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Thermoplastic Recycling: Properties, Modifications, and Applications

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Abstract

The increasing rate of plastic waste generation coupled with undesirable disposal, especially in the urban areas, has resulted to environmental threat in the globe which has been attributed to legislation, poor biodegradability, economic growth, rural to urban migration, increase in consumption, and standard or cost of living. This chapter will focus on overview, properties of virgin and recycled thermoplastics, recycling techniques, and applications of different types of thermoplastic articles such as HDPE, LDPE, PVC, PET, and polypropylene (PP) with improved properties based on modifications using eco-friendly materials for sustainable applications in order to save human existence from the menace of environmental and economic issues.

Keywords: thermoplastics, recycling, modifications, properties, applications

1. Introduction

Globally, poor solid waste management remains an issue of concern in an environment due to inadequate policies, legislation, and public enlightenment on waste disposal [1]. The policies of the government on the environment are merely by mouth with poor implementation. The enlightenment programs remain poor with lack of needed coverage, intensity, and continuity so as to change the attitude toward the management of the waste disposal to the environment. However, the poor activities of government agencies for a safe environment may be attributed to improper funds, inadequate facilities and human resources, low technology know how, and taxation system [2]. Integrated solid waste management, 3R (i.e., reduce, reuse, and recycle) principles have contributed to minimization of waste in the environment. Successful means of solid waste management required an integration of technical, economic, and sociocultural involvement. The generation and disposal of plastic waste in environment have been undesirable activities that posed serious threat to humans' existence due to large quantities, low biodegradability, and its significant effect on economic growth [3]. In Japan, the waste quantities increased from 46 million tons in 2001 to 65 million tons in 2010 and are expected to have 0.7 kg/capita/day production in 2050 [4] and range from 0.44 to 0.66 kg/capita/day production in Nigeria [5]. The increase in solid waste generation in which plastics are included, in the urban area, is dependent on the increase in migration from rural to urban area, rate of consumption and standard of living, lifestyle, population density, and climatic changes [5, 6] (see **Table 1**).

| S/N | Waste material | Percentage (%) | |
|-----|---------------------|----------------|-------------|
| | | Japan (%) | Nigeria (%) |
| 1 | Paper and cardboard | 34 | 4 |
| 2 | Organics | 32 | 78 |
| 3 | Plastics | 17 | 9 |
| 4 | Metals | 6 | 4 |
| 5 | Glass | 5 | 3 |
| 6 | Inorganic | 4 | 1 |
| 7 | Special waste | 2 | 1 |
| | Total | 100 | 100 |

Table 1.
Solid waste generated [4, 5].

| Plastics | | Japan (%) |
|----------|--------------------|-----------|
| 1 | Polyethylene | 24.1 |
| 2 | Polypropylene | 23.1 |
| 3 | Polyvinyl chloride | 15.2 |
| 4 | Polystyrene | 7.0 |
| 5 | PET | 4.0 |
| 6 | ABS | 3.5 |
| 7 | Others | 13.3 |

Table 2.
Recycling and generation of thermoplastics [11].

In the USA, about 30 million tons of plastic wastes were produced in 2009 and only about 7% was recycled. Plastic wastes end up in landfills, beaches, rivers, and oceans, thereby causing environmental problems [7]. In the UK, about 5 billion of plastic wastes are generated every year [8]. In some developed countries like Japan, plastic waste is found to be the third major municipal and industrial waste [4] but second in developing countries like Nigeria [9, 10]. Based on production and utilization of plastics in Japan, about 90% of the plastics are thermoplastics (a type of plastic that undergoes a reversible chemical reaction for its curing and melting at high temperature) used for containers and packaging materials (films, sheets, bottles), daily necessities, household appliances, and automobiles as presented in **Table 2** and **Figure 1** [10, 11]. About 60–70% of thermoplastics are polyolefins, while PET, PS, and PVC make other compositions [12]. In Europe and developing countries, the incineration and landfill techniques used for management of plastics waste covered about 74%, despite advanced effect. Plastics are less expensive, weight saving, durable articles which can readily be molded into a variety of products and found useful in a wide range of applications [13], but its production and usage caused several environmental problems through disposal [14, 15]. Moreover, durability of thermoplastics is a consequence for disposal and accumulation in landfills.

Plastic recycling refers to a process of achieving useful products from waste plastics after its reprocessing or re-melting. Recycling is one of the most important actions currently available that provides a solution on environmental and ecological

