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A review of recent trends and status of plastics recycling in industries

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Abstract

This paper reviews and analyses the trends in plastic recycling processes and current practices. The aim is to delineate the effectiveness and efficiency of each technique. The analysis derives from over ninety-five peer-reviewed articles sourced from reputable repositories. The research focuses on a fourteen-year data span (2006 through 2019) to elicit the most recent developments in the field. Detailed analysis and description of each method prepare fertile ground for highlighting the most efficient recycling technique for various plastic types. Based on the study, a glaring waning of recourse to primary recycling is evident, while there is a significant intensification of both research and applicability of secondary and tertiary recycling technologies. Categorically, secondary recycling seems to be the most applicable technique within the study stretch. The results show that there is an upsurge of recommendations for further works on sustainable recycling processes, with much attention to automation, cost efficiency, and green environment. Towards this direction, a vast majority of developing countries are yet to embrace the latest trends, from the standpoint of this research.

Keywords: Plastics recycling, Status, Plastic recycling techniques, Applicability, Sustainability

Nomenclature

DMT	Dimethyltryptamine	*PLA*	Polylactic acid
EG	Glycols	*PP*	Polypropylene
HDPE	High density polyethylene	*PS*	Polystyrene
PE	Polyethylene	*PVC*	Polyvinyl chloride
PET	Polyethylene terephthalate		

1. Introduction

Recycling as an alternative to waste disposal can be a veritable source of raw materials reduction and achieving sustainability. The option is filled with considerable benefits, though the main aim is to close the life cycle of a product by beginning a new one [1]. Improvements in the technology used in manufacturing has contributed in making it easier for organizations to take part actively in recycling and encouraged investment in the required equipment [2]. In particular, pollution caused by plastic wastes are most prevalent in developing countries. Frequent plastic recycling in industries can assist in checking the pollution problems of plastic origin adequately [3]. The obstacles encountered in plastic recycling include but not limited to; the level of contamination in the recycled plastics, the wide range of recycled plastics and the complex sorting and collection techniques [4]. The cost of sorting and collecting plastic based waste in South Africa can be higher than the collection of general waste such as paper, fruit peels, iron based wastes or scraps, electrical and electronic wastes [5]. Sherriff et al. [6] maintain that the main obstacles to plastic recycling are the inefficient handling of increasing plastics and unregulated plastic recycling methods. The authors identify two obstacles: inefficient handling of increasing plastics and unregulated plastic recycling methods.

Plastic recycling includes the reprocessing of plastic materials or the recovery of monomers for polymerization [7]. It can occur in three broad categories, namely; primary, secondary and tertiary recycling. Each of the recycling techniques are defined by the plastic types and the techniques used in processing the plastics for recycling. Primary recycling is specifically the re-extrusion of plastics. That is, plastics that are released as waste during a manufacturing process are re-processed (through either cleaning or cutting), in order to return the plastics into the production process as raw material once again. Secondary recycling is a mechanical recycling technique, which processes plastics in a more complex and much longer process than primary recycling. This process requires plastics to be sorted, thoroughly shredded, extruded before forming into pellets. Tertiary recycling involves chemically breaking down the plastic polymers into monomers.

The recycling process is the second technique in the waste hierarchy with regards to the waste recovery techniques [8]. Other disposal methods for plastic waste include energy recovery and landfill. However, plastic recycling has been found to be the

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most efficient method by a vast majority of researchers [9-11]. The increasing price of crude oil increases the price of obtaining virgin plastics, therefore recycling can be a more feasible option for manufacturers that emphasise on cost savings [10]. Recycling also ensures that water pollution and air emissions are mitigated [12]. Out of all the various plastic types, polyethylene terephthalate (PET) carries the most value as it finds application in the manufacture of water and soft drink bottles, plastic films, plastic sheets and most packaging material [13-15]. Increasing the use of plastics can elevate the amount of plastic wastes released into the environment [16, 17]. Reusability and recyclability are significant benefits of using plastic products in manufacturing concerns [18]. There is abundance of literature that shares the view that manufacturers prefer virgin materials in order to maintain the strength and properties of the product. The properties can deteriorate during the recycling process due to thermo-mechanical deterioration [11, 19, 20].

In order to recycle a particular plastic type effectively, the cost of the recycling process should be lower than the cost of manufacturing the virgin products [7]. In addition, plastic products should be designed for recycling prior to manufacturing [7, 19, 21]. As mentioned earlier, Plastic recycling can be divided into primary, secondary and tertiary recycling [16, 22, 23]. Primary recycling includes the reprocessing of plastic materials during manufacturing. It is the most efficient in cost savings and has a low degree of contamination [24]. Secondary recycling involves the separation and reprocessing of the plastic materials into either concrete mixes or granules through extrusion. This is also known as mechanical recycling [16]. The benefit of primary and secondary recycling is that they can be implemented on both small and large scale [25]. Tertiary recycling includes chemical recycling which is the only recycling technique that follows the sustainability principle [26]. The preparation process of chemical recycling is similar to that of mechanical recycling [26]. Implementation of the process involves washing plastics and chopping them into small pieces, as well as sorting according to the various plastic types before processing to produce feedstock monomers [16, 27].

