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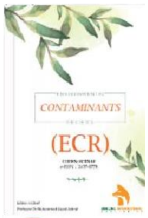

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RESEARCH ARTICLE

INNOVATIONS FOR SUSTAINABLE PLASTIC WASTE MANAGEMENT IN NIGERIA

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ABSTRACT

The use of plastic is increasing rapidly every year and this trend is likely to continue because of the extreme versatile nature of the properties of plastic materials which gives it use for wide range of purposes. This paper presents a current scenario of plastic consumption in Nigeria and also attempts to address the problem of plastic waste disposal and its attendant environmental hazards by discussing the various innovative ways of utilizing plastic wastes in order to promote a sustainable environment. The paper highlighted the challenges faced by the different innovative techniques and also the approaches that can be adopted to overcome the challenges for its survival in the circular economy. The literature review touched on works of related studies and discussed many innovative approaches for utilizing plastic waste. The key sources of literature in this review paper included peer-reviewed articles, news post, project briefs and professional reports. It is hoped that the implementation of the noble ideas and innovative technologies discussed in this work will enable proper and effective management of plastic waste in Nigeria.

KEYWORDS

Biowastes, Ecosystem, Greenhouse gases, Plastic, Polymeric materials, Pyrolysis

1. INTRODUCTION

Plastic pollution is a global problem threatening both the health of humans and ecosystems all over the world. Every year, millions of tonnes of plastic end up drifting or sinking in oceans. The generation of waste increased drastically with economic improvement (i.e. rapid industrialization and population explosion, and most of the waste is generated by urban cities (Ilochi et al., 2016; Onuegbu et al., 2010). Research showed that about 10% by weight of municipal solid waste content are plastics as plastic waste (PW) occupies about 90% of the populous rivers in the world (Kehinde et al., 2020). Plastics is commonly used in many products of different scales and packaging because they are cheap, easy to manufacture, versatile, impervious to water, has light weight, high impact, bacteria and chemical resistance and ability to be formed into shapes (Awoyera and Adesina, 2020; Yu et al., 2021).

Plastic products are singly used for packaging and other purposes after which their service life is exhausted, and the plastic becomes waste. PW causes land, water and air pollution. Burning of wastes including PW and disposal in landfill are the major waste management practices in Nigeria. When burnt, PW fumes release polychlorinated biphenyls, dioxins and furan into the atmosphere. This can raise danger of heart disease, aggravate respiratory ailments and damage the kidney, liver, nervous system, cause skin cancer and death (Kehinde et al., 2020). Landfills contribute about 20% of greenhouse gases (GHG) such as CO_2, CH_4, S, N gases and fossil fuels. The gases reduce solar radiation leading to global warming. PW causes water pollution when disposed in water bodies, reducing the oxygen content of the water body and causing death of fishes and other organisms. PW disposed in landfills discharges toxic substances into the soil, which flows underground and other water sources in the surrounding.

Plastic has low biodegradability. This poses a huge limitation on its recyclability and disposal into the environment. There is need to find applications where plastics waste can be useful and sustainable plastic waste management. The inefficient management of waste by individuals, households, consumers and waste management companies can be attributed to inadequate information on waste management benefits, lack of producers' involvement in waste management and poor implementation of government policies (Abila and Kantola, 2013)

In a bid to reduce or limit the effect of chemicals from plastic on the environment, some of the chemicals with known hazards used in plastic production have been phased out and replaced by another, but unfortunately, it was found that most of the chemicals replaced with have similar or different and potentially worse hazards. Example, bisphenol A was phased out of bottles and cans due to endocrine disrupting concerns, and replaced by bisphenol S and bisphenol F which has similar endocrine disrupting concerns (OECD, 2021).

In Nigeria, plastic constitute between 40% and 60% of the volume of solid wastes (Dalen et al., 2017). Majority of plastic consumed by application is by packaging (55%), construction 16%, automotive 6% and the remainder by various industries (Verna et al., 2019). Less than 12% of the PW generated in Nigeria is recycled by private firm, about 80% of these wastes end up in landfills and dumpsites (Babayemi et al., 2018). Globally, Nigeria is ranked 9th for plastic pollution with an estimated 2.5 million tons of PW generated annually and less than 12% recycled (Yalwayi et al., 2022). In addressing the challenge of plastic pollution in Nigeria, Dumbill and Henderson suggested that Nigerian society must embrace culturally specific solutions to the challenge of plastic pollution and avoid relying on top-down solutions that may not be effective on ground (Dumbili and Henderson, 2020). As reported by Akinwale, the waste recycling plants located across Nigeria to eradicate the problem of plastic waste are at different stages of deterioration (Akinwale, 2018). Nigeria is not catching up with the movement to eliminate PW.

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Reduction, re-use, recycling and recovery of plastic waste have been used in many countries to deplete plastic waste from the environment and put them into good use (Jefferson et al., 2009). The techniques involved includes innovative approaches which either provide suitable alternatives to the plastic and reduce the need to produce them in the first place, or utilize the PW in a new product, giving it a second life and preventing it from ending up in landfills and water bodies (circular economy). By recycling, valuable raw materials are preserved, CO_2 emission is also reduced. This work reviews recent relevant literatures on the innovations for plastic waste recycling and reduction. The approaches discussed in this work can be adopted, practiced and sustained in Nigeria. This work also discussed the challenges associated with recycling technologies.

