Introduction to Recycling

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Abstract Recycling continues to contribute to the sustainable management of plastic solid wastes (PSWs) and it's among the important approaches currently used for reducing the impacts of PSWs in the plastic industry. It provides opportunities for reducing quantities of wastes disposed, oil usage and carbon dioxide emissions. Further, opportunities in form of job creation, global warming reduction, reduction of virgin material consumption, reduction in landfill contamination etc. It also presents demerits such as being costly, contamination, littering, pollution etc. The chapter outlines the concept of recycling with particular attention to plastics. It discusses the two strategies of recycling: open-loop recycling and closed-loop recycling. These strategies are compared and the difference is that, open-loop recycling provides an opportunity for new product development while closed-loop is confined to the original products. Different recycling processes such as primary recycling, secondary (mechanical) recycling, tertiary recycling and energy recovery are discussed by focussing on the processes, merits and demerits. Recycling is contributing to the sustainable management of wastes and, because of advances in technologies and systems for segregating, collecting and reprocessing of recyclable wastes, it is rapidly expanding. It is creating new opportunities for integration with industries, communities and the governments.

Keywords Recycling · Plastics · Strategies · Processes · Merits · Demerits

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1 Understanding Recycling

To support the survival and wellbeing of mankind, various technologies and systems have been invented. These technologies and systems have focused on several aspects of survival. One sector in which these technologies and systems, have contributed massively is the manufacturing sector. This sector has produced many products that continue to excite mankind as well as present opportunities for innovation. Nevertheless, among the many industries that exist in the manufacturing sector is the recycling industry. This industry continues to contribute to many goals for achieving sustainability and circular economy. As a result of numerous benefits and challenges associated with recycling, it is important to provide a detailed overview on recycling with particular interest to the plastic industry.

Recycling involves activities in which unwanted/or waste materials are reused for the reproduction of new products. Coelho (2011) affirms that, recycling reintroduces unwanted materials and/or energy back into the production system. The unwanted materials reintroduced into the production system can be plastics, metals, papers etc. The materials used in the recycling activities are substitutes for virgin materials that would have been obtained from scarce natural resources such as petroleum, trees, coal and many others. From the sustainability angle, there are many benefits associated to recycling other than virgin material substitution. Al-Salem et al. (2009) adds that, recycling is important for various causes including oil preservation, minimization of greenhouse gas (GHG) emissions, energy preservation etc. Recycling is a cardinal element in the waste management (WM) hierarchy where it sits as the third strategy on the 3Rs "Reduce, Reuse and Recycle."

1.1 Recycling Strategies

Many studies on recycling processes have been conducted. Ragaert et al. (2017) conducted an extensive review on the recent strategies for polymer recycling through chemical and mechanical processes. The study also established the relationship between recycling and design while emphasizing the function of design from recycling perspective. Maris et al. (2018) reviewed the strategies for compatibilizing blends of mixed thermoplastic wastes. The study confirmed mechanical recycling as the most economical, ecological and energetic option for managing plastic wastes. Al-Salem et al. (2009a) affirms mechanical recycling as the most common process for recycling plastic wastes and it includes collecting, sorting, washing and grinding. It is worth noting that, mechanical recycling is not the only recycling process in the plastic industry. A number of processes including chemical recycling has emerged as a result of the drawbacks experienced in mechanical recycling (Kumar et al. 2011; Angyal et al. 2007). These recycling processes are discussed in more detail later.

From the circular economy perspective, categorization of recycled materials is based on the product manufactured from the secondary raw materials (Ragaert et al.

2017). The two terms that focus on material to product processes are "closed-loop" and "open-loop" recycling. These two terms are most important for making an objective division on the new product manufactured. Thus, the terms are subjected to labels such as "up-cycling" and "down-cycling," indicating an added value to the process of recycling (Ragaert et al. 2017).

1.1.1 Closed-Loop Recycling

This term is most applicable to many PET packaging products such as water bottles. Under this process, recycled plastics are utilized to manufacture similar products they were originally recovered from. The new product is manufactured entirely from recycled plastics or in some cases a mixture of recycled plastic is produced with its virgin counterpart. The type of dilution allows continuation of the recycling and recovering cycles.

1.1.2 Open-Loop Recycling

Examples of products recycled using this process include textile fibers from manufactured bottle-PET. Recycled plastics are utilized to manufacture a different product from the originally recovered one. The application does not imply the new product is of less value than the original one.