Tertiary recycling can include thermal recycling which is a process that releases toxic gases in the air [10]. This makes chemical recycling the more preferred tertiary recycling technique [28]. For this reason, this study does not include thermal recycling. The secondary or sometimes mechanical recycling comprises of several steps which include, sorting, identification, washing and shredding. These are considered to be the introductory phase [29]. The secondary phase includes, agglomeration, extrusion and pelletizing [30]. However, due to a large number of chemicals in plastic materials, it is difficult to determine a standard procedure for recycling all plastic types at once [7]. Understanding each step in the recycling process assists with maintaining efficient production planning [17]. The recycling technique that could be used is usually determined by polymer type, package design, and the source of the plastic [31]. This paper aims to analyse the trends in production planning, control of plastic recycling and highlight the advantages and disadvantages of each alternative.

2. Materials and methods

This work considers qualitative and secondary data as the most credible option. Majority of the data came from articles in well-established databases and repositories, which are restricted to literature materials on plastic recycling available between the years 2006 and 2019. The study presents a review of plastic recycling and delineates the status and current trends. The data collected includes peer review journals articles, books, online materials, case studies, conference papers and related publications. Terms such as "production planning of plastics recycling, plastic polymerization, "plastic recycling case studies" and plastic recycling techniques" were relied upon, in search of the research data. Figure 1 presents the distribution of the publishers of articles on primary recycling while Figure 2 shows the distribution of publishers of materials on secondary recycling. Also, Figure 3 displays the distribution of publishers of literature articles on chemical recycling. Figure 4 displays the distribution of papers collected on each topic while Figure 5 presents the time distribution of the overall research data. A section of the analysis is dedicated to the description of each recycling technique present in literature. The cost and benefits of adopting each plastic recycling process also form part of the analysis. We discuss thematic areas amenable to plastic recycling under individual recycling techniques and further present handy literature that can provide more insight for interested researchers and practitioners. The study later implements a tabular categorization of references in line with the recycling techniques, in the first instance, and thematic areas present in the citations. Some of the authors expectedly present three techniques while some deal with up to two. To attempt an optimal representation and reach a truce, this work sticks to a categorization paradigm, which allows an individual citation to stand for up to three recycling methods and more than one thematic area as necessary. This categorization paradigm necessitates the presentation of some citations in multiple thematic considerations. This study treats each literature as background to data source for plastic recycling methodologies and status, including the merits of each and the applicability. As a result, the study did not concern with the detail and essence of most of the past presentations, which can form part of future research effort.