Figure 1: One of the dumpsites littered with plastic wastes in Nigeria

2. Recycling of Plastic Waste

Plastic recycling refers to the process of recovering waste or scrap plastic and reprocessing the material into functional and useful products. Recycling reduces high rate of plastic pollution while putting less pressure on virgin materials to produce brand new plastic products (Rick, 2020). Plastics can be recycled mechanically or chemically. Mechanical recycling of PW involves physical degradation of the waste by grinding and shredding (Awoyera and Adesina, 2020). Mechanical processes such as grinding, washing, separating, drying, re-granulating or pelletizing and compounding are used to recover plastic and convert it into recyclates that can be converted into plastic products, substituting virgin plastics. Mechanical recycling is currently the dominating method of plastic recycling, but it is applicable to only thermoplastics materials such as polyethylene (PP), polyethylene (PE), polyethylene terephthalate (PET), etc. (Ragaert et al., 2017).

Thermoplastics materials are polymeric materials that can be re-melted and reprocessed into products through techniques such as injection molding or extrusion (European Bioplastics, 2022; Sugam, 2019). Mechanical recycling works well in the presence of well sorted and clean plastic waste which would lead to high quality plastic. Future and emerging techniques in mechanical recycling of plastics are tribo-electric separation, froth floatation, magnetic density separation, x-ray detection, etc. (Sugam, 2019). Chemical recycling of plastics involves breaking down (depolymerization) of the plastics into monomers or chemically modifying it to give virgin raw materials for the production of new plastic materials (Awoyera and Adesina, 2020). Chemical recycling can also be used to recycle plastics that are difficult or uneconomic to recycle mechanically such as films, multilayered and laminated plastics, etc. The different depolymerization routes for conversion of plastics into monomers are methanolysis, ammonolysis, aminolysis, hydrogenation, glycolysis, solvolysis, etc.

Other means of chemical recycling of plastics are pyrolysis and thermal cracking (catalytic and hydrocracking) which gives fuel, and gasification which converts PW to gases (Ragaert et al., 2017; British Plastic Federation, 2020; Xuyuan et al., 2019). Pyrolysis is the broken down of PW into a range of basic hydrocarbons by heating in the absence of oxygen at temperature of about 300-650^oC. Heavy wax, oil and gases are produced. Polymers (plastics) that can be pyrolyzed are polystyrene (PS), polymethylmethacrylate (PMMA), polyolefins such as PE, PP, polybutylene (PB), etc. (British Plastic Federation, 2020). In gasification, PW are pretreated to remove moisture and increase calorific value. PW is treated with gasifying agent e.g. steam, oxygen and air at a temperature of about 500-1300^oC to produce syngas (Dang et al., 2019). Syngas is a stream made up of H_2, CO_2, CH_2N_2. This method can be used to recycle all plastics. Hydrothermal process involves the use of hot compressed water to recover monomers and chemicals from PW so that they can be in plastic production.

Hydrothermal processes of recycling has been used for recycling waste carbon fiber reinforced plastics (CFRP) and printed circuit boards (PCB), PET, nylon 66, nylon 6, electronic waste plastics into synthetic crude oil, which is separated, purified and upgraded to get standard products (British Plastic Federation, 2020; Xuyuan et al., 2019; Jaime, 2020). The process of recycling is a good technology to reduce PW in the environment. However, some problems may be encountered during the process such as high cost of recycling, high technical know-how, loss and contamination of material, re-introduction of pollutants into the environment (e.g. through the discharge of waste water), etc.

3. Innovations for Plastic Waste Recycling

Research has showed that PW can be used for the production of many important and useful materials as follows:

3.1 Plastic Roads

PW are used for road construction. Research showed that incorporation of PW into materials of road construction such as bitumen, asphalt, concrete, etc, increases the fatigue life, durability, water impermeation, hardness, specific gravity, road resistance to deformation, making such roads to last long (Essawy et al., 2013; Mogaddam et al., 2013; Sasidharan et al., 2019). The idea of using PW in road construction is new. PW has been used for road construction in India, UK, Indonesia, Netherland, Ghana, Ethiopia and South Africa (Sasidharan et al., 2019). This innovation has not been practiced in Nigeria despite Nigeria's huge deposit of PW in the environment. Different research have been carried out on the use of plastic waste for road construction in order to develop the prototype design. Different types of PW have been incorporated into bitumen or asphalt for road construction, e.g. PP 4% by weight of total mix, PP and polyester fibers, HDPE and LDPE and bitumen, PET and bitumen (Chavan, 2013; Essawy et al., 2013; Mogaddam et al., 2013; Awwad and Shbeeb, 2017).

Laboratory test showed that when small amount (5-10%) by weight of plastic is incorporated in bitumen mix, there is improved pavement stability, strength and durability. Such roads will have higher resistance to deformation and water induced damage. There is also reduction in bitumen consumption, resulting in reduction of cost (Sasidharan et al., 2019). A group researchers prepared and compared the properties of bituminous and plastic bituminous road in order to determine the optimum proportion of PW to be added in the bitumen mix for the required strength (Azmat et al., 2017). The study showed that addition of PW enhances the various properties of the ordinary bituminous road and increase the Marshall Stability value of the samples. A group researchers produced plastic-bitumen road from PW and bitumen, by mixing shredded PW with hot bitumen (heated to 160^oC-170^oC), and stirring continuously for 20-30mins (Kurmadasu et al., 2016). The water penetration and ductility tests of the plastic bitumen composites were conducted and the results proved that incorporating plastic waste into bitumen increases road life.