1.2 Types of Recycling Processes

The disposal of plastic solid wastes (PSWs) has become a critical global environmental problem (Environmental Impact of Polymers 2014). Despite this, large quantities of PSWs continue to be generated and introduced into the environment through disposal and production processes and this has continued the accumulation in the ecosystems across the oceans and globe (Ivleva et al. 2017). Given the serious environmental, economic and social challenges caused by PSWs, several decrees and regulatory guidelines focusing on the recovery of PSWs have been imposed by many authorities of different countries. Coupled with these guidelines and decrees, many methods of recycling PSWs that depend on sources of plastics, polymer type and package design have been developed. The difference in the recycling processes presents some challenges and hence some studies have been conducted to explain the sequential steps involved (Hopewell et al. 2009). However, the first study concerning the classification of recycling techniques was conducted by Clift (1997). Further, the classification has been standardized into four categories by the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM). Many studies have applied this classification (Al-Salem et al. 2010; Saiter et al. 2011; Brems et al. 2012; Ignatyey et al. 2014).

1.2.1 Primary Recycling

This recycling process reintroduces pre-consumer residues i.e. (scrap, single polymer edges, parts etc.) into the extrusion cycle in order to manufacture products of the same material (Maris et al. 2018). This is the best recycling method for plastics because of its merits on less energy consumption and fewer resources while more retain on fossil fuels. This recycling method is referred to as the closed-loop recycling strategy because of its ability to reuse products in their original structure (Grigore 2017). Primary recycling presents advantages such as; simplicity and low cost. Nevertheless, scraps of PSWs must be from a single waste source and pure (Bartolome et al. 2012). The existence of low number of cycles for each material is a major disadvantage of primary recycling (Singh et al. 2017; Francis 2016). Further, different materials and polymers cannot be recycled (Park and Kim 2014).

1.2.2 Secondary Recycling

Secondary recycling also referred to as mechanical recycling involves operations that recover PSWs through mechanical processes. This process substitutes recycled materials for virgin polymers or a portion of virgin polymers in the new manufactured plastic products. However, mechanical recycling has a demerit of deteriorating the properties of recyclable materials and hence degrading the polymers. Occurrence of low molecular weight compounds and heterogeneity of plastic wastes is another disadvantage.

Grigore (2017) asserts that, secondary recycling represents a physical methodology in which recovered PSWs are transformed through cleaning and drying, sizing, agglomeration, extrusion and manufacturing. Transformed PSWs can be combined with virgin materials for excellent results. However, it is challenging to recycle PSWs or wastes that are complex and contaminated. Therefore, wastes are cleaned to remove contaminates and it is a first process.

Mechanical recycling is utilised as a profit oriented process (Al-Salem et al. 2009) with products of different shapes being manufactured. Examples of products manufactured through mechanical recycling include; grocery bags, windows and pipes (Al-Salem et al. 2009). Companies in developing continue to utilise this process because of the merits it presents (Mwanza 2018). Nevertheless, drawbacks to mechanical recycling can be, the presence of impurities, complexity of PSWs, mechanical stress and poor quality of recycled wastes (Tshifularo and Patnaik 2020). The quality of the manufactured product is compromised through processes of waste preparation, cleaning and separation (Park and Kim 2014). Waste deterioration, unbalanced shapes and sizes of PSWs and dissimilar colours influence the complexity of mechanical recycling. Upasani et al. (2012) adds that, products stored in PET bottles speed contamination and deterioration. In addition, life cycle of recycled polymers influence the quality.

1.2.3 Tertiary Recycling

This process is also referred to as chemical recycling and involves processes that chemically produce small molecules from polymer chains that are later used as feedstock in the manufacture of fuels (Kunwar et al. 2016; Lopez et al. 2017; Mohanraj et al. 2017); other chemicals (Serrano et al. 2012) and new polymers (Kwan and Takada 2017). Globally, many chemical processes exist, gasification, hydrocracking, pyrolysis, depolymerisation, methanolysis and aminolysis (Nikles and Farahat 2005; Genta et al. 2005; Pingale et al. 2010; López-Fonseca et al. 2010; Fukushima et al. 2013). It is a paramount process for manufacturing food packaging products (Patterson 2000).

Chemical recycling is a sustainable recycling method (Tshifularo and Patnaik 2020) and will continue to be used without difficulties in the future (Wang et al. 2009). Its purpose is to achieve higher rates of the monomer with reduced reaction time (Al-Sabagh et al. 2016). The presence of depolymerizing agents, monomers and resin synthesis are some of the advantages presented in chemical recycling. The process of recycling PET is grouped into methanolysis, glycolysis and hydrolysis.

