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RECYCLING POLYPROPYLENE FROM WASTE POLYMERS: A REVIEW

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Abstract: Recycling is a critical component of sustainable waste management, turning waste materials into valuable resources and conserving energy, reducing pollution and decreasing the amount of material that ends up in landfills. Polypropylene (PP), as one of the most common recyclable polymers, is a kind of lightweight, high-strength and multi-purpose thermoplastic. This review presents the structure and major properties (stiffness, heat resistance, low water absorption, and finally chemical stability) of PP as well as an overview on the main commercial grades: homopolymer (HPP), random copolymer (RCP), and impact copolymer (ICP). Overall efficiencies, environmental aspects and polymer quality are compared for the basic mechanical processes, chemical methods and strategies into energy recovery. To stress out practical performance, tested data presented evidence that recycling can improve stiffness and flow properties: Young's modulus goes from 1200 MPa (virgin PP) to 1400 MPa (recycled PP), +16.7%, whereas melt flow rate increases from 6.3 up to 11 g/10 min (+74.6%), as expected by the occurrence of chain scission phenomenon leading to a molecular-weight reduction during reprocessing (melt-compounding). With further reprocessing cycles the tensile strength and impact properties usually diminish, as does elongation at break even though it flexural modulus may be increasing (from increased brittleness and internal structural changes). Despite the fact that chemical recycling is more involved and more expensive compared to mechanical recycling, it's highlighted. Finally, major PP applications are outlined, including fibers, films, sheets, molded products, packaging, and automotive components (e.g., bumpers, ducts, and battery casings), underscoring PP's role in circular-economy strategies and global sustainability goals.
Keywords: polypropylene, circular economy, polymers recycling methods, waste polymers recovery.

1. INTRODUCTION

Recycling is a process of turning waste materials into new products in order to prevent the waste of potentially useful materials, reduce the need for conventional waste disposal, use less energy, reduce air and water pollution, and emit fewer greenhouse gases than the production of plastic. Recycling material can recover a variety of waste types (Gencer, 2016). In addition to waste reduction, waste reuse, and waste recycling, trash disposal is a part of the waste management hierarchy. Wastes are undesired items that are no longer useful and are disposed of in order to maintain a clean and sustainable environment. Pollution from improper garbage disposal contributes to environmental deterioration, health issues, and climate change (Nmere et al., 2020). Polypropylene (PP) is one of the most commonly used plastics in the manufacturing of automobiles and industrial lead-acid batteries (Ferg and Rust, 2007). Lead-acid batteries are the most commonly used batteries in the telecommunications, automotive, and transportation industries (Van Men et al., 2021).

The complete battery recycling process comprises recycling the robust and chemical-resistant polypropylene (PP) plastic from the outer casings in addition to recovering lead and sulfuric acid. Rather than being dumped in landfills, where it would take centuries for it to break down, this precious material is reprocessed.

The recycling loop is essentially closed within the same industry when the recycled plastic is transformed into raw materials for the production of a variety of goods, including new automotive parts like battery trays. Along with consumer goods like tool handles, outdoor furniture pieces, and floor tiles, it is also utilized for long-lasting items like garbage cans, non-pressurized drainage pipes, and storage containers. This procedure keeps this valuable material from ending up in landfills for centuries by reducing trash and reusing it (Zhao et al., 2024).

One of the most widely used plastics today across various industries is PP, a thermoplastic polymer produced in large quantities. Chemically, PP belongs to the class of simple-structured polymers. Its importance is not reduced by its structural simplicity, as it offers a wide range of adaptable qualities. The length and molecular weight of a PP polymer chain are closely connected. Besides polymer chains, PP plastics typically contain a variety of additives. Furthermore, several key factors influence the final properties of the polymer and plastic material, including the type and amount of additives used, the polymerization process, and the presence of fillers and reinforcements (Smolander, 2011).

2. POLYPROPYLENE (PP)

The physical properties of PP include exceptional workability, stiffness, heat resistance, and a low specific gravity. It is also utilized in many different applications, including films, industrial parts for cars, etc. The successful synthesis of high molecular weight, highly crystalline PP (Ogawa, 2009). Polypropylene has a special symbol to distinguish it from the rest of the polymers during the recycling process, which is the number “5”, as shown Figure 1.

Fig.1. Polypropylene recycling symbol (Dimitris and Achilias, 2014).

2.1. General Properties of Polypropylene

One of the most popular plastics is PP because of its many great qualities: Its low density (0.90 g/cm^2) makes it the lightest of all commodity plastics.

2.1.1. Physical and Mechanical Characteristics (Maddah, 2016)

- Rather stiff (more so than high-density polyethylene (HDPE).
- Excellent fatigue resistance and good impact resistance, as well as good tensile strength (3200-5000 Psi).
- High melting point (160–166 degrees Celsius).
- Water Absorption: Very Low (0.01% in 24 hours).

2.1.2. Chemical Properties (Maddah, 2016)

- Good resistance to aldehydes, esters, and ketones.
- Limited resistance to oxidizing agents and aromatic and halogenated hydrocarbons.
- Excellent resistance to concentrated and diluted acids, alcohols, and bases.

2.1.3. Additional Characteristics Include (Maddah, 2016)

- Heat resistance (Vicat Softening Point between 140 and 150 °C).
- Good electrical insulation.
- Safe for food contact and non-toxic (particularly homo-polymer).
- Recyclable.

2.2. Main Types of Polypropylenes

Polypropylene is classified into three main types based on its chemical structure and properties:

2.2.1. Polypropylene, a Homopolymer (HPP) Composition

solely composed of propylene monomer, the polymer is semi-crystalline, high-stiffness, and has a high melting point; good chemical resistance, lower transparency, and reduced impact strength in comparison to other varieties are some of its characteristics. The most prevalent sort of market share is between 65% and 75%. Uses; Injection-molded items, fibers, sheets, and containers (Maddah, 2016).

2.2.2. Polypropylene Random Copolymer (RCP)

A tiny quantity of ethylene monomer (often less than 7%) is copolymerized with propylene at random along the polymer chain to create this composition. The ethylene units result in a lower melting and softening point, A little improvement in impact