A group researchers examined the effect of blending waste thermoplastic polymers (HDPE) and PP in conventional AC-20 graded bitumen at various plastic compositions (Appiah et al., 2017). The plastic was shredded and blended with bitumen at 160^oC-170^oC. Analysis of the modified bitumen showed enhanced rheological properties of the polymer such as viscosity, ring and ball softening point, penetration, compared to the unmodified polymer. The Ministry of Railways guideline for use of PW in road construction stated that PVC shall not be used for road construction because it is carcinogenic and release lethal levels of dioxins into the atmosphere (Ministry Railways, 2019).

It has been shown that addition of PVC pipe waste as a modifier up to a level of 3% and 5% of bitumen enhances both the bituminous binders and bituminous mix properties, and also reduces the rutting values, and increase the fatigue life of the bitumen mix (Ambika et al., 2019). Also, a group researchers investigated the use of recycled PVC particles for improving the mechanical properties of stone mastic asphalt (Mansour et al., 2022). Mechanical tests such as static creep, deformation strength, skid resistance and indirect tensile strength tests were conducted on the plastic asphalt mixture and conventional bitumen. The results showed that addition of recycled water pipe particles improved the mechanical properties listed. The study also revealed that increasing the percentage of recycled materials in the asphalt mix had a negative effect on skid resistance.

Recycled plastics can either serve as a binder or modifier in road construction, but no road has been reported to be constructed entirely from plastic. Although roads constructed with PW have proved to have good longevity and pavement performance, the long term outcomes of the roads have not been established as roads constructed using this technology is only about 10years old. Although it has its disadvantages (plastic still exposed to atmosphere), the advantage of better wear resistance (less potholes and repair) outweigh the regular asphalt concrete roads (Sasidharan et al., 2019). The challenges associated with the use of plastic waste for road construction are leaching of toxic components and generation of hazardous chlorine based gases during the road construction into the environment, adequate regulatory framework for the use of plastic waste in road construction, training for construction workers on health and safety issues and awareness of plastic waste management.

3.2 Construction Materials Such as Plastic Tiles, Bricks and Panel Boards

Since plastics are strong, durable, waterproof, light weight, easy to mould and recycle, it can be converted into building materials for low income population. The use of plastic for different construction application seems to be one of the effective ways to meet future infrastructural demand. The innovative sustainable use of plastic waste in construction application will significantly reduce the amount of plastic wastes disposed into the marine environment and will proffer alternative materials to meet the demand of the construction industry as well as minimize the cost of building product. PW can be used to make long lasting, high strength, reduced flammable, low water absorption and eco-friendly tiles for both residential and commercial applications. Plastic tiles float on water, making it good for marine application (Archit et al., 2019). Different types of plastics have been incorporated into different materials for floor tile production, for e.g., PET waste bottles and fly ash, LDPE with sawdust, LDPE and fly ash, PET, fly ash and river sand aggregate (Taiwa et al., 2021; Dhawan et al., 2019; Archit et al., 2019; Taiwo et al., 2021). Tests conducted on the mechanical properties of tiles revealed that PW improved the plastic tile's compressive strength, tensile strength, machinability, compared to ceramics tiles (Archit et al., 2019; Taiwo et al., 2021; Daftardar et al., 2017; Taiwo et al., 2021).

Many studies have been reported on the use of plastic waste as both additives and parent materials for production of construction materials. Waste plastic bags have been recycled for the production of floor and wall tiles with lesser flammability and enhanced tensile strength. Plastic waste mix was reinforced with fly ash and a flame retardant at different loadings, and molded into composite tiles. Morphological and structural properties of all the composites produced showed resistance to different acids, bases, organic solvents, water absorption and improved tensile strength (Dhawan et al., 2019). The effect of varying sand and plastic added on mechanical properties of cement matrix tiles was studied (Kehinde et al., 2019). Plastic waste and sand were mixed in various amounts in cement matrix production, while cement (5%) and laterite (30%) quantities were kept constant. The resultant mixtures were compacted by a load of 25kN into a mould and fired at 2200^{o}c for 35 mins. Tile specimens of thickness 15±1mm and facial dimensions of 150mm x 150mm were produced. Analysis of the fired tile specimen showed that the specimen with PW: sand ratio of 65 : 0 had the best water absorption, water shrinkage, flexural and compression when compared to other samples produced. The study suggested that increased PW and decreased sand content in cement matrix tiles is desired to achieve better physico- mechanical properties of the tile samples.

Another innovative and efficient way to capture value from post use plastic is in the use of PW for the production of plastic bricks. Plastic materials that can be used for plastic brick production include PE, nylon 66, PET, LDPE, HDPE (Aman et al., 2020). A group researchers produced high strength bricks that pose thermal and sound insulation properties and light weight from LDPE bags (Aman et al., 2020). The bricks also have high crushing strength (5mPa) and very low water adsorption (1.5%). Analysis of the compressive strength of PE bricks prepared by Shikhar showed that the compressive strength of plastic bricks increased with increase in the quantity of PW incorporated (Shikhar, 2017). Increase in compressive strength of plastic bricks with increase in amount of plastic was also observed (Kameshwar et al., 2017). A group researcher compared the properties of cement (30%) and sand (70%), plastic (16%) sand (84%), and plastic (12%) sand (80%) and coal tar (8%) bricks (Sachin and Dnyandev, 2017). Compressive strength and water absorption tests of the bricks showed that sand-plastic-coal tar has the highest compressive strength of 3000kf/cm^3 while plastic-sand bricks have the lowest % water absorption (0.92%).