PET producers recycle using Methanolysis and PET is reduced using methanol at higher pressure and temperature. The pressure is between 2 and 4 MPa and temperature between 180 and 280° (Paszum and Spychaj 1997). Its drawbacks include; high cost, high temperature and pressure (Shukla et al. 2009).

Glycolysis begins by crushing the PSWs into flakes and these are cleaned to remove contaminants. The dried flakes are then extruded into desired products. In other cases, virgin PET is blended with the flakes for quality improvement (Tshifularo and Patnaik 2020). Glycolysis is also used to recycle PET bottle wastes under pressurised reactor kept between 238 and 242°.

Hydrolysis process involves the reaction of PET with water in an alkaline, acid or neutral environment resulting into total depolymerisation into its monomers (Grigore 2017). It is not a preferred method for manufacturing virgin PET for packaging food because of high cost. High temperatures of between 200 and 250° and pressures of between 1.4 and 2 MPa are the major disadvantage of hydrolysis recycling. Ghaemy and Mossaddegh (2005) adds that, pollution and corrosion related problems are another set of disadvantage. Compared to glycolysis and methanolysis, it is slow.

1.2.4 Quaternary Recycling

This term is also referred to as energy recovery. It involves the incineration of PSWs and recovery of energy via the generation of heat and/or electricity. In developed economies such as the European Union (EU), energy recovery is the most used recovery method for post-user PSWs (Plastics Europe 2016). It is an appropriate process for application in instances where mechanical recycling cannot be applied as a result of separation difficulties, excessive contamination or deterioration of polymer properties. The high caloric value in PSWs makes them a suitable source for energy production.

In a report by Bartolome et al. (2012), the amount of chemical energy present in PSWs is recovered through incineration. This shows that, in any burning process of PSWs, energy is present and can be recovered. However, the amount present in burning is much lower compared to an incineration process. Quaternary is the best recycling option for complex to collect and segregate waste as well as harmful and toxic wastes.

The drawbacks of quaternary process is the poisonous air generated that is harmful to human health (Park and Kim 2014). As a result of the inability to produce another product from a recycled materials, quaternary does not fully fit in the recycling definition (Tshifularo and Patnaik 2020).

1.3 Merits and Demerits of Recycling

Recycling as a strategy of waste management and number 3 in ranking on the waste management hierarchy has changed the ways in which humanity deals with wastes. It is interesting to indicate that, recycling has existed as far as the 1800 (Bradbury 2017) and the process has continued to grow globally. The growth and innovations in recycling has come with advantages and disadvantages. A study by Hopewell et al. (2009) discusses the opportunities and challenges found in plastic recycling but still points out that, recycling is one of the vital options available for minimising the environmental impacts caused by plastics. Further, the plastic industry is represented dynamically by recycling.

1.3.1 Merits of Recycling

Recycling has enabled producers to create a wide range of products from clothing to furniture to kitchen utensils. It provides a platform for giving new life to valuable materials and hence closing the loop. It has expanded rapidly and provides several merits to the recycling industry and the society at large. The following are some of the benefits of recycling.

Reduction of landfill contamination

Majority of the manufactured plastics are non-biodegradable and cause a lot of harm to the environment. Recycling of plastics and other materials enables to reduce the contamination to the environment. The contamination takes long but its effects have lasting implications to the environment and all the living things.

Diversion of waste materials into other recovery streams

It is not certain that the operation efficiency of a recycling program will be at 100% for society to benefit. Major metropolitan cities continue to generate huge tonnes of wastes per annual and with diversion of 50% by least recycling technologies, an extensive amount would be reusable and return to the markets.

Reduction of raw material consumption

Establishment of recycling programs costs more but it contributes to less consumption of virgin materials. For example, plastics are manufactured from petrochemicals which are produced from fossil gas and oil and 4% of annual petroleum is converted into plastics (British Plastics Federation 2008). This is not sustainable consumption considering that, majority of the plastics are manufactured into post-consumer products with a short life cycle. Hopewell et al. (2009) mentions that recycling provides opportunities to reduce oil usage hence virgin material consumption reduction.

Ability to work as an open and a closed loop system

Recycling can be implemented as a closed and open loop system. Products can be transformed into different products. For example, transforming a plastic bottle into a refuse bag (open-loop system). For closed loop systems, products are transformed into the same products. For example, aluminium cans transformed into aluminium cans.