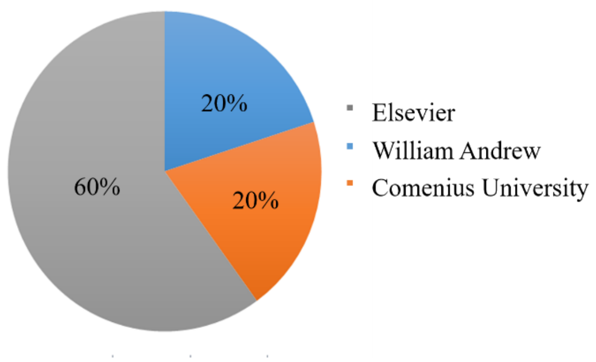

Figure 1 Primary recycling data distribution

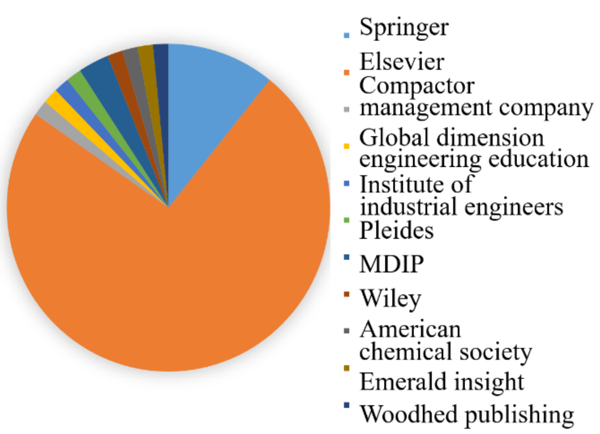

Figure 2 Secondary recycling data distribution

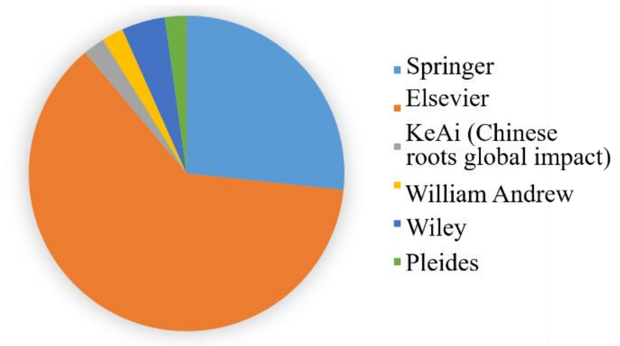

Figure 3 Chemical recycling data distribution

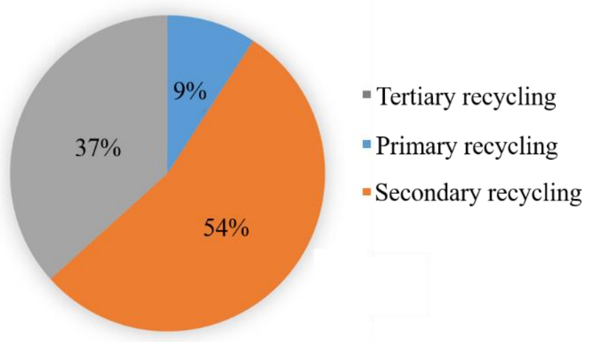

Figure 4 Distribution of papers found in each topic

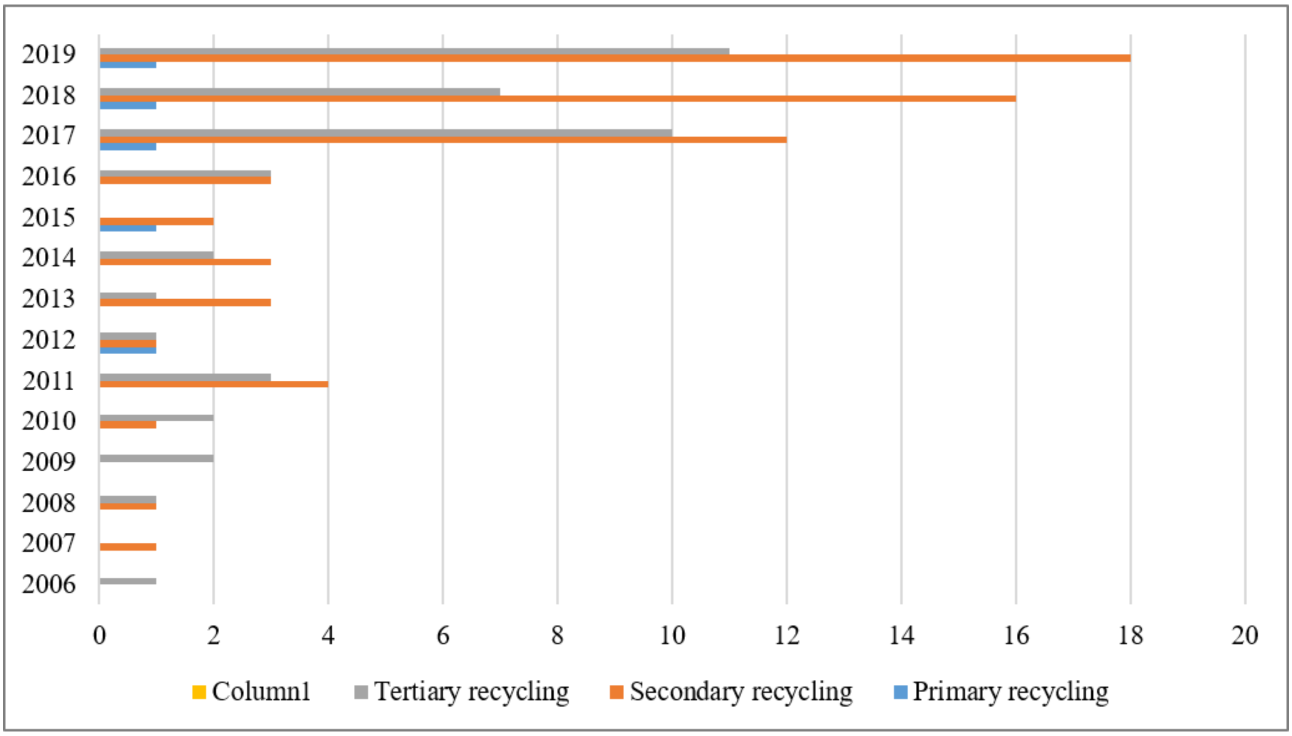

Figure 5 Collective distribution of data according to research period

3. Classification of plastic recycling processes

3.1 Primary recycling

Primary recycling or closed loop recycling refers to the reprocessing of plastics or re-extrusion [18, 28, 32]. The recycling technique takes place solely on clean uncontaminated and single-type plastics. The technique is not specific to any plastic type [33, 34]. Plastics with high level of purity and low molecular contamination are best suited for the process [35]. This recycling technique uses less energy and resources compared to the other recycling techniques [31]. Primary recycling takes place in an efficient and low cost process with the use of scrap plastic materials that contain the closest properties to that of virgin materials [28]. Primary recycling focuses mostly on pre-consumer waste or unusable components emanating from the manufacturing processes [19, 22, 31]. This recycling reduces industrial waste and processing costs [36]. One of the dangers in primary recycling is that contaminants could be absorbed into the final product [16]. Therefore, ensuring that plastics are cleaned thoroughly prior to recycling is crucial [22]. Primary recycling does not directly assist in reducing pollution caused by post-consumer waste as it takes place on plastic wastes within a manufacturing process [36]. Figure 6 presents the primary recycling process. What differentiates primary recycling from secondary recycling is that primary recycling does not include processes such as; size reduction by shredding, granulation or crumbing, cleaning and drying [22]. In addition, primary recycling produces standard products while secondary recycling produces products with improved properties [37]. Another method of primary recycling includes filling plastic bottles with plastic food wrappers in order to form eco-bricks [38]. High-density polyethylene (HDPE), Polyethylene terephthalate (PET) and PVC plastic scraps or products are the major types of plastics that can be recycled by primary recycling.