Investigation on the mechanical and thermal properties of different PET/polyurethane (PU) binder interlocking bricks of composition 20/80, 40/60, 60/40, 80/20, using Response Surface Methodology to obtain a mix design showed that PET/PU of 60/40 ratio is suitable as non loading bearing masonry brick and recommended to be used as partition walls (Alaloul et al., 2020). A studied the physical and mechanical properties of plastic sand bricks in different plastic sand ratios of 1:3, 1:4, 1:5 by their weight using plastic as a binder (Kameshwar et al., 2022). The bricks showed 0%water absorption, compressive strength increased with increase in amount of plastic, while thermal resistance increased with increase in amount of sand. A study studied the viability (structural and integrity) of PET as a substitution for concrete in building material (Laura et al., 2020).

A group researchers designed a plastic-made emergency shelter module prototype and investigated the thermal behavior and resilience to climate conditions using dynamic simulations (Andres et al., 2020). Findings from the experiment suggested that recycled plastic materials have high resilient capacity to face different weather conditions and are suitable for construction of shelter modules for housing spaces, schools, or health centers in a post-disaster reconstruction scenario. The properties and behavior of recycled HDPE as a replacement to natural coarse aggregate was studied by (Ashwin et al., 2021). HDPE was recycled by segregation, extrusion and crushing to 20mm aggregates at 160^{o}C-190^{o}C. The recycled HDPE was replaced in 0%, 15%, 20%, 25%, 30%, 35%, 40% by weight of M_{25} grade of concrete mix developed according to ISI 0262 - 2019 standard.

The compressive, split tensile and flexural strengths, and workability results of the concrete-plastic mixture showed that up to 15% of recycled HDPE is suitable for structural concrete, the remaining is best for non structural usage. A group researchers also investigated the mechanical properties (compressive strength, water absorption, efflorescent and fire resistance) of different ratios of plastic sand bricks (1:2, 1:3. 1:4) in order to find the optimum proportion which gives the desired results (Chauhan et al., 2019). The PW was heated to 180^{o}C-200^{o}C and the sand added and homogenously mixed. The study reported an increased compressive strength with increased quantity of the PW and low water absorption of 0.9%-4.5% for the plastic sand bricks. The study recommended the bricks for underground tanks and sanitary landfill underlining.

PW has also been used for the production of panel boards which are used as wall building materials. Plastic panel board which is clear, resembles glass and can be used for interior designs was produced from PET flakes, resin (binder), other additive mixtures comprising of methyl ethyl ketone peroxide (catalyst to harden the resin faster) and kaolin (filler) (Purwanto and Darwaman, 2017). Plastic panel boards have also been produced from non metallic waste printed circuit boards and automotive plastics (Raghu et al., 2016). Analysis of the physical and mechanical properties of plywood panel prepared using LDPE as an adhesive indicated increased tensile strength and modulus of elasticity with increased polymer content. The glue shear strength of the plywood was influenced by the quantity of polymer and sufficient quantity of polymer and is necessary for strong bonding of the mix (Sidhartha and Shakti, 2022).

3.3 Plastic Composites

Plastic composites with improved mechanical properties have been made from different materials and PW. A composite is a material made by combining two or more materials to give a unique combination of properties (Kalyana et al., 2015). Plastic composites are plastics that are strengthened with fibers, fillers, particulates, powders and other matrix reinforcements to improve strength and stiffness. They are multiphase materials in which reinforcing fillers are integrated with a polymer matrix, resulting in synergistic mechanical properties that cannot be achieved from either component alone (Greene, 2022). The polymer composites may contain glass, carbon, wood, metal, ceramics, textile and so on as the reinforcement, and polymers as the matrix or binder (Murcia et al., 2022; Amor et al., 2021). Thermoplastic and thermosetting resins have been used extensively as the matrix. The thermosets are of low viscosity, while thermoplastics have the possibility of recycling and reusing, since they are moldable after initial production (Ayesha and Yashir, 2020).

Plastic (polymer) based composites have gained much attention in recent years owing to their properties such as light weight, high tensile and flexural strength, design flexibility, corrosion resistance and remarkable long service life. Polymer composites are also known for their thermal stability, improved creep and wear, and can be tailored to satisfy performance requirements. Different polymer matrix components exist and have been studied extensively. Examples are textile-reinforced polymer composites (made of polymer matrix reinforced with textile materials), glass fiber reinforced plastic composites (made from glass fibers and polymer matrix), carbon fiber reinforced polymer composites from carbon fiber and polymer matrix, glass carbon reinforced polymer composite (from glass and carbon and polymer matrix), metal reinforced polymer composites and wood reinforced polymer composites (Yilmaz et al., 2018; Sulochani et al., 2022; Bhattacharya and Agrawal, 2017; Tam and Bhatnagar, 2016; Sathishkumar et al., 2014; Hussain et al., 2011; Fekete and Hall, 2016; Ozkan et al., 2020; Turgirumubano et al., 2020; Sergio et al., 2021; Vinay et al., 2016).