Reduction of pollution levels

It is possible to reduce the amount of air pollution by 70% through a recycling program. For example, 1.5 tons of CO_2-e per ton of recycled PET is given as a net benefit in greenhouse gas emissions (Department of environment and Conservation 2005). LCA studies have also shown that, recycling contributes to the reduction in emissions (Patel et al. 2000). 100% recycled PET has the ability to reduce life-cycle emissions from 446 to 327 g CO_2 per bottle compared to 100% virgin PET (WRAP 2008). This shows that, recycling reduces the threat of environment impacts.

Creation of educational opportunities

Availability of knowledge on recycling is a driver to community participation in recycling programs. Mwanza (2018) shows that, lack of information on recycling prevents communities from participating. Therefore, creation of recycling programs is an opportunity to provide knowledge and education. Informing communities on waste recycling contributes to sustainable management of waste and households can be taught how to reduce disposal and focus on recovery.

Profitability of recycling programs

Depending on the size of a city, significant profits can be obtained from a recycling program. For example, $90 per bin per year can be created and this depends on the effectiveness of the recycling program.

Creation of jobs

In developing economies, majority of the PSWs is recovered by the informal waste sector. The livelihood the informal waste sector get from recovering has contributed to sustainable recovery and management of PSWs. Therefore, the existing of recycling processes has contributed to job creation in the recycling industry.

Minimization of global warming

When the wastes disposed at landfills are combusted, emissions in the form of greenhouse gases are generated and these contribute to climate change and global warming. Therefore, the diversion of wastes for recycling minimizes the environment impacts caused by wastes. The process of recycling generates less greenhouses compared to landfilling since the amount of fossil fuels burnt less.

1.3.2 Demerits of Recycling

According to (Tshifularo and Patnaik 2020), the demerits presented in new products manufactured from recycled plastics have poor thermal and mechanical properties and lower melting viscosity. The presence of contaminants and reduced molecular weight of the recycled wastes is caused by degenerated mechanical and physical properties of the recycled wastes and this is another demerit of recycling. Besides these demerits presented in recycled plastics, a number of demerits on recycling exist such as.

Recycling is costly compared to landfilling

Other than the costs of constructing recycling plants, purchasing of required recycling equipment and machinery, and educating locals on available recycling programs and seminars, it is costly to recycle compared to landfill. Statistics published on Credit Donkey show that the cost of recycling prevent communities to recycle. Mwanza (2018) shows that, costs associated with waste recovery, logistics, and production and labour are obstacles to recycling in developing economies. However, Mwanza (2018) also shows that, comparative of recycling cost to landfilling is slowly promoting recycling. The cost of landfilling a ton is around $28 compared to $147 a ton to recycle. Further, landfill management is less costly than managing a recycling facility.

Communities lack of compliance to recycling programs

Lack of compliance by communities presents demerits of recycling. Communities desire to recycle but lack the understanding of rules for wastes to include in the curb. This creates a lot of problems for recycling programs. Mwanza (2018) shows that, lack of information on PSWs recycling prevents communities to participate in recycling. Despite most recyclable products having recycling symbols, compliance from communities is still very low because most of them do not understand these symbols and therefore end up mixing these recyclable wastes.

Unhygienic and unsafe recycling sites

Majority of recycling sites are unhygienic and unsafe because a location where waste piles is a conductive environment for debris to form. Workers and waste collectors face several toxins at collection points and landfills. Workers are exposure to chemicals, fluids, and microbial agents and every collection point creates a possible health related problem.

Problems created by contaminants

The presence of any contaminant has high possibilities of damaging the entire batch prepared for recycling. It is a big challenge in the recycling industry despite specific rules been established for wastes.

Litter creation by waste collectors

In developing economies, major of waste collectors are in the informal sector. This sector does not have adequate capacity in terms of waste collection equipment and vehicles. This challenge has continued to create problems of littering after waste recovery. Scenes of this kind are observed neighborhoods despite waste management trucks with hydraulic arm to lift the container been used.

Non-durability of recycled products

The durability is always questioned and majority of the products manufactured products cannot be compared to those manufactured from virgin materials. Quality is always an issue in recycled products.

Energy Consumption and Pollution

Throughout the life of a product, energy is required. During recycling, energy is consumed from transportation of waste from collection points, during sorting, cleaning and manufacturing. In all these processes energy is consumed. Further, wastes in form of pollutants are created. The vehicles used in the transportation processes create pollution. Chemicals pollutants from the waste materials are harmful to the environment.