3.2 Secondary recycling

Secondary recycling is also known as mechanical recycling or material recovery. Its process defines the recycling procedure. That is, plastics are recycled in a mechanical process, which has the ability to result in various plastic products. The resulting plastics can combine with virgin plastics during new plastic product manufacturing [31, 36, 39]. Mechanical recycling can also stand as re-extrusion in line with the nature of the inherent transformation process [40]. Mechanical recycling has been

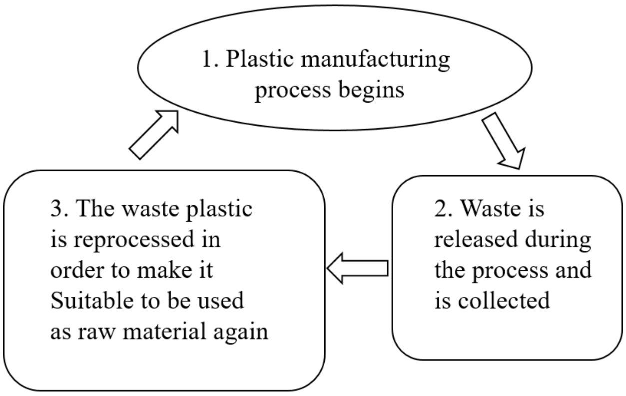

Figure 6 Primary recycling process

found to be the most commonly used and preferred recycling method [41-43]. Mechanical recycling comprises of a high efficiency process with low secondary pollution [44], this technique requires sorting, decontamination, treating (washing, drying, grinding) prior to taking the plastics through the core recycling process [16, 45]. Mechanical recycling can be conducted on thermoplastics (plastics with only one type of resin), e.g. PP and HDPE. This plastic type is preferred for its toughness, chemical resistance and electrical insulation properties [10], [33], [46-48]. Thermoplastics are linear polymers [49]. The thermoplastics promises to be the most consumed plastics today [50]. Thermoplastics are easy to melt and re-shape. They are solid at ambient temperatures and molten at elevated temperatures [11]. Once the plastic solidifies, curing does not take place and formation of cross-links becomes difficult [21]. Therefore, a better choice should be to conduct the recycling on mono streams-thermo-plastics [51]. Another commonly used plastic is thermosetting plastics. It is not easy to recycle thermosetting plastics since their properties are at variance with thermoplastics. This category of plastics require mechanical forces of heat for recycling [52]. There is yet another brand known as engineering plastics whose recycling is not mechanically possible [18]. Plastics from household waste contribute the most to contamination of other plastics during recycling. For this reason, recycled plastics is not usually applicable in food packaging as its chemical composition is difficult to establish [11, 12, 53]. The packaging materials are made of high-density polyethylene (HDPE). The properties of HDPE plastic include its strength, easy processing material and its resistance to abrasion. These properties increase its demand in the recycled form [54]. Other plastics that are not part of household waste but contribute to contamination are plastics that include additives and ink [26, 40]. Mechanical recycling requires low investment cost and uses simple equipment and material [16]. Mechanical recycling provides environmental benefits since it leads to the reduced use of crude oil for the production of virgin plastics [55]. The use of mechanical recycling can save organizations up to 50% of costs in manufacturing. This is opposed to the use of virgin plastics [43]. Recycled plastics also protect the use of natural resources as opposed to virgin plastics [56]. The recycling steps in secondary/mechanical recycling include sorting, washing, shredding, pelletizing and extrusion. In other cases, these steps can occur in a different order [20, 51]. Kamimura et. al. [57] recommend the implementation of suitable recycling steps for each specific plastic. These steps have been set as a requirement for recycling by the International Organization of Standardization (ISO) 15270:2008 [31]. Other recycling processes include steps such as compacting, curing and homogenizing [56]. An effective and efficient order of the recycling steps should consider the quality and environmental impact of the entire process [58].

3.3 Techniques in secondary recycling

3.3.1 Sorting/separating

All recycling techniques begin with sorting [59]. The sorting process is dependent on the size, density, shape, colour and chemical composition of the plastics [19, 51, 60]. Plastic sorting techniques are developed by the use of various technologies, which include x-ray, infrared and fluorescence. Sorting or separating techniques covered in this study include wet shaking table, sink float method, electrostatic separation, air table and manual sorting [18, 51, 61].

These are all physical separation techniques [62]. Sorting plastics extensively ensures achieving pure plastic types and prevents contaminants from entering the recycling stream [46], [63-64]. The aim of sorting plastics is to remove plastics that are not suitable for processing. Sorting results in obtaining good quality plastics that are appropriate for reprocessing [19]. During processing, the area of application of the plastic products should be born in mind. For example, plastics used for food and non-food packaging applications should be handled separately in order to avoid chemical contamination [53]. Also, biodegradable and non-biodegradable plastics should not be mixed together [65]. Efficient plastic sorting increases the plastics reusability value and decreases environmental risks [66]. If plastics containing different chemical compositions are mixed during recycling, the materials can form into different phases. This can reduce the quality of the products. This is also affected by the different processing requirements and the heterogeneity of the plastic [50, 11, 67]. The sorting step in recycling takes up the most cost [11, 31]. Mastellone [60] suggests recycling only plastics with mono materials as a means of cutting out the sorting phase, which further reduces the prohibitive cost.