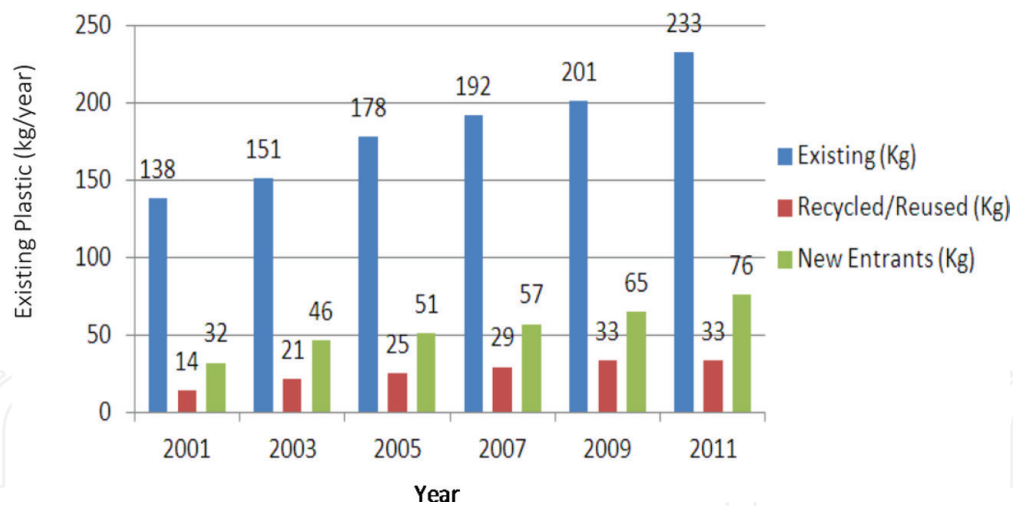


Figure 1.
 Existing, recycled, and new entrants of plastic wastes [10].

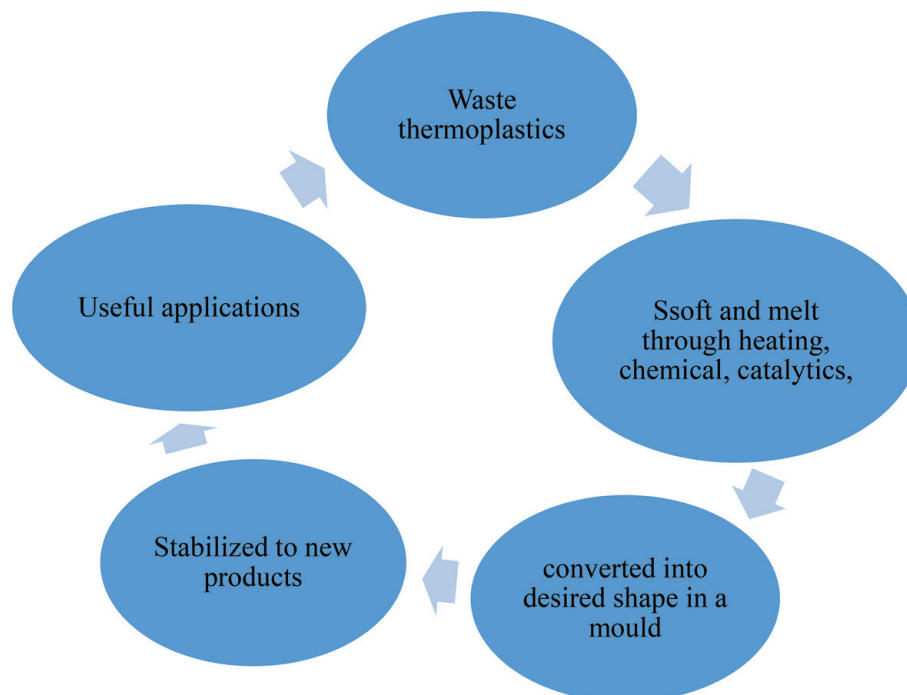


Figure 2.
 Thermoplastic recycling process chart.

threats posed by reduce oil usage, carbon dioxide emissions, and the quantities of waste requiring disposal [14, 16]. Despite plastic recycling remaining to be the best means of minimizing plastic waste, its quality is influenced by polymer cross-contamination, additives, non-polymer impurities, and degradation [17]. Recycling of thermoplastics posed many benefits such as provision of raw materials for manufacturing industry, reduced environmental threat to humans since it is non-biodegradable, minimized incineration and landfill issues, less energy consumption for sustenance, and it serving as a source of income and providing job opportunity [18]. However, economic factors that influenced the viability of thermoplastic recycling include the price, cost of recycling compared with forms of required disposal, suitability for specific applications, lack of information about the availability of recycled plastics, and quantity and quality of supply recycled thermoplastics compared with virgin thermoplastics [17, 18]. Thermoplastic recycling follows the pattern of **Figure 2**.

Waste polymer recycling can be carried out by four approaches in accordance with ISO 15270, namely:

1. Primary recycling refers to the recycling of the scrap material of controlled history. This process remaining to be the most popular as it ensures simplicity, low cost, and applicability to clean uncontaminated single-type waste. It involves melting with use of solvents and remolding of clean materials [19].
2. Mechanical recycling: waste plastic is recycled or reprocessed by mechanical process using melt extrusion, injection, blowing, vacuum, and inflation molding method after sorting [2, 20, 21]. This method utilizes a 100% utilization and conversion of waste plastic to produce the same or other valuable products but with reduced qualities which can be enhanced by the application of additives. It may or may not be necessarily separated depending on desired products and quality. It is applicable to reprocessing plastics that require pretreatment or decontamination.
3. Chemical or feedstock recycling: waste plastics serve as raw materials and convert into monomer or other products such as fuel oils and cooking gas through decomposition and depolymerization of feedstock with the use of thermal energy or catalyst [22, 23]. This method seems to be economical but reduced the yield of new products [24] and less than the yield of the mechanical recycling of thermoplastics due to no loss of materials and accumulation caused by pipeline blockage as a result of shutdown of the machine, thereby lowering melting points during solidification stages. Pipeline blockages or clogs may be difficult to remove. This method involves decomposition of waste polymers to lower-molecular-weight species for reuse with applications of solvents like benzene, chlorobenzene, trichloroethylene, toluene, and xylene called dissolution/reprecipitation (DR) or solubilization before pyrolysis (applied high temperature and pressure in the absence of oxygen) [25]. This provides an insight to the solution of clogged pipeline issues but at increased processing cost and time with high-energy consumption compared to mechanical recycling.
4. Energy recovery: This is an effective means to reduce the quantity of organic materials by incineration, with difficult environment pollution control from the waste plastics [24, 26]. It involves cement kiln and waste power generation.