1.4 Recent Developments

Globally, the innovations, manufacturing and usage of plastics continues to increase exponentially annually, resulting in continuous increase in disposed end-of-life plastics in dumpsites, landfills and natural environments. Although recycling is ranked third on the waste management hierarchy, it has become an extremely important ecological and economic issue because of the merits it presents such as; low cost of energy, reduction of pollution and preservation of virgin materials. The desire to reduce the amount of plastics on the environment is growing from developed to developing economies and this has seen many legislations on plastics coming up. However, the relatively low costs of landfilling is proving to be an obstacle to the expansion of recycling especially in developing economies. Nevertheless, the drive for circular economy and political pressure has resulted in the creation of strict legislations focused on reduction of PSWs landfilling.

The majority of PSWs generated comes from post-consumer products because of their short life-cycle compared to pre-consumer products. Majority of plastic materials is manufactured as post-consumer products such as packaging products. The short life-cycle of plastic packaging products entails continuous demand for virgin materials. However, with the efforts to educate the public on sustainable resource utilisation, several legislations and systems have been devised to make inappropriate disposal costly and recycling more feasible, if possible mandatory. More and more wastes are been channelled into sustainable routes either through buy-back strategies or reduced recycling quotas. From these changes, recycling has increased and continues to increase globally.

Recycling approaches focus on; mechanical recycling, chemical recycling and energy recovery. Mechanical recycling is the most promising strategy from the environmental and economic aspects. However, if sorting is not conducted because of economic or technical constraints, recovered PSWs will constitute of different polymers and this presents a challenge to mechanically recycle. Thus, the drive for waste segregation is growing because for any recycling strategy to sustainably work, wastes should be segregated appropriately. Segregation of wastes results in reduced process time and hence reduced production costs. Chemical recycling through monomer recycling and pyrolysis are technologies that are showing a lot of potential in the recycling industry. Therefore, the recycling industry should invest in research that can provide feasible implementation plans for these technologies. Mechanical recycling as an established business in many developed economies is profitable and can generate new polymer with minimum investment. It is a comparatively an advantageous route to polymer manufacturing and can be used to recycle many polymers. For example, mechanically recycling LDPE and HDPE has the potential to generate the largest profit by 2030 (Hydrocarbon processing 2019). As a result of the demerits found in mechanical recycling such as quality deterioration and residue build-ups, chemical recycling through pyrolysis provides an optimal value treatment option while monomer recycling provides the highest recycling profitability levels.

Contextual development of recycling systems has the potential to improve recycling rates. The focus should be to design systems and deploy appropriate technologies that fit contexts. For example, most emerging economies lack waste sorting infrastructure and therefore, the wastes recovered is a small percent of the waste flow. An assessment of wastes generated and collected should be the starting point. Once these waste management capabilities are established, waste segregation strategies should follow. When this is achieved, pyrolysis of mixed PSWs can be the most efficient option.

By 2030, plastics reuse could increase to 50% of its production (Hydrocarbon processing 2019) assuming enforcement of regulatory frameworks and adjustments in the oil prices. The regulatory frameworks should be supported by industry stakeholders and consumers. To achieve a 50% reuse in plastics, capital investments is required.

The demand for plastics will continue to grow worldwide and it is imperative to establish effective systems for managing PSWs. Development of sustainable paths for quadrupling the amount of PSWs being reused and recycled should be focused on. The pathways will demand alignment of regulators and behaviors from major stakeholders such as consumer goods and society. Establishing partnerships will enable players to access the required technologies or secure access to the feedstock supply-chains. Collaborating with research institutions and creating long term agreements with private waste companies, landfill sites, municipalities and the communities will improve the supply-chain management of feedstock. For contextual supply-chain management of feedstock, integration of the informal sector into formalized systems will work for most developing economies.

1.5 Conclusion

Based on the reviewed literature, recycling is a vital element within the waste management hierarchy and will continue to contribute to sustainable development of the global. The different recycling strategies present a number of merits and demerits. These merits and demerits have enabled the recycling of different types of PSWs. As innovations and technological advancement continue to emerge, improvements within the recycling space continue to advance. This advancement in technology through research is needed by the recycling companies because the plastic manufacturing industry is not waiting for recycling technology to advance before they design and manufacture new products.

Integration of the required stakeholders, regulation enforcement, knowledge and awareness on recycling and systems development are needed for successful implementation of recycling programs but should be contextually aligned. Societal integration in the recycling process is necessary because waste is generated from all aspects of life i.e. workplaces and households. Lastly, the different strategies for recycling PSWs are not 100% sustainable but are contributing to resolving the PSWs problems.

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