3.3.2 Wet shaking table

The wet shaking table technique is also known as jigging [68]. This process uses a gravity centred method that removes bulk materials of different gravities based on their movement [61]. During this process, plastic particles can move to the deck by gravity. The water flow resistance can assist in separating plastic particles water movement down the deck [61]. This technique has a low cost per ton of waste and consumes low amounts of electricity. In order to separate the particles effectively, the process should be conducted repetitively until all particles are removed successfully [61]. The air table contains a porous deck due to the longitudinal vibration that creates a side deck [61]. The continuous side-by-side tilt then creates an end deck where high-density particles settle on the deck and low-density particles stay on the bed of the air table [61]. In other cases the air table is used to remove dust, foam particles and glass from the plastics [68].

3.3.3 Sink float method

The sink float method or the friction washing process requires submerging plastics in water [61]. The separation takes place by the use of either centrifugal force or the force of gravity [69]. Hydrogen ion concentration (pH) levels, froth content, wetting agents and depressants can assist in identifying plastic types in the sink float approach. However, the method is mainly dependent on plastic density [50, 61].

Sink float method is mostly preferred for polyolefin plastics, which include Polyethylene, high-density Polyethylene (HDPE) and low-Density Polyethylene (LDPE) [69-70]. During this process, some plastics float while others sink [11]. Plastics such as polypropylene and polyethylene will float while polyethylene terephthalate (PET), polystyrene (PS) and Polyvinyl chloride (PVC) will sink. However, this is more efficient when sorting shredded flakes [46, 51, 68]. The colour of the plastic does not affect the process and the process can easily be automated [50]. The sink float method appears cheaper than the other sorting techniques [51]. The process is mostly preferred because of its high efficiency in plastic separation requiring energy saving. The technique is equally efficient for plastics containing metals, halogens and hazardous components [71].

3.3.4 Electrostatic separation

The mineral industry still claim initial application of electrostatic separation technique but it has recently gained application in plastic recycling. In particular, it has gained significant consumption in plastics used for electronics [72]. In the electrostatic separation technique, plastics are charged with opposite polarities through a particle-to-particle charging process. The collision of particles with each other results in the production of positively and negatively charged particles [51]. After charging the particles, the tribo-charging process is employed. This involves the use of electric forces to sort particles that are 5 mm in size [28, 61, 68]. Other techniques of electrostatic separation include triboelectrostatic separation, corona discharge and electrostatic induction [61]. The collision of the plastics is strengthened by electrostatic induction [50]. Triboelectric separation is mostly suitable for plastics with different mixtures or binary plastics and plastics that are in granular form [50, 51]. The plastics that most suits triboelectostatic separation are PP and high impact polystyrene [62]. Electro static separation seems to be very reliable due to the inherent low cost processes. At the same time, the technique does not lead to secondary pollution [46].

3.3.5 Manual sorting

Manual sorting can require an experienced sorter, depending on the type of plastics under consideration. The high sorting proficiency can also be due to the type of plastics that will be produced with the sorted materials. The sorting method promises to be very efficient but there is the possibility of high cost associated with embarking on the procedure [51]. This process removes sundries and unnecessary packaging on the plastics [55]. Manual sorting is labour intensive, and compared to automated sorting techniques, it is not possible to sort large quantities at a low cost [73]. Embarking on manual sorting for some plastic types, for example, PET and PLA is not feasible as they find application in the manufacturing of transparent plastics.

3.3.6 Plastic identification

Fourier transform infrared spectroscopy (FTIR), differential Scanning calorimetry (DSC), image recognition and optical colour recognition are examples of Plastic identification methods found in literature [1, 61, 63]. Ragaert et. al. [51] states that companies can do well to conduct laboratory analysis aimed at identifying plastics correctly. Prior to sourcing plastics for recycling, the plastic source should be considered because it can affect the recyclability of plastics [33]. Some identification and sorting techniques can overlap one another [74]. Hence, additional explanation of the concept of each method cannot be an overkill for this study.

a. Fourier transform infrared spectroscopy

Fourier transform infrared spectroscopy (FTIR) is a procedure that can be used to obtain infrared spectrum of absorption or emission of matter (solid, liquid or gas). It can find application in identifying plastic polymers. The technique can assess the plastic quality and conduct a compositional analysis of plastics [25, 61]. This process is one of the most commonly used identification techniques. It is fast and non-destructive [51, 74], [75]. During FTIR process, plastics are sorted and stored in piles of different types, such as PET and HDPE [51]. The plastic absorbs infrared light in the mid-infrared position, and the spectrum that comes from it gives a fingerprint that can be used to identify the plastic [61]. A thermo-scientific Nicolet spectrometer is a typical equipment that can conduct an FTIR. The machine analyses the data using an omnic spectra software [10]. This technique can apply to testing for any structural changes in plastic once the recycling process is complete [23]. A Fourier transform (a mathematical analytical process) is required to convert the raw data obtained during the FTIR procedure into the actual spectrum. Hence, the origin of the name of the process called Fourier transform infrared spectroscopy.