This chapter focuses on modifications of thermoplastic materials (HDPE, LDPE, PVC, PET, and PP) and mechanical recycling for enhanced properties, performance, and quality of the products for sustainable applications.

2. Recycling of modified virgin and waste thermoplastics

The choice of recycling of waste thermoplastics depends on processing equipment such as injection, single-screw extruder and film blowing machine, and processing conditions (temperature, time, content of materials, and rheological behavior) and product uses [27–32]. The application of additives or modifiers like compatibilizer (nonreactive and reactive), fillers or fibers (inorganic and organic) have been attributed to ease processing and improvement in compatibility [28, 31]. More so, the recycling of waste thermoplastics is cheaper than virgin types, but its inferior properties [20, 21], contaminations, and poor suitability [33] remain an

issue of concern for effective applications. Blending technology remains a proffer solution due to low cost to produce, lower technical risk, and eco-friendly materials when compared to developing new polymers [28]. Sorting or separation before recycling through manual [34] application of principle of density and solubilization with the use of solvents (hexane, benzene, xylene, and toluene) provides solution to contamination [2] but not cost effect and risk. Techniques for modifications of thermoplastics may be due to the use of different waste or virgin thermoplastics and natural materials, thereby producing composites with enhanced properties and durability [35]. This can be influenced by processing, crystallization, and phase morphology as reported by Lin et al. [32]. The use of different waste or virgin thermoplastics seems to be uneconomical due to cost of blended and non-compatibility of the thermoplastics which may require a new compatibilizer. The use of natural materials for modification of virgin and waste thermoplastics remains a potential technique for thermoplastic recyclates. Therefore, the major reasons for modification of plastic resins in the industries include to meet specific processing and performance specification of a plastic product that is not satisfied by a single component, to upgrade the properties of postconsumer plastic wastes, for scientific research, for interest and development, and for financial optimization [31, 32]. However, degradation of thermoplastic materials by chemical processes is a function of reaction between the components and the environment. The reduction in photodegradation of thermoplastics by ultraviolet absorber as an antioxidant shows a retardation effect of oxidation [36]. Therefore, the aging process of thermoplastics can be influenced by the synergistic action of factors like electromagnetic radiation and thermal energy on the oxidation, favoring the initiation of degradation by excision of chain and radicals of thermoplastics [36].

2.1 Modifications and properties of recycling of virgin and waste HDPE

The incorporation of the carbon nanotube, zeolite, LDPE, PP, natural fillers, and fibers with treatment into the waste polymer for reuse has resulted to an improvement of the composite strength and enhancement of compatibility of blended components of composites as presented in **Table 3**. The improvement has been reported to be a function of compatibilizer types, size and particle shape, branching, and dimensions of polymeric chains as reported by [37]. In the case of natural fibers or fillers, it seems fibers or fillers containing compatibilizer which may or may not have been identified. Moreover, the melting flow rate of recycling of postconsumer or waste HDPE remains inconsistent with stabilization, and the consistency can be achieved with a mixture of phosphite and phenolic. This might be uneconomical. The enhancement in mechanical properties and performance of the HDPE matrix and composite product by additives (sodium hydroxide (NaOH), sodium lauryl sulfate (SLS), and acetic anhydride) have also been attributed to increased interfacial adhesion coupled with its improved water absorption [21], biodegradability, biocompatibility, antimicrobial activity, and non-toxicity with the use of chitosan compounds [38]. The density of recycled virgin and waste HDPE is within the range of 0.02–0.96 g/cm³ [36, 39]. Increase in density can be ascribed to chemocrystallization, annealing effects and changes in lamellar orientation, fiber loading, moisture absorption, and aging of HDPE products [35]. Annealing effect involves changes in spherulite size of HDPE material after heat effect, and aged surface shows loss of gloss observed as a result of environmental effect through oxidative stress and disappearance of crystalline molecule of the HDPE materials produced by a surface contraction. The surface contractions initiate micro-cracks and lead to embrittlement of ductile HDPE polymers [35].