Carbon fiber reinforced plastic is used in repairing and strengthening of reinforced concrete structures. Glass fiber reinforced plastic has several advantages including high strength to weight ratio, flexibility, high fracture toughness and excellent corrosion and thermal resistances. Polymer composites transformed the growth of industries especially automobiles, construction, aerospace, etc, as they are used in almost every type of advanced engineering structure with their usage ranging from aircraft, helicopters, sports goods, chemical processing equipment, civil infrastructure such as bridges and buildings, ships, boats and offshore platforms, etc. (Amor et al., 2021; Masuelli, 2013). Of all the composites, wood plastic composite is one of the most important natural fiber reinforced composites mainly produced by thermoplastic polymers PP, PE, PVC, PS and biomass particles and fibers from forestry and agricultural wastes. Wood plastic composites begin to replace some conventional wood products like particle boards, plywood, wood veneer, medium density fiber board, etc (Kaimeng et al., 2021). But wood plastic composites can be affected by moisture, and the colour can be degraded by UV and sunlight over a long period of time.

In literature, there are several methods used for the development of fiber reinforced plastics. Textile reinforced polymer composites can be fabricated using injection molding, vacuum bag molding technique, hand layup technique, extrusion method, etc. A group researcher produced wood plastic composite from LDPE and coir pith extracted from coconut (Kalyana et al., 2015). The plastic was put in a mold and melted at 90-100^{o}C to become molten liquid and coir pith was added in layers, with the top layer being the plastic melt. The mixture was allowed to solidify for 8-24hrs. Analyses of the mechanical properties of the composites such as Izod, Rockwell and compression tests showed that the composite material has good hardness and compressive strength, with moderate impact strength compared to plastics. The mechanical properties of wood flour polypropylene and maleic anhydride- grafted polypropylene (as additive) (ratio 25:74:1(wt%)) composite, prepared using a twin-screw kneader at 190^{o}C for 13min at a rotary speed of 30rpm was studied by (Murayama et al., 2019).

Evaluation of the strength of the composites revealed that impact strength of the composites increased as milling time increased due to increase in the amount of small wood flour particle. A group researchers examined the effect of particle size of wood flour content on the properties of polystyrene filled with white oak flour (Hernandez et al., 2019). The wood plastic composites were prepared in the ratios 10:90, 30:70, 50:50% (wt/wt) and particle size 40, 50, 65, 100 mesh, and blended using a co-rotating twin screw extruder equipped with a round profile die, at a temperature of 170-195^{o}C. The extruder strands were cooled in water trough and pelletized. From the analyses of tensile, bending, impact bending strength of the pellets, it was observed that the mechanical properties were strongly influenced by wood flour content and particle size, as impact strength increased with particle size and content, while tensile modulus, elongation and deflection, bending strength reduced with increased particle size.

The development of polymer composites is a welcomed idea as it provides biodegradable plastic materials when made from biodegradable sources such as wood, textile, etc. A study by a study showed that wood plastic composites as termite bait decreased in weight, even though the mass loss was comparatively small (Nuryawan et al., 2020). Micro-confocal Raman Imaging Spectrometer revealed that termite guts from insects feeding on wood plastic composites contained small amounts of LDPE. This shows that termites consume plastics in the form of wood plastic composites, though the actual fate of the LDPE in termites is still unknown. The effect of filler content (peanut husk) and compatibilizer (maleated polyethylene) on the mechanical properties of LDPE studied by Obasi, showed that compatibilizer led to a better dispersion and homogeneity of agro-filler in the matrix (Obasi, 2015).

Also, the physical and mechanical properties of thermoplastic composites depend mainly on the interaction between the natural filler and thermoplastic material. A group researchers evaluated the properties of recycled PET, rubber wood and silica (in ratios 10:20:70, 10:30:60,10:40:50%wt), prepared by heating the mixture at 180^{o}C and compressing at 5.5mPa for 10 min (Aujcharuja et al., 2022). Water absorption of the composites increased with increased quantity of silica, hardness and compressive strength increased with increased percent by weight of the PET waste. The study added a valuable environmental friendly composite to be used for different applications such as window and stairs rails, etc. High cost of producing the composites, low throughput rates at which the composites can be manufactured and high technical know-how (of both the machineries and production procedures) are the challenges associated with this technology.

3.4 Fabrics for Textile Industry

Recently, fabrics have been made from PW in a move to reduce plastic pollution and make the fashion industry more sustainable. PW have replaced fossil materials used in making synthetic fibers. This has positive effect on the circular economy and the environment as it helps to provide usage for the PW, thereby reducing plastic pollution and its negative effect, as well as provide income and employment to people (Sezgin and Yalcin, 2021). Synthetic fibers have replaced natural fibers in recent years owing to their low cost, and this has made plastic materials one of the most important sources of the textile sector (Eionet Report – ETC/WMGE, 2021). PW are recycled into fabrics for clothing in many parts of the world. In India and other foreign countries, textile companies such as Arora Fibers, Chenap Textiles, Orient Suntex, Patrick Yarns have successfully converted plastics into fibers and yarns.

A group researcher listed insufficient raw materials among others as one of the problems facing Nigerian Textile Industry (Diogu et al., 2014). Information on recycling of PW into fabrics in Nigeria is on a very small scale, which cannot be enough for Nigeria's textile industry (Trend Desk, 2022; Voice of Africa, 2018). The fabrics that can be made from PW are polyester and nylon, and it has potential for use in many applications owing to their properties such as high strength, resistance to shrinking, elasticity, chemical and heat resistance, etc. (Carmichael, 2015; Subramanian et al., 2021). In mechanical recycling, PW are shredded into flakes by a machine, the flakes melted down into pellets and the pellets are extruded into long continuous filaments. The filaments are spun into yarn. Across the production process, many chemicals are added to provide the textiles with colour prints and additional properties (Eionet Report – ETC/WMGE, 2021). The yarn may be crocheted, knitted, cut and sewn into clothing.