b. Differential scanning calorimetry

Differential scanning calorimetry (DSC) is a thermo-analytical technique in which plastics are identified by the changes to the polymers' physical or chemical structure once the plastics are exposed to heat [76]. The rate of temperature required differs with plastic material differences and the purity of plastics [61, 77]. The process is conducted using a differential scanning calorimeter instrument, which requires a few milligrams of non-altered plastics placed in a crucible before heating [10].

c. Image recognition

This technique can assist in identifying plastic types through the different characteristic colours [63]. In implementation, the plastics are identified according to their position on the conveyor belt. Thereafter, plastics can be identified from their respective colours (light blue, lilac, brown, blue, light green, dark green and colourless) through manual classification or automatic classification, which can require the deployment of a machine [63]. Automatic classification is more efficient than manual classification and can generate efficient results when the process takes place before crushing the plastics [63]. Optical colour recognition is another image-based option that divides PET plastics into clear, blue and green plastics [51]. The use of infrared equipment helps to achieve collection of smallest size of plastics for the process [60, 66].

3.3.7 Washing/cleaning

During washing, drum screens are used to remove solids and dust on the plastics. Subsequently, manual separation is used to remove wood, aluminium and plastics that cannot be used for recycling [12]. The washing process is required in order to remove all micro and macro contaminants. When the washing process is completed, all plastics should be dried using thermal drying techniques [9, 51], and washed again before being taken through the final drying process [12]. The plastics are washed thoroughly due to the influence of the dyes on the quality of the product [36]. The washing of plastics takes place in two different phases. In the first instance, washing is carried out at room temperature with a ratio of 1:10 (solid: water). Later, the plastics are washed at a lower temperature at the same solute-solvent mix ratio [9]. However, according to Picunto et. al. [75], washing can proceed in three stages, in which the additional step would be rinsing.

Another decontamination process includes the use of a specialized decontamination reactor where hot air steam can flush out odour. This takes place after extrusion [78]. Inadequate washing and sorting practices can lead to returning the plastics to the production process for reprocessing [75]. If the washing process is not administered correctly, it can change the chemical composition of the plastics [67, 79].

3.3.8 Shredding

The purpose of shredding (also known as granulating) is to obtain the correct size of plastics and reduce volumes in order to ease further processing [8, 16]. This process also allows the easy separation of non-plastic materials [9]. A rotor knife and fixed counter knife together with water are used to shred plastics, water is required for this process since the heat on the blades could melt the plastic and to also soften the plastic [12]. This process is particularly important if plastics are to be turned into pellets [12]. In some organizations the recycling process stops at shredding while for others plastics are taken further through the process [4].

3.3.9 Agglomeration

The agglomeration process should be conducted carefully and correctly because fragile plastic agglomerates can break down easily [65]. During agglomeration the plastics are heated and moulded together and shredded further. The mechanical properties of the plastics may change due to the exposure to heat [80]. The different combinations of polymers that are discovered during mixing can limit mechanical recycling. However, the use of thermoplastics in secondary recycling maintains the purity of the plastics as the technique is sensitive to impurities [7, 35, 66].

3.3.10 Extrusion

During extrusion, the polymers are heated in a barrel to allow for homogenization. Once heated, the polymers are forced into a plastic dye machine, which has the required specifications, once the polymer is forced out of the plastic dye machine, it will be in a form that is according to the extrusion dye specifications [28, 55]. This could be either flakes, resin or pellets [58]. These plastics are then cooled in a bath of water at room temperature [43, 53] and are then taken for packaging [12]. The main function of the extrusion process is to optimize and clarify the colour and mechanical properties of the plastics [78]. The melt processing device, which is the screw extruder, requires a long time to melt PET [14]. The type of effluent plastic released depends on the process ability of the plastic. For example, thermoplastics can be melted and remoulded easily. This implies that the plastics have a high process ability. Thermoset plastics cannot be easily moulded. There is an inherent difficulty in processing this plastic type for recycling. Plastics with recycling process difficulties are said to possess low process ability. In particular, blow-moulding of buckets are done with plastics with high process ability [53]. The plastics admit additives during the extrusion process to ensure that they meet the specified requirements [12]. Typical examples of these additives include virgin polymers, fillers, fibres, compatiblizers (to improve the properties of plastic) and reactive polymers [11, 31]. These additives can contaminate the plastics if not added correctly [19]. All steps conducted prior to extrusion should be carried out with upmost caution as waste plastic is highly contaminable or could potentially be contaminated during the sorting and collecting process [9, 19]. During the process, there can be some issuing gases, which can cause pollution with an inevitable increase in resource consumption [55].

3.3.11 Pelletizing/ further extrusion

The pelletizing or further extrusion process normally result in production of plastic pellets or re-granulates [18]. Pelletizing essentially includes processing plastics into granulates which makes the plastics easier for use. During pelletizing, melt filtration is suitable for removing non-melting contaminants [12], [51]. Pelletizing takes place using a pellet cutter that contains a rotation knife. Alternatively, it can take place by the use of a piston driven extrusion head, where plastics are processed while ensuring that the plastics are not mixed with any contaminants and released through a nozzle [53, 81]. When completed, the resulting plastics can act as feed or raw materials in production of other plastics. The quantity of pellets depends on the specification of an individual plastic element under production [28, 81].

