. [152] maintained that moulding with plastics commenced at the end of the 1800s by John Wesley Hyatt in the bid to use plastic billiard balls as an alternative to the frequently used ivory billiard balls of that time. Moulding has evolved over the years, with plastics used to make various objects [153]. The moulding process can be categorised into different subprocesses: injection moulding, compression moulding, rotational moulding, thermoforming, die extrusion, and blow moulding [131,154,155]. However, the moulding system that is favourable to small-scale mechanical recycling (due to its cost implications) – includes die extrusion, injection, and compression moulding, which are described in further detail below.

Die extrusion can be defined as the process of pumping extrudate in a die during extrusion [156]. Dies are defined as customised machine tools designed to form materials into required shapes [157]. These dies come in different forms and shapes, such as flat, annular, and profile [140]. Extrusion entails the process of melting and extruding plastic resins with the use of an extruder. In an extruder, polymers in the form of flakes, chops, pellets, granules, or powders are fed to the extruder via the hopper and propelled through the flow channel in the space between the screw root and the barrel, where they undergo mixing and melting, and are finally pumped via the die of the extruder [158]. The shear force and drive (rotational movement) created by turning the screws in the barrel and the heating bands attached to the barrel facilitate the melting and extrusion process. Producing plastic products with the extruder alone is achievable because the die of an extruder can be utilised. However, if a unique-shaped product is needed, as normally expected, a specialised die with accompanying accessories will need to be attached to the extruder [159]. Currently, major manufacturers in the industry around the world, such as Procom Plastics Extrusions Pty. Ltd. (Australia), Jifram Extrusions Inc. (USA), and Technoplast Industries (France), are engaging in this form of die extrusion. On the other spectrum lies the hobby and underdeveloped scale of die extrusion production facilities such as those used by Precious Plastics [160]. Consequently, there is a need to test and develop the small-scale die extrusion system considering its practical benefits in tackling the plastic waste problem. Areas of focus include the mass flow rate; melt uniformity and distribution of the flow of the polymer extrudate from the barrel through the die; temperature changes and cooling during and after the discharge; and the balancing and insulation of the die channel [161].

Injection and compression moulding are the other moulding types that are considered in small-scale recycling processes. Injection moulding remains one of the most commonly applied forms of moulding polymers [154]. It is similar to the die extrusion process; however, the difference is that in the injection process, the extrudate is injected directly into custom moulds under pressure [162]. This pressured injection is facilitated by additional machine sensors and controllers [163].

A comparison of the merits and demerits of the die extrusion, injection, and compression moulding processes is presented in Table 4.

Table 4. Advantages and disadvantages of die extrusion, injection, and compression moulding.

Moulding Process	Advantages	Disadvantages
Die Extrusion	<ul style="list-style-type: none"> ✓ Can be applied to a variety of shapes [164] ✓ Dies may be low-cost and reusable [165] ✓ Availability of adjustable gap control features [166] 	<p>Pump may be needed to push extrudate forward [131].</p> <p>Molecular orientation of extrudate may be imparted by forcing it through the die-cast at low temperatures [131].</p>
Injection Moulding	<ul style="list-style-type: none"> ✓ Low cost for mould pieces [167] ✓ Ease of material handling and automation [168] ✓ High speed of operation [169] ✓ Intricate parts are easily produced [169] ✓ Can be redesigned to mould compression parts [168] 	<p>May not be suitable for reinforced polymers [170].</p> <p>A high stress level may affect the products [131].</p>
Compression Moulding	<ul style="list-style-type: none"> ✓ Low capital cost [167] ✓ Can be used for thermosets and thermoplastics [168] ✓ Low maintenance costs [170] ✓ Products have low residual stress [131] ✓ Products retain superior physical properties [170] 	<p>Not economical for making small parts [171].</p> <p>May require secondary processing – trimming, machining [172].</p> <p>Limitation on the depth of mould [168]</p> <p>May not be suitable for complex parts [131].</p>

On the other hand, compression moulding, reported as the oldest method of producing plastics [150], can be described as a simple moulding process whereby powdered or extruded plastic resins are placed in moulds and pressed into various shapes with the help of piston-type machinery. This method is appropriate for thermosets and thermoplastics and can be applied using a cold or hot-press system [173]. In this case, a mould can be defined as a temporary cavity for maintaining the form of extruded polymer resins [174].

It is also necessary to posit that several factors (including part dimensions) can affect the moulding force requirements for products. Tatara [172] argued that resin form, viscosity, fillers or additives, temperature, thickness, and complexity of parts could affect the

moulding force needed in compression moulding, while suggesting that press force capacity can be approximately 100 T for small parts with short production runs, and possibly extend to > 5 000 T for larger and more automated designs.

Compression moulding may be considered a favourable choice for thermoplastics because of the low capital and maintenance costs and the improved physical properties of the generated materials due to reduced internal stresses. In constructing such moulds, the parameters that must be ascertained and analysed to determine their effectiveness include: mould constituent materials, temperature changes, shrinkage, and lifespan [172,174]. Consequently, testing and varying these parameters is necessary to determine the optimum conditions needed for producing recycled plastic products, and this should be documented for future applications.

4.4. Modelling and Optimisation

Mechanical recycling revolves mainly around plastics undergoing secondary recycling. Rheological and thermal behaviours of polymers during the extrusion process are key factors in process efficiency [71], since extrusion is the most commonly used mechanical recycling process [175]. Morris [176] described rheology as concerned with analysing how materials change or flow when the applied force is initiated, as process conditions in the barrel of the extruder are neither isobaric nor isothermal and are often dissimilar [177]. This rheological study is necessary because it relates to the overall characteristics of plastics, such as the melting and structure of the final generated product [178,179]. Since polyolefins (PP and PEs – high and low) constitute some of the highest percentages of plastics that are recycled due to their inherent properties, such as the ease of recycling and favourable chemical resistance, the need to optimise and model their reprocessing cannot be overemphasized [180]. Generation of such information would be beneficial to small-scale recyclers who may require knowledge of the impact of the process conditions on the thermoplastics and the necessary parameters to operate so as to improve quality and prevent degradation of end-products. Thus a research opportunity exists regarding identifying optimised parameters of these properties in small-scale recycling systems. Researchers have carried out works aimed at analysing the effect of the addition of composites on the qualities of polyolefins, as summarised in Table 5.

Table 5 shows that the modelling and analysis of polymers involve composites or additives, not just recycled polyolefins. Even though the addition of similar or dissimilar virgin plastics, compatibilisers, and fillers or additives can improve the mechanical and thermal qualities of plastics [71,181], excessive use of additives in the recycling process can create challenges related to end-product degradation, safety, and complication of the process [182].

In their process model, Rieckmann et al. [183] determined that the PET quality criteria can be sustained if specific temperature, residence time, as well as surface areas for degassing during a reprocessing procedure are maintained. However, shear effects were not accounted for in their extrusion process.

Hyvärinen et al. [177] reviewed the extrusion modelling process of polymers and acknowledged that determining the correlation between product properties and process parameters can be intricate, costly, and restricted if carried out at a laboratory-scale only. However, these authors maintain that a successful simulation model can lead to a swift and cost-effective establishment of optimal relationships, and also emphasized the need for structural optimisation of the extrudate.

As previously mentioned, some researchers at the experimental scale have proven that temperature variation during polymer processing can result in structural differences in the end-product [184,185].

Table 5. Summary of effects of additives on the quality of polyolefins. LDPE – low-density polyethylene, HDPE – high-density polyethylene, PP - polypropylene.

Reference	Polyolefin and composites	Output
Wang et al. [186]	✓ PP and talc-filled PP	Mechanical properties of both materials decreased with increased recycling (reprocessing) of the polymer. The 3-dimensional constitutive model used showed results on the propylene-based material's mechanical performance.
Olesik et al. [187]	✓ LDPE reinforced with glass powder containing polyvinyl butyral (PVB)	Wear resistance of the polyolefin can be enhanced with the addition of reinforcement. The addition of composites led to a slight increase in crystallinity compared to unreinforced LDPE.
Navarro et al. [188]	✓ PP blends hardened with various elastomers (ethylene/ α -octene copolymer, ethylene propylene diene monomer [EPDM]/PP blend, and other blends formed by polystyrene and a styrene-butadiene copolymer)	The addition of limited amounts of additives did not alter the stability and thermal properties of the recycled plastic mixture. Results in an economic improvement in the mechanical strength and value of the products.
Pulipati and Jack [189]	✓ Large-format forward core composite structures made from HDPE and glass-filled polypropylene	Material performance of the model showed a volume fraction of the glass fibres and the volume ratio of the closed-cell foams.
Li et al. [190]	✓ PP, ethyl methacrylate (EADP), and a commercial ammonium polyphosphate coated by melamine resin (MAPP)	The crystallisation temperatures changed when composites were added to PP compared to the pure PP. Besides, there were fluctuations in the melting temperature using differential scanning calorimetry (DSC). Polarised optical microscopy (POM) analysis also showed a decrease in PP crystal size when EADP composites were added.

Another factor evident from the literature review is that there remains no agreement on the melt temperature of the thermoplastic process. For example, Liang [191] varied

temperatures between 140–170 °C in assessing the effects of the extrusion rate, temperature, and die diameter on melt flow properties during capillary flow on LDPE.

In contrast, Polymer Database [192] maintained that the melting temperature of PEs varied up to 160 °C. This can be attributed to the material used since additives can alter the physical and chemical qualities of materials [193]. Since polymers are inherently poor conductors, and processing temperatures can vary by up to 50 °C or more, a heating band that is too low during extrusion will result in the polymer not melting well as well as increased shear heating, which leads to higher energy consumption in the motor; however, if the temperature is set too high on the barrel of the extruder, it can lead to excessive heat dissipation [120]. Hence an optimal operational setting is needed for both energy conservation and extrudate quality. Relationships between melt temperature, screw speed, and feed rate have been studied in the past for the twin-screw extruder using predictive model controllers [194]. Nevertheless, the method used was not developed under processing conditions and was designed for the twin-screw extruder.

Deng et al. [120] developed a fuzzy logic system for melt pressure and temperature and determined that the melt pressure is proportional to the screw speed. These authors also concluded that a higher screw speed results in lesser specific energy usage and that the screw speed should be set as high as possible for more consistent melt quality. The study was conducted on LDPE in a single-screw extrusion process, and different thermoplastic resins may display dissimilar results under the same processing conditions due to rheological differences [125]. Moreover, it was determined that despite the apparent energy efficiency and greater power factor of running at a higher speed, the resultant effect on product quality and thermal uniformity of extrudate shows degeneration [195].

Finally, Abeykoon et al. [125] established the likelihood of a varying relationship between the energy demands of heaters and thermal fluctuations that can affect melt quality and recommended future studies to develop the power factor relationships of the single-screw extruder. Therefore, the research challenge is to develop a comprehensive and effective system to model and optimise the reprocessing parameters of the selected thermoplastics, taking into account and analysing the effect on the physical and chemical properties of the resins. This information will be valuable to the advancement of the small-scale plastic recycling industry.

5. Conclusions

5.1. Overview of Conclusions

Solid plastic wastes have been amassing in terrestrial and marine environments due to inadequate recycling approaches and uncontrolled production. Thermoplastics, including PET and polyolefins, constitute > 80% of plastics utilisation. This extensive usage of thermoplastics consequently results in waste generation.

There are many ways that these plastic wastes can be recycled. However, mechanical plastics recycling has proven to be practicable and achievable, thereby attracting considerable interest on a small-scale level. Nevertheless, reprocessing these plastics on a small-scale level presents challenges related to processes and equipment.

5.2. Sorting, Cleaning, and Sizing

Separation and sorting of plastics can be achieved through automated and manual means. The automated sorting system can be classified into macro and micro quantities based on size; however, each category comes with accompanying challenges such as equipment cost, reliability, and water management.

Training and standardisation of the process have been ascertained to be crucial to effective application of the manual separation system. Furthermore, a combination of manual sorting methods can be necessary, as identifying the correct resin category can be complex, especially in mixed plastics waste streams.

Cleaning (decontamination) and shred size selection were also found to be processes that can be impactful to small-scale mechanical recyclers. Hence, it was established that

chemicals and water may be utilised as cleaning agents; however, the technology continues to be developed and may involve substantial costs.

Smaller plastic shred sizes result in improved mechanical strength when reprocessed. Therefore, it can be beneficial to target shredding machinery with smaller screen holes and test their effect on the reprocessed plastic materials.

5.3. Managing Energy Requirements and Operation Cost

Controlling energy losses during the recycling operation (particularly extrusion) is essential to minimise cost and improve efficiency. Furthermore, the energy and cost management of a small-scale mechanical reprocessing plant lies in the proficiency of the recycler in choosing the most economically efficient forms of extruders, since larger extruders lead to additional costs. Single-screw extruders with optional screw adjustments can be deployed productively in small-scale mechanical plastics recycling plants.

Selecting the appropriate moulding machinery also contributes to the effective cost control of small-scale operations. Compression moulding may be considered amongst the alternatives; nevertheless, the dimensions and complexity of desired products could pose a challenge. Hence, to determine the optimum required conditions, it is necessary to test and vary the parameters involved in moulding the products, such as temperature changes, mould constituent materials, and lifespan.

Finally, the rheological behaviour of the polymers undergoing the extrusion process also contributes to determining the general efficiency of the process. It affects how evenly the plastics melt in the process and the structure of the final product. Various researchers have modelled the reprocessing parameters of different thermoplastics to determine the optimum process conditions. However, recommending general process settings for different plastic resins and extruder types has proven difficult due to the differing rheological nature of polymers. Nonetheless, there is a strong relationship between the process melt temperature and screw speed. This connection has a resultant effect on the energy consumption of the operation as well as the extrudate quality. Consequently, it can be beneficial for small-scale recyclers to run the operation under various process settings and determine the outcome on energy consumption and product quality in order to determine the most profitable conditions.

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