Different types of plastic materials can be used in production of plastic textile. PET, polyamide (nylon), polyolefin (PP and PE), PVC are used singly or combined in blends with other synthetic and natural fibers (e.g. polycotton) to produce a lot of clothing materials. The reason for blending the different waste fiber types with natural or synthetic fibers is to reduce cost, or build fabrics with combined properties that cannot be achieved with a single fiber (e.g. polycotton). The plastic fibers can be made into clothing (fleece, blanket, sports and leisure wears, etc) and technical textiles such as conveyor belts for machinery, filters for air conditioning and medical applications, construction material, tyre cord reinforcements for vehicles and industrial safety fabrics, carpets, ropes, airbags, etc. (Eionet Report – ETC/WMGE, 2021; Niinimaki et al., 2020).

There are also investigative studies on the properties of the fabrics produced to ascertain their shell life and also to compare them with the fabrics made from virgin products. A researchers investigated the mechanical properties of monofilament yarns produced from blending virgin PET (V-PET) and recycled PET (R-PET) bottle flakes (Nabo et al., 2015). The V-PET/R-PET pellets were blended in the ratios of 0/100, 10/90, 20/80, 30/70, 40/60, 50/50and 100/0 using a twin-screw extruder and then thermally drawn to improve the mechanical properties. Results of the analysis of the monofilament yarns showed that the V-PET/R-PET of 100/0 pellets exhibited maximum intrinsic viscosity, high molecular weight, high crystallinity, minimum thermal shrinkage and hence have superior mechanical properties compared to other blend composition.

The study revealed that R-PET content above 80% in the blended yarn is not recommended as they have poor mechanical properties. Uyanik investigated the bursting strength properties of knitted blend yarns containing viscose fiber and recycled polyester fiber at different blend ratios, and pure yarns with virgin polyester fiber (Uyanik, 2020). The study revealed that the recycled PET fibers provided bursting strength values which are close to that of virgin PET fibers for the knitted fabrics having coarse yarns, but they do not contribute positively to the knitted fabrics having fine yarns. The quality properties of open-end spun recycled yarns made from blends of recycled fabric scrap wastes and virgin polyester fiber was studied by (Ahu and Eren, 2019). The effect of yarn count, blend ratio, waste type, waste origin, twist coefficient and rotor diameter on the quality properties of the recycled yarns were evaluated through statistical methods. The statistical results showed that blend ratio, yarn count and twist coefficient significantly affect the quality, and that incorporation of virgin polyester to fiber to recycled fiber tends to bring about improvement in yarn quality.

Sarioglu and Kaynak studied the use of textile fiber from recycled PET (r-PET) bottles in producing a cotton blended yarn (Sarioglu and Kaynak, 2017). The study compared the properties of cotton blended virgin polyester fiber with r-PET in order to determine the advantages and disadvantages of r-PET fiber. The study concluded that v-PET yarns have higher tensile strength than r-PET as a result of the recycling and reforming processes undergone by r-PET. A group researcher also produced a yarn from PET bottles which is used for sunscreen curtains (Srithummarong et al., 2022). Study of the yarn property of the PET sunscreen curtain showed that the mean strength, mean toughness, tensile stretch before breaking and the mean percentage of elongation before breaking was 30.25N, 5.74gf/den, 37.46mm and 149.83% respectively. A group researchers developed recycled PET (rPET) into different types of comfort materials such as lumbar, cervical body, therapeutic and neck pillows (Radhakrishnan et al., 2019). Comfort properties of the materials such as water vapor permeability and thermal conductivity was also conducted.

A study compared the properties of recycled-PET and virgin-PET in terms of technical aspect and market potential (Bhattacharya et al., 2021). From the market potential point of view, the study reported that textile fabrication is forwarding towards sustainability through reprocess polyester. The order for reprocessed PET fiber is amplifying in the garments, fashion and retail sectors, with first world countries across the globe promoting the idea of using reprocess polyester in many companies. The order for high quality reprocess PET filament is increasing as the textile industries are getting over with the technical problems such as dyeing uniformity with respect to extracting PET by mechanical process. From the comparative analysis of the two PET types, the study concluded that virgin polyester can be replaced with recycled polyester as their physical properties are quite similar.

Although making fabric from recycled plastic use so much energy to convert the old stuff into new fabric, they do not use as much energy or resources as in creating fibers and fabrics from scratch (Sezgin and Yalcin, 2021). The drawbacks to mechanical recycling of plastic waste into fabrics include presence of impurities in the fabrics, poor quality of some recycled waste, complexity of plastic solid waste, reintroduction of micro-plastic into the environment through the discharge of effluent from textile industry and huge machinery needed for the production (Tshifularo and Patnak, 2020; Eionet Report – ETC/WMGE, 2021). These drawbacks can be curbed by practicing sound textile waste management, proper waste water treatment and incorporating screen changer machine to separate the contaminants from the plastic (Eionet Report – ETC/WMGE, 2021; OECD, 2017; Agrawal et al., 2014). Some researchers discussed the different stages of value chain for polyester clothing from the perspective of sustainability with reference to environmental challenges such as pollution from textile factory waste water and microfibers released from clothing during the laundry cycle (Palacious-Mateo et al., 2021). The study recommended meaningful and effective ways to improve the environmental sustainability of polyester textiles on a global scale. People's perception can also be a challenge to the use of plastic waste for fabrics, because most Nigerians prefer foreign made textiles to the locally made one.