3.4 Tertiary/ chemical recycling

Chemical recycling is a technique based on breaking down of polymers by the reaction of other chemical or thermo-chemical agents [7, 36]. It is suitable for thermosetting plastics only [66]. Chemical recycling includes chemical processes that aim to transform plastics into feedstock materials through the process of depolymerisation, creating monomers or oligomers [51, 82], [83]. Chemical recycling is also known as compound reusing, which is one of the various factors that make chemical recycling a preferable recycling technique [32, 81]. This process involves breaking down polymers into smaller molecules or monomers [59-60] and oligomers or chemical intermediates [84]. These monomers finds application as raw materials in a polymer synthesis, which is used as starting material for recycled plastics [37, 57, 71, 81]. They can equally stand as feedstock for producing fuels [31]. This process contributes to the reduction of fuels in virgin plastics [51] and can lead to the permanent recycling of PET [85]. Chemical recycling is a technique that can recycle complex, and highly degraded streams of plastic, which includes contaminated plastics or complex plastic compositions which cannot be recycled using mechanical recycling [18, 60, 78, 85]. Chemical recycling also develops a product of better quality as opposed to mechanical recycling [16]. Barboza, et al, [86] maintains that chemical recycling techniques can differ by depolymerisation agents. The techniques include methanolysis, glycolysis, hydrolysis, ammonolysis, aminolysis and pyrolysis [51]. Hydrolysis, glycolysis and chemolysis are good examples of principle chemical recycling techniques [40]. In order for this process to take place effectively, the plastics should go through an effective washing treatment [57, 86]. One of the disadvantages of chemically recycled polymers is that they contain high raw material cost, high capital investment and large scale of operation [51]. It also requires complex technology and consumes large amounts of energy [87]. Fibres containing high strength can be obtained from chemical recycling [47]. Plastics used in the production of electronic devices are not suitable for chemical recycling as they contain chemical retardants [26].

3.4.1 Chemolysis and methanolysis

Chemolysis is a homogenous process where chemical agents are used for the depolymerisation of plastics [22]. Prior to this process, plastics are subject to extensive purification in order to completely remove all impurities [7]. The purpose of this technique is to recover raw monomers and synthesizing polymers with properties similar to virgin plastics [7].The sensitivity of the plastics increases with increasing addition of catalysts [26]. The methanol treatment takes place at high temperatures (between 180-280˚C) and high pressures of between 1.4Mpa - 2MPa [7]. The methanol treatment takes place at high temperatures and high pressures, due to the high vapour pressure of methanol [88]. The Dimethyl Terephthalates (DMT) and Glycols (EG) are the main products. However, chemolysis is more expensive than glycolysis because the former produces alcohols, glycols and phthalate derivatives. It is noteworthy that refining these products increases costs [51, 85].

3.4.2 Glycolysis and hydrolysis

One of the oldest and simplest methods of chemical recycling is glycolysis. It is a commercial technique that is practiced by various organizations [51, 83]. Glycolysis is most preferred due to the variety of products that emanates from the process [89]. During glycolysis, polymers are broken down using glycols at temperatures of 180-190˚C [7], [88]. Glycols (or EG) are diffused into the plastic, causing it to swell. The swelling increases the reaction rate. The process performs better in heterogeneous depolymerisation [82]. On the other hand, hydrolysis process employs water in breaking down the polymers [7]. Prior to this, the plastics should be thoroughly purified [83]. The water conditions are either neutral, acidic or basic with high temperatures and high pressure. However, this process is slow and not economically feasible due to the weakness of water and its nucleophile nature [51, 83, 84]. In order to prevent deterioration of the plastics, it can pass through drying in hot air for up to four hours [86]. Unsaturated polyester resin offers the best candidate material due to the degradation requirement [87]. This process produces TPA and EG as end products [83]. Incorrect drying of plastics can cause a catalyst effect capable of leading to lower flame resistance [88].

3.4.3 Ammonolysis and aminolysis

The ammonolysis process uses concentrated ammonia and results in therephthalamide (TAD) and EG as by-products [84]. Whereas Ammonis is compulsory for breaking down polymers during the ammonolysis process, amines are the necessary reagents for breaking down polymers during Aminolysis [7]. The later process is suitable because the PET ester group does not only change to amines but also metamorphose into hydroxyl group [71].

3.4.4 Pyrolysis

Pyrolysis is a thermo-chemical process in which heat acts on wastes (plastics) in the absence of oxygen for degradation purposes. The step places waste or scrap plastics back into the production process while producing tars, char, waxes, liquids and gas [36, 65, 89, 90]. The end product is materials instead of fuels [60]. This process takes place in non-reactive atmospheres [91]. The addition of a catalyst also assists in removing the impurities in plastics [64]. This process takes place at temperatures between 300˚C and 900˚C with red mud as a catalyst. Other catalysts of clay origin can apply [92]. According to Dewulf et al. [93], the optimum temperature for pyrolysis is 500˚C. The main by-product of this process is in the form of a liquid residue [89]. The benefits to this technique is that it assists in reducing the depletion of fossil fuels [64]. It uses less water and finds application in mixed and dirty plastics [65]. Pyrolysis is efficient as it transforms heterogeneous plastics to homogenous plastics [90] and can be conducted on a small scale [60]. The resulting liquid from this process can apply in an energy source for the pyrolysis process [47]. One of the challenges of the process is that most plastics are not compatible with one another, which limits the process [64].The cost is equally high [40]. Sustainability wise, the process contributes to CO2 emissions and has a high level of energy consumption [94]. Other products from pyrolysis include but not limited to polypropylene (PP) and ethylene [95]. Pyrolysis mostly takes place on PE, polyester and polyamides [96-98]