| Materials | Modification | Tensile strength (MPa) | Tensile modulus (MPa) | Flexural strength (MPa) | Flexural modulus (MPa) | Hardness | Impact strength (J/m ²) | References |
|-------------|--|------------------------|-----------------------|-------------------------|------------------------|----------|-------------------------------------|------------|
| Virgin HDPE | — | 21 | 189 | — | — | — | 6.8 | [33] |
| Virgin HDPE | Using LDPE | 22.5 | 860 | — | — | — | 135 | [28] |
| Virgin HDPE | 3% Carbon nanotube and 2 cycles | 36 | 1700 | — | — | — | 5 | [40] |
| Waste HDPE | Natural zeolite, clinoptilolite (K ₂ ,Na ₂ ,Ca) Al ₆ Si ₃ O ₇₂ . 23H ₂ O of 1–2% with particle size <40 μm | 21.8 | 218 | — | — | — | 25 | [37] |
| Waste HDPE | — | 24.619 | 836.25 | 27.114 | 1390.7 | 21 | 859.3 | [20] |
| | <i>Combretum dolichopetalum</i> fiber | 32.427 | 939.6 | 18.2 | 1568.1 | 28 | 496.0462 | |
| | Acetic anhydride-treated <i>Combretum dolichopetalum</i> fiber | 38.5153 | 1220 | 8.5111 | 19944.24 | 33 | 787.3806 | |
| | NaOH-treated <i>Combretum dolichopetalum</i> fiber | 34.9041 | 984.99 | 32.067 | 2277.15 | 39 | 469.5912 | |
| Waste HDPE | — | 27.628 | 792.59 | 34.519 | 1390.7 | 24 | 962.8 | [21] |
| | <i>Cissus populnea</i> fiber | 30.4827 | 839.022 | 36.1904 | 1425.89 | 30 | 155.795 | |
| | <i>Cissus populnea</i> fiber treated with NaOH | 29.6903 | 793.05 | 39.3962 | 1568.44 | 35 | 398.62 | |
| | <i>Cissus populnea</i> fiber treated with SLS | 31.8013 | 823.245 | 39.568 | 1455.68 | 38 | 394.683 | |

Table 3.
Mechanical properties of modified virgin and waste HDPE materials.

2.2 Modifications and properties of recycling of virgin and waste LDPE

The high quantity of waste LDPE and its average mechanical properties coupled with influence of aging of the product have not motivated utilization in many packaging applications such as bags, film, and pallet covers, but modifications may improve the mechanical properties. Also, the qualities of LDPE composites have been linked with poor interfacial adhesion between both phases of individual constituents which explain weak mechanical properties. This interfacial adhesion has a direct relation to compatibility. The processing conditions of machine also influenced the compatibility of the polymers. Some modifications of LDPE are presented in **Table 4**. The use of virgin and waste or recycled PP to modify LDPE using twin and single-screw extruder has been reported by Sylvie and Jean-jacques [12]. In the report, PP increases some mechanical properties such as tensile strength and modulus with reduced impact strength of the LDPE for single extruding machine, although the twin extruding machine gave better mechanical properties due to improvement in homogeneity of the polymer. The use of compatibilizer such as EPDM, graft copolymer (PE-g-poly (2-methyl-1,3-butadiene), and

| Thermoplastics | Modification | Tensile strength (MPa) | Tensile modulus (MPa) | Hardness | Impact strength (J/m ²) | References |
|----------------|---|------------------------|-----------------------|----------|-------------------------------------|------------|
| Virgin LDPE | Starch grafted with maleic anhydride | 16.34 | 520.16 | — | — | [45] |
| Virgin LDPE | Virgin PP | 25.1 | | | 5.5–6.5 | [36] |
| Waste LDPE | Natural zeolite, clinoptilolite (K ₂ ,Na ₂ ,Ca)Al ₆ Si ₃ O ₇₂ . 23H ₂ O of 1–2% with particle size <40 μm | 19.5–22.9 | 195.73–232.14 | | 18–26 | [37] |
| Waste LDPE | Waste 10% PP | 8.7–12.1 | 241–336.1 | | 23–37.2 | [41] |
| Waste LDPE | Waste 10% PP + EPDM | 7.6–8.5 | 211.1–236.1 | | 46.4–53 | [36] |
| Waste LDPE | — | 30.33 | 240.7 | 2.3 | 583 | [47] |
| Waste LDPE | Husk filler | 31.58 | 565.7 | 13.15 | 600 | [48] |
| Waste LDPE | Okpa filler | 35.14 | 861.2 | 17.53 | 583 | [47] |
| Virgin LDPE | 10% PP using single-screw extruder | 9.4 | 205 | | 15.2 | [12] |
| Waste LDPE | 10% PP | 10.0 | 248 | | 12.3 | [12] |
| Virgin LDPE | 10% PP using twin screw extruder | 9.6 | 226 | | 8.5 | |
| Waste LDPE | 10% PP using twin screw extruder | 10.3 | 256 | | 12.6 | |
| Waste LDPE | 10% PP + 5% graft copolymer using twin screw extruder | 11.8 | 280 | | 12.5 | |
| Waste LDPE | 10% PP + 5% EPDM using twin screw extruder | 10.1 | 245 | | 16.5 | |

Table 4. Mechanical properties of unmodified and modified virgin and waste LDPE.