3.5 Fuel and Other Valuable Chemical Products

Another way of utilizing PW is by converting them to fuel and other valuable chemical products. This has dual benefits, first, the fuel and chemicals produced can be used in many ways, and second, pollution caused by the PW is minimized. Countries like Japan, Germany, India and US have already implemented the plastic to fuel conversion process with much success. The fuel obtained from conversion of plastic is environmentally friendly due to absence of toxic substances (like sulphur), it also has longer burning time compared to gasoline (as a result of higher molecular weight compounds). Some of these countries have successfully created business models out of the conversion process, resulting in the conversion model becoming a profitable business one (Saptarshi, 2017).

Currently, the technologies for conversion of plastic waste to other valuables include pyrolysis, heat treatment, gasification and advanced oxidation. The popular processes are pyrolysis and gasification. Pyrolysis is the controlled heating (at about 500^{o}C) of a material in the absence of oxygen while gasification is a thermo-chemical process (800-1200^{o}C) that converts materials into combustible gas in the presence of oxygen, water or carbondioxide. In plastic pyrolysis, the macromolecules of long plastic polymers are broken down into short chain hydrocarbons which yield valuable liquids with properties similar to diesel or naphtha. This reaction can take place in the presence of a catalyst (catalytic pyrolysis) or heat (thermal pyrolysis).

Oil produced by catalytic pyrolysis has high quality compared to thermal pyrolysis. Catalysts also target the specific reaction and reduce the process temperature and time. The most commonly used catalysts in literature for PW pyrolysis include ZSM-5 zeolite, Y- zeolite, FCC, MCM-41 and silica alumina (Miandad et al., 2019; Jha et al., 2020). Different types of plastic can be used as the feedstock, singly, or combined in different ratios. There are many researches involving thermal and catalytic degradation of plastic waste into liquid fuel, resulting in successful outcomes with high yields of hydrocarbon liquids. A group researchers produced fuel from different synthetic plastic in a pyrolysis stainless steel reactor at a temperature of 550^{o}C, heating rate of 15^{o}C/ min (Fahim et al., 2021). The products of the pyrolysis-oil and gas vapour were condensed to produce fuel oil, heavy oil and light hydrocarbon.

The calorific value of the fuel produced was 9829.3515kcal/kg and is close to that of diesel. The emission and performance characteristics of PW made from the pyrolysis of HDPE and oxygenated additives (10% ethanol and 10% ethoxy ethyl acetate) fuelled in a single cylinder diesel engine was analyzed by (Padmanabhan et al., 2022). The oil output for the HDPE is 50% weight of pyrolysis oil with 25% wax formation, 25% gas and coke formation. The pyrolysis of plastic mixture containing mainly PET using ZSM-5 zeolite was studied by (Olugbenga et al., 2021). The gas obtained had blue flame, indicating the presence of light hydrocarbon fuel. In the process described by thermal degradation was used to heat plastic waste to form liquid slurry at temperature ranging from 370-420^{o}C (Sarker et al., 2011). The slurry turns into vapor which was distilled at various temperatures to produce liquid fuels with similar characteristics like gasoline, naphtha, kerosene, aviation fuel and diesel, confirmed with GC/MS, FTIR and DS.

A group researchers compared the efficiency/ yield of thermal pyrolyzed HDPE pellets at temperature range of 500-700^{o}C using 30g sand in the bed and N_2 as a fluidization agent and catalytic pyrolyzed HDPE at 450-500^{o}C using 30g of zeolite catalyst in the bed, at flow rate of 1g/min for both processes (Arabiourrutia et al., 2017). The products obtained were gas fraction (C_1-C_4), gasoline fraction (C_5-C_{11}), diesel fraction (C_{12}-C_{20}), wax fraction (>C_{21}), with yield of about 40 wt%, 35 wt%, 15 wt%, 10 wt% at 700^{o}C respectively for the thermal pyrolysis, and (C_2-C_4) olefins, light alkanes (C_4), non-aromatics (C_5-C_{11}), single ring aromatics (C_{12}-C_{20}), wax fraction (>C_{21}), with yield of about 60 wt%, 15 wt%, 13 wt%, 10 wt%, 2 wt respectively at 500^{o}C. A group researchers produced and characterized alternate diesel fuels from pyrolysis of HDPE, LDPE and PP using a local experimental set up comprising of a pyrolyzer, pipes and collector (Ram et al., 2020).

The Brake thermal efficiency, Brake specific fuel consumption, CO and hydrocarbon emissions were analyzed, and the results showed that 1kg of plastic yielded about 600 to 750ml of diesel fuel, CO emission vary by 2.40% by volume while hydrocarbon emission vary from less than 36ppm to 58ppm at full load. Science Daily News reported on the photo-degradation of polyethylene by sunlight in the presence of vanadium catalyst in a solvent, into formic acid, a chemical used in fuel cells to produce electricity (Science Daily News, 2019). Plastic waste has also been co-pyrolyzed with biomass using red mud (a by-product in Bayer process) as a catalyst. It was discovered that the quality of biofuel obtained was enhanced as the activated energies of the biomass, plastic, biomass-plastic and biomass-plastic-catalyst are in the ranges of 78-268, 172-218, 67-307 and 202-292kJ/mol respectively (Bhagat et al., 2018).