3.5 Thematic categorization of references

The three main plastic recycling processes have been enumerated as primary, secondary and tertiary recycling. This presentation thoroughly investigates each recycling methodologies and elicit researchers' thoughts on their merits and applicability. The primary recycling technique appears to be the best choice as per cost effectiveness and overall less energy demands [31]. However, this assertion must entertain some restraint due to the category of plastics amenable to the technique. The technique is best suited for Plastics with high level of purity and low molecular contamination. The use of scrap plastic materials that contain the closest properties to that of virgin materials is not always easy to obtain outside the industry

Table 1 Thematic classification of references on primary plastic recycling

Techniques	Subject	Reference
Primary Recycling	Methodology (Re-extrusion)	[2, 4, 17, 18, 23, 28, 33, 34, 61]
	Suitable Plastics	[19, 22, 28, 35, 31, 36]
	Risk and Safety measures	[36, 16, 22]
	Characteristics	[22, 37]

Table 2 Thematic categorization of references on secondary plastic recycling

Techniques	Subject	Reference
Secondary Recycling	Process	[18, 19, 51, 50]
Sorting	Methods	[19, 51, 61]
	Cost	[11, 31]
Wet Shaking table and Air Table		[68, 61]
Wet Shaking table and Sink Float Method; Electrostatic Separation		[11, 28, 51, 61, 62, 68, 70, 72]
Manual Sorting and Identification		[1, 51, 55, 63 73, 74]
Fourier transform infrared spectroscopy		[10, 23, 25, 61, 74, 75]
Differential scanning calorimetry		[10, 61, 76, 78]
Image Recognition		[12, 60, 66, 71]
Washing or Cleaning		[9, 12, 36, 51,67, 75 78; 79]
Shredding and Agglomeration		[7, 8, 9, 16, 35, 43, 65, 66 79]
Extrusion Palletizing/ Further extrusion		[9, 12, 14, 18 19, 28, 43, 51, 53, 55, 58, 78, 81]

Table 3 Thematic references of tertiary plastic recycling

Techniques	Subject	Reference
Tertiary Recycling	Candidate material	[7, 18, 32, 36, 57, 60, 79, 80, 82 83, 84, 85, 86, 88] [88]
Chemolysis and methanolysis		[7, 22, 26]
Glycolysis and hydrolysis; Ammonolysis and aminolysis		[7, 51, 83, 84, 86, 87, 89, 71]
Pyrolysis		[36, 65, 90; 91, 92, 96, 97, 98]

where unsuitable virgin materials are re-integrated into the production system. The difficulty in sourcing requisite materials for primary recycling can explain the minimal research effort in the area. In the light of this research, organizations can opt for primary recycling where there is abundant source of virgin scraps or scraps with the extent of sanitary demands of the technique. There is a general expansion of research in secondary recycling within the period of focus of this study, more than any other recycling techniques. This can be due to the attendant low investment cost, simple equipment and more prevalent raw material. The technique is environmentally friendly because it reduces the use of crude oil for the production of virgin plastics. Since the high cost of procuring virgin materials is not part of the design considerations, the option can save organizations about 50% of manufacturing cost [55] as well as protect the use of natural resources [56]. This study presents a robust excerpt of the technologies of secondary recycling, together with the applicability and benefit issues. The technique has received more attention of researchers than the other recycling methods, from the standpoint of this work. The choice of tertiary recycling often comes without cost considerations since its technologies differ greatly from the other recycling procedures. In effect, this category of material recovery process leads to the development of end-products with better qualities than can obtain using secondary method [16, 99, 100]. The method is normally the choice for complex and highly degraded streams of plastic materials. Tables 1 through Table 3 categorize the references belying each recycling technique.

4. Conclusion

This research present a detail review of the trends in plastic recycling for a fourteen years period (2006-2019). Based on the analysis, it is evident that there are numerous research effort that exist on plastic recycling. Primary recycling requires reprocessing and recycling within the original manufacturers' facility. There is a decline of research in primary recycling from the standpoint of this study. This decline is probably due to the high standards of the operating requirements required within the facility, despite low cost. Secondary recycling, which is a process that requires mechanically reprocessing the plastics through thorough shredding and extrusion, seems to be the most researched technique between the years of research covered in this study. The reason may be due to the moderate effects on the environment, in addition to the ample cost saving potentials to industries. Chemical or tertiary recycling, which requires chemically breaking down plastics has equally received significant attention by researchers, especially within the study stretch.

It offers the benefits of yielding materials of improved quality than the secondary recycling technique but can present serious cost consequences. This paper highlights that each recycling technique is most effective for different plastic types and the end use of the plastic. Each recycling technique meets various objectives of potential recycling organizations; for example organizations that focus on minimizing cost could implement primary recycling. The plastic recycling status and opinion of recent researchers is to explore techniques with good emphasis on automation, low cost and low pollution production. The developing countries seems to be struggling with the tenets of this new direction as seen from overall consideration of literature explored in this research.

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