ethylene-propylene copolymer enhanced the interaction between the polymers and resilience, thereby improving the mechanical properties of the LDPE/PP composites. The use of compatibilizer in virgin and recycled polyolefins influenced the quality of the composites based on technology and recycled waste of LDPE by the addition of EPDM compatibilizer [41]. The presence of ethylene-propylene diene monomer (EPDM) revealed the variation in properties such as wide-angle x-ray diffraction (WAXD), differential scanning calorimetry (DSC), and mechanical properties of virgin and recycled LDPE/PP [36]. The destruction of thermal and mechanical properties of virgin LDPE and PP as well as blended LDPE/PP was found to be greater than those from recycled polyolefins because of the absence of antiaging in the virgin products. The impact EPDM modifier have been reported on stability of LDPE/PP products based on natural and influenced ageing conditions with improved mechanical (tensile and impact strength) properties of the LDPE/PP with increase in modifier content. The impact EPDM modifier significantly improved the compatibility of recycled LDPE and PP and reduces the recrystallization of PP in the blends during aging and decreases the formation of the imperfect β polymorph crystal which depends on the presence of additives resulting in chain mobility retardation, presence of shear stress changing the chain structures, and fast cooling conditions at foil production as reported by Borovanska et al. [36]. Moreover, the significant improvement in rheological property such as viscosity, crystallinity index, and tensile properties of the recycled LDPE can be achieved by linear low-density polyethylene (LLDPE) blend with a ratio of 4:1 and applicably good for film products at 60% blended LLDPE [15]. The modification of recycled LDPE by PP using injection molding machine was also reported that the tensile properties increases with reduction in impact strength as increase in PP content as well as reduced processing temperature [42].

The effect of wood flour of *Pinus radiata* as fillers at a constant loading of 45 wt.% of recycled post-consumed plastic waste reported to be influenced by virgin PP [43]. In the report, the addition of virgin PP improved tensile and flexural moduli and flexural strength of wood plastic/LDPE composites (WPC). The highest mechanical properties of recycled LDPE composites have been reported for wood polymer composites with virgin PP (5%) and lower mechanical properties with higher virgin PP content of 55 and 71.5% compared to PE. The moisture absorption of WPC with virgin PP blend reported to be higher than without PP with adverse effect on the mechanical properties when immersed in water. More so, the use of virgin PP delay degradation and lower the thermal stability of WPC. This is also stay in agreement with report of Zhao et al. [44]. The decrease in tensile strength with increasing starch content in starch/LDPE composites attributed to incompatibility of the hydrophobic LDPE and hydrophilic starch and the increase in stiffness attributed to better dispersion of starch in LDPE matrix [45]. This incompatibility demands the use of compatibilizers such as styrene/ethylene-co-butylene/styrene grafted with maleic anhydride (SEBS-g-MA) and anhydride grafted polypropylene (PP-g-MA), Mixture Irganox 1098/Irganox 1078-Irgafos 168/Chimassorb 944 [44, 46].

The novel application of natural materials (filler or fibers) is to enhance undesirable properties and poor biodegradation of LDPE matrix. The use of rice husk, bambara, and mahogany fillers with improved tensile strength and modulus, flexural strength and modulus, and hardness with reduction in impact strength has been reported [47–49]. The increase in mechanical, thermal, and biodegradation behaviors of the composites was attributed to improved interfacial adhesion and compatibility. The reduction in impact strength is a result of fiber dispersion, uneven distribution, and micropore formation in the composites. It can be deduced that natural fillers or fibers contain a compatibilizer which has not been identified. There is also limited report on the modifications of fillers and fibers for enhancement of mechanical,

physical (water absorption, density, etc.), thermal, and electrical properties (conductivity, dielectric properties, etc.) of LDPE matrix. Chemical recycling (pyrolysis) had been a major technology for waste or postconsumer LDPE to save the environment, but not cost-effective; emissions of some constituents and required additives or modifiers (catalysts) for considerable yields of the products in many applications [24, 30]. Incorporation of natural zeolite, clinoptilolite ($(K_2, Na_2, Ca) Al_6 Si_3 O_{72}$), improved the strength of the filled composites, rheological behavior, thermal, compatibility of the individual polymeric components, morphology, and texture of the moldings from recycled polyolefins which strongly depends on the type of zeolite, size and shape, branching, dimensions, and types of polymeric chains [37].

Chemical materials have been used as catalysts in the pyrolysis of plastics to obtain liquid products with higher yield and selectivity. Hence, numerous experiments were performed to find out the best catalyst to produce the most desirable products, taking the economic factor into consideration. Pyrolysis of plastic waste to fuel involves many limitations that prohibit the industrial plastic recycling process including the difficulty in modifying it from batch process to continuous process. In industrial process, plastic waste is fed into the reactor directly through hopper for melting in pyrolysis reactor with high melting point (300°C and above, depending on the types of plastic). Therefore, any temperature lower than its melting point may result to solidification of the plastics in the process pipelines, hence causing blockage of the pipelines.

2.3 Modifications and properties of recycling of virgin and waste PVC

The increase in commercial vehicles and road usage with construction resulted to increase in demand of bitumen for pavement and road construction. Yet, the durability of the bitumen depends on appropriate binder for enhancement of performance of bitumen. The use of little quantity of virgin thermoplastics provides a reasonable performance with bitumen but is uneconomical compared with only bitumen. The utilization of waste PVC for effective performance as bitumen binder in pavement and road construction products seems to be interesting because of its low cost and because it is one of the abundant thermoplastics that causes environmental threat [50]. The applications of PVC have been reported to hinder and be not suitable for many applications because of incompatibility as a result of many factors [51]. PVC possesses high melting points which hindered the mixing, and it is impractical to make any further attempts to incorporate it in some applications like bitumen road construction. Recycled LDPE/PVC blends have been modified using EPDM as effective toughening, compatibilizer, and dispersant agent in applications. Recyclability of PVC waste can be achieved mechanically without modifications or use of new plasticizer since the separation of other mixed plastics is possible through triboelectrostatic technology [50, 52]. The technology of triboelectrostatics depends on the ability of polymer to the electron loses or gains because electrons gains and charges negatively may be as a result of higher affinity of polymers, whereas loss of electrons and positively charge may be attributed to polymer with the lower affinity. Because of high electronegativity of chloride ions, it can mix with many polymers such as PET, PP, PS, and PE with enhanced properties as reported by Hamad et al. [50]. The use of wood fillers or fibers as natural modifiers have been reported to improve mechanical properties of recycled PCV rather the recyclability [53], and slightly reduction in mechanical (tensile, flexural, hardness and impact) and structural properties (i.e., decrease in molecular weight due to molecular chain scission caused by shear stress involved in reprocessing) [54]. The reduction in properties exists because of incompatibility or poor intermolecular interaction which can be modified by surface techniques.