A group researchers also reported on the biomass: polystyrene (1:1) co-pyrolysis coupled with metal modified zeolite catalyst in a two-stage fixed bed reactor to produce upgraded bio-oils for production of liquid fuel and aromatic chemicals (Andrew et al., 2022). The catalyst was impregnated with different metals Ga, Cu, Fe, Ni to determine their influence on bio-oil upgrading. The highest yield of polycyclic aromatic hydrocarbons was obtained with Ga-zeolite. Polyethylene sachet waste has been pyrolyzed to obtain polyethylene wax and used to produce shoe polish. The produced shoe polished compared favourably with the paraffin wax based shoe polish in terms of their viscosity (Orijiakor et al., 2022). A group researchers reported on various literatures on the investigative approaches of the performance of plastic waste fuel in various diesel engines (Padmanabhan et al., 2022). There is also extant literature on the potential of adsorbents derived from PW for the removal of different harzadous contaminants, including the capture of CO_2 (Mara and Mercedes, 2012; Hussin et al., 2021).

The challenges of converting PW to fuel oil and other valuable products involves sorting and separation of mixed PW into separate parts, this is necessary because pyrolysis of single types of plastic is required for high yield. Again, valorization process produces fuel oil on a smaller scale and requires intricate post-processes to meet commercial fuel requirement. High skilled personnel and high-level technology are also needed for a cleaner waste polymer. Segregation of the plastic waste at the point of use into their various components will improve its recyclability and boast circular economy.

3.6 Biodegradable Plastics

Petroleum based plastics are not degradable and can last for years in the environment. This is because they are inert to micro-organisms, heat and water. Biodegradable and photodegradable plastics as well as bio-based plastics have been developed by researchers in order to reduce the cost of disposal as well as their menace to the environment. Biodegradable plastics are plastics that can be decomposed after disposal to the environment by the activity of micro-organisms to produce the final products CO_2 and H_2O while photodegradable plastics are plastics that are decomposed by the action of light, particularly sunlight, ultra violet rays, etc. (Nik-Abdullah et al., 2014).

Bio-based plastics are plastics which are made up of carbon obtained from renewable resources. Major types of biodegradable plastics which are produced commercially are polylactic acid (PLA) and polyhydroxy alkanoate (PHA) (Mohanty et al., 2000). Bioplastics can be gotten from plant biomass through different methods, e.g., by direct extraction of plant biomass, chemical conversion into sugar or bacteria fermentation followed by extraction, chemical conversion into building blocks or polymerization, etc. (Geuke, 2015). It can be processed using conventional technologies such as injection molding, blow film, extrusion and thermoforming, compression molding, etc. (Mostafa et al., 2015). These plastics have been made into components of cars, eating utensils, bottles, etc.

Investigative studies on biodegradable plastics include that by who produced cellulose acetate biofiber from flax fibers and cotton linters (Mostafa et al., 2015). Analysis of the cellulose acetate which includes XRD, FTIR, gel permeation chromatography confirmed the structure of the biodegradable plastic. Chemical test showed that the cellulose acetate reacted with strong alkali and acid such as NaOH and hydrogen tetraoxosulphate (vi) acid. Biodegradation tests showed biodegradability of 44% and 35% after 14 days for cellulose acetate from flax fiber and cotton linters respectively. Mukesh discussed the production of biodegradable plastic from cheese whey using bacterial strain and media –T thermophiles HB8 in mineral salt, banana peels, cassava, potatoes and corn (Mukesh, 2019). Jayakumar *et al*., [114] produced biodegradable type of plastic from protein found in milk (casein) together with clay by polymerization method at 65-70^{o}c (Jayakumar et al., 2013). The plastic was made into any shape by using a molder. 20% of the bioplastic was able to decompose after 18days in a landfill. Quality assurance tests showed perfect biodegradation.

Decomposition of the biodegradable plastic begins with fragmentation, i.e., the material undergoes chemical decomposition when exposed to living and non living factors. The products are mineralized micro-organisms and are metabolized into end products. Organic carbon is converted to carbondioxide in the process of aerobic metabolism (Krzan, 2012). The major challenge of bioplastics are the cost of production and use of agricultural food crops in bioplastics which can increase the price of food stuff as a result of high demand of such crops.

4. Conclusion

The issue of unmanaged and mismanaged PW constitutes a great threat to Nigerian environment. Proper and effective plastic waste management such as recycling will enable the mitigation of the negative impacts of plastic waste in Nigeria. It can also help to boost Nigeria's circular economy which is linear currently. Information about plastic waste recycling on a large scale in Nigeria is limited in literature. This work has discussed key technologies available for recycling of PW. The technologies discussed can be useful in decision making towards achieving a circular economy in Nigeria. The literatures cited have established the possibility of utilization of PW in the various areas, however, extensive research should be carried out on the durability and performance of the produced products or materials (i.e. PW textiles, bricks, chemicals, etc) over a long period of time. The advantages and gains of these innovative technologies coupled with the environmental impact have necessitated their implementation and sustainability in Nigeria.

Competing Interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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