2.4 Modifications and properties of recycling of virgin and waste PET

Polyethylene terephthalate (PET) is a transparent semicrystalline, long-chain thermoplastic polyester which can be produced by a polymerization of terephthalic acid with ethylene glycol and remains the most used thermoplastics in many applications [55, 56]. It is characterized as easy to handle, durable, strong, thermally with low glass transition temperature, and chemically stable with low gas permeability [57]. It exhibits brittle behavior, good mechanical properties, and dimensional stability as well as good gas and chemical resistance which resulted to its wide applications [58]. Waste PET may be in bottles, foils, and cords from tire [57, 58]. Globally, the rate of generation of waste PET is about 20 million tonnes that amounted to about 15% which is alarming due to population growth, urbanization, standard of living, and cost of production, but the recycling rate of waste PET found to be 29.3% lower [56]. The issue with the reuse of waste PET may be associated with size, content, mixing process, type of mixer, temperature, time profile during mixing process, and contaminations or additives like stabilizers and pigments [58, 59]. In bitumen asphalt modification for the road construction, the mixing process may be wet or dry process. The wet process involves blending of thermoplastics and bitumen in a mixer and then mixing of thermoplastic modified bitumen to aggregates, while the latter involves incorporation of thermoplastics to very hot aggregates prior to mixing with bitumen [56]. Waste PET recycling employs dry process, and it can be modified to achieve better feasibility in terms of adhesion between the aggregates and binder, stability, and even mixing and minimizes the pore formation and moisture absorption. Appropriate recycling process conditions of waste PET make significant environmental and economy impacts through conservation of natural resources, environmental pollution, energy, and enhancement of engineering and physical properties of construction materials [58]. An increase in recycled PET content caused a decrease in melt flow index or rheological properties of the aggregate [29]. Recycled PET exhibits pseudo-plastic behavior, and it has been used to improve the rheological properties of asphalt as well as increased the viscosity and stiffness and enhanced the softening of stone mastic asphalt (SMA) [58].

Incorporation of recycled PET with appropriate content and size increased the compressive, tensile, and flexural strength/s and ductility of concrete, creates lightweight aggregate of development of building materials, or decreases the bulk density of the composites, thereby helping polymer concrete in saving energy and minimizing the problem of solid waste posed by PET as well as other thermoplastics provided the impurities were removed prior to reprocessing [58].

Synthetic thermoplastics such as HDPE and acrylonitrile butadiene styrene (ABS) blend nano silicon (IV) oxide (SiO_2), and polylactic acid (PLA) can modify PET waste to improve its performance using the extrusion process based on a different mixing ratio. The use of virgin HDPE has been reported to improve rheological and mechanical properties when compared to waste PET using a less than 5% virgin HDPE [60]. The mechanical properties of composites of recycled PET improved with increase in incorporated nano silicate (SiO_2) content blended with ABS [61]. Modification of PET waste by the addition of small amounts of virgin PLA using melt mixing technology also shows reduction in viscosity of the composites with higher thermal sensitivity and mechanical properties compared to recycled PET [50, 62]. It should be noted that the performance of recycling of waste PET was hindered due to the presence of impurities, decomposition, and degradation of polymer chains as reported by Imamura et al. [57]. The modifications by compatibilizer like ethylene glycidyl methacrylate (EGMA) modified PE copolymer significantly improved the miscibility of recycled PET with PP, PE,

and PS molecules, respectively, unlike linear low density polyethylene copolymer (LDPE) [57]. The use of natural materials to modify the properties of recycled PET such as fibers or fillers is not available in literature. The efficacy and performance of recycled PET applications required optimum conditions of modified process, PET size and content, and additive or modifier content.

2.5 Modifications and properties of recycling of virgin and waste polypropylene

Due to favorable qualities of PP like density, versatility, photodegradation, and cheapness in cost of production, it is replacing many materials used for artifacts such as packaging products and automobile bumpers. The increasing rate of use of polypropylene coupled with inherent incompatibility of polyester and polyolefins seeks for improvement in the performance of PP in many applications [63]. The improvement in PP performance has been achieved through modification techniques by incorporation of grafted maleic anhydride (PP-g-MAH), clay-based nano-fillers, inorganic nanoscale particles, and poly(trimethylene terephthalate) (PTT) blends using organically modified montmorillonite (Cloisite nanoclays) as compatibilizers for the purpose of improving compatibility, mechanical, crystallization, and melting behavior of PP composites [64–66]. PTT is an aromatic polyester with combined properties of PET and poly(butylene terephthalate) (PBT). The factors that influence the properties of the PP composites are mix or blend ratio, crystallization temperature, compatibility process time, and size [63]. There is loss of mechanical properties for composites of LDPE and HDPE modified with PP which is due to incompatibility of recycled PP/LDPE and PP/HDPE composites [39]. The modification of recycled PP with HDPE reveals a partial compatibility which caused an improvement in tensile strength and elongation with the use of EPDM compatibilizer [67]. The modification of recycled LDPE/PP with 1% montmorillonite nanoclay exhibits appreciable improvement in strength, physical properties, and stability of bitumen [68].

3. Microstructural behavior of recycled thermoplastic matrix and its modifications

The microstructural behavior in this content is limited to Fourier-transform infrared spectroscopy and scanning electron microscopy as discussed in subSection 3.1.

3.1 Fourier-transform infrared spectroscopy

FTIR analysis of recycled thermoplastics exhibits no extra peaks for the blends, neither any shifts nor changes in the absorption bands of the carbonyl, hydroxyl, and carboxylic groups of HDPE, LDPE, PET, PVC, and PP resins which indicates the absence of any specific interaction, entanglement, or chemical reaction between the polymers and modifiers as reported by Mamoor et al. (**Figure 3**) [29]. In the case of modification of recycled thermoplastics using untreated natural fiber, there exists a shift or change in the absorption peaks of the carbonyl, hydroxyl, and carboxylic groups of the fiber-reinforced recycled thermoplastics, thereby influencing the physical and mechanical properties of the matrix and interfacial between the fiber and HDPE as reported by researchers [21, 69]. This resulted in improved quality of the thermoplastic products. The shift, change, appearance, and disappearance of absorption peaks correspond to reaction of the functional groups. This

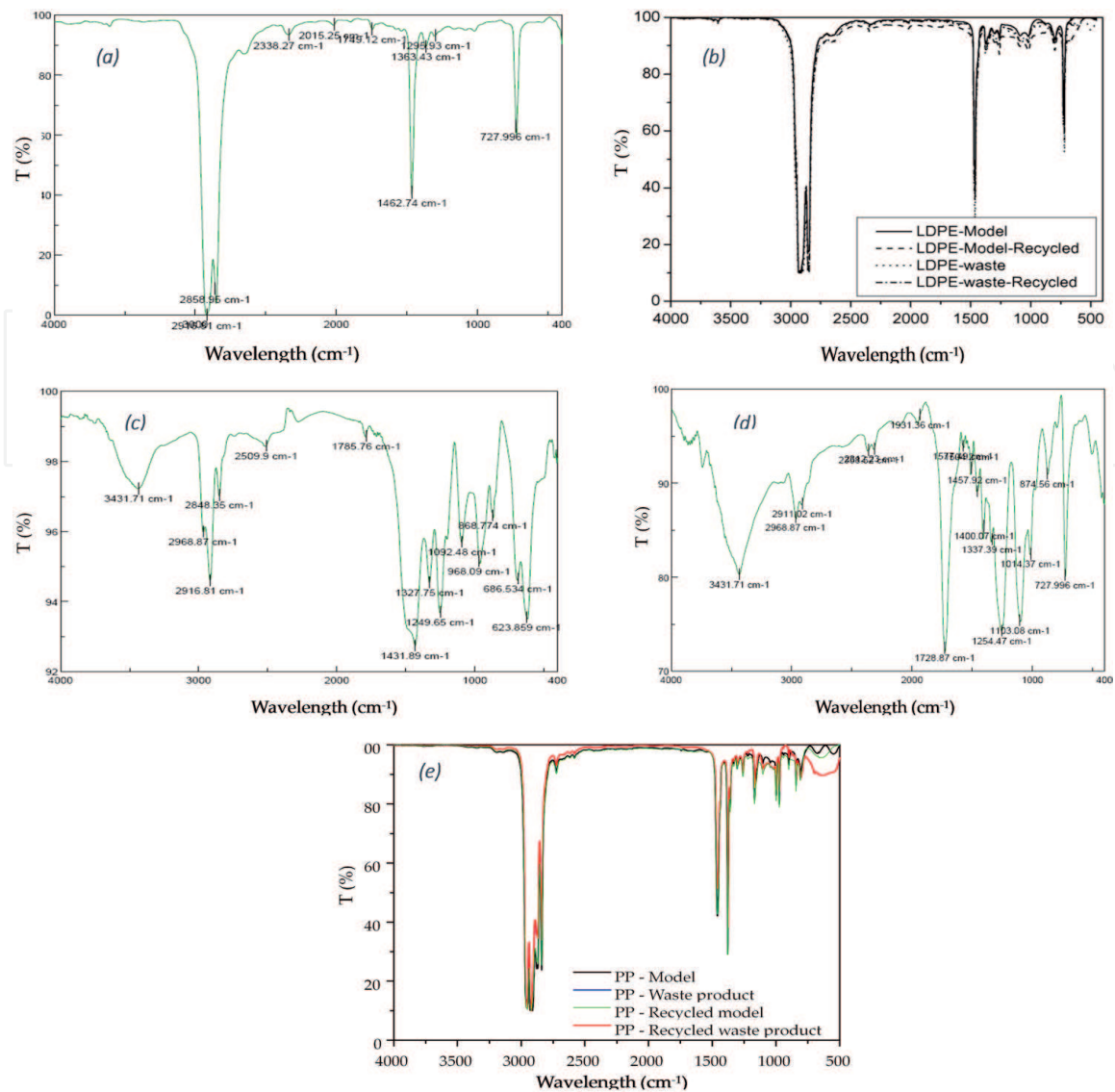


Figure 3. FTIR of recycled thermoplastics (a) HDPE [29], (b) LDPE [30], (c) PCV [29], (d) PET [29], and (e) PP [29].

functional group dictates chemical reaction between the polymers and modifier, resulted to change in absorption peak correlate change in strength and modulus of the thermoplastics.

3.2 Scanning electron microscopy

The scanning electron microscopy depicts the morphology of virgin and recycled thermoplastics at fracture surfaces when stressed and characterized the ductile, toughness, stiffness, and brittle nature of HDPE, LDPE, PCV, PET, and PP without modification [32], but improvement in compatibility using EPDM compatibilizer has been reported [2, 70]. The improvement in rheological morphology does not indicate an improvement in compatibility as well as mechanical properties [71]. Modification of recycled HDPE with treated natural fiber using NaOH, SLS, acetic anhydride, CaCO₃ filler, and zeolites as well as synthetic fibers is characterized with improvement in polymer dispersion, even distribution of fibers, interfacial adhesion, fiber tearing, micro-crack formation, modifier content and size, nature of the modifier, and reduction in void formation [20, 43, 72–75]. This indicated the enhanced compatibility which corroborates the improvement in physical, mechanical, and thermal properties of the modified recycled thermoplastics and dictates its applications.

4. Application of recycled thermoplastics

4.1 Applications of recycled HDPE

The application of the HDPE composites is a function of the favorable properties coupled with cost implication of the production, and it may be affected by additional modified agents such as fiber or filler, NaOH, acetic anhydride, zeolite, and sodium lauryl sulfate. The use of recycled HDPE composites has been reported for many applications such as packaging (food storage containers and bottles for milk jugs) [13, 28, 38], banners, swimming pool installation, corrosion protection for steel pipelines, folding chairs and tables, electrical and plumbing boxes, plastic surgery (skeletal and facial reconstruction) [27], modified asphalt for pavement and road construction [29, 59, 75], housewares, industrial wrapping and gas pipes [30], and storage sheds, enhancing the economic, health, and social values as well as minimizing environmental issues that might be posed by HDPE disposal [38]. Applications of recycled HDPE in the encapsulation of radioactive, hazardous, and mixed wastes have been reported by Lageraen and Kalb [76].

4.2 Applications of recycled LDPE

Incorporation of recycled LDPE at concentrations ranging from 2 to 5% by mass of bitumen possesses consistent desirable properties for bitumen asphalt applications [51, 69]. Utilization of LDPE for production of liquid milk packaging [16], bread packaging and sandwich bags, housewares, toys, buckets, wire and cable jacketing, and carpet [13, 38, 68] and use of recycled thermoplastics for encapsulation of hazardous, radioactive, and mixed waste disposal save the environment from economic, environmental, and health issues [76].

4.3 Applications of recycled PVC

Polyvinyl chloride waste has been used in plumbing pipes and fittings, but its utilization as a binder in bitumen applications has been found unsuccessful due to high melting points which hindered the mixing as a result of poor compatibility [51]. PVC sheets have been reported to be employed for making food trays, cling film and blister packages [13], household appliances, packaging, construction, medicine such as human rehabilitation, electronics, automotive and aerospace components [29], and building floor applications [52].

4.4 Applications of recycled PET

Recycled PET could be used for making waterproof [13] water and soft drink bottles, thermally stabilized films (e.g., capacitors, graphics, film base and recording tapes, etc.), electrical components, and textile products [58] if properly modified. The use of recycled waste PET as a modifier in bitumen road and pavement construction is hindered by mixing ratio and processing conditions due to high melting point [51]. It is widely used in making automobile part, electronics, food packaging, house ware, lighting product, power tools, sports tools, x-ray sheets, and photographic applications [55, 59].

4.5 Applications of recycled PP

Recycled polypropylene can be used for packaging articles, automobile bumper, foams, bottle tops, carpets, and household components [13] and in making straws

and sweet wrappings, PP powder, and PP mulch at concentrations ranging from 2 to 5% by mass of bitumen consistently desirable for bitumen asphalt applications [51]. The recycled PP is also applicable in 3D printing filament [77]. An application of recycled PP is dependent on good compatibility with modified materials with synergistic effects.

5. Conclusion

Globally, disposal of postconsumer or waste thermoplastics into the environment is alarming and posed a serious economic, environmental, health, and social burden. Employing appropriate technology, especially mechanical recycling with modifications of thermoplastics, can save the world from threat that might be posed by thermoplastic wastes. Appropriate additives such as natural fibers and fillers with eco-friendly, less expensive, available, and degradable potentials should encourage saving the world from this serious menace. The use of recycling technique with appropriate modification will not only exhibit conservation of the waste thermoplastics but altered the physical, rheological, mechanical, electrical, and thermal properties of the recycled thermoplastics for effective applications. An effective and sustainable application of recycled thermoplastics depends on optimization of process conditions, parameter, modifying agents and techniques, equipment, and time. Hence, the quality and performance of the recycled aggregates or composites are enhanced.

Conflict of interest

There is no conflict of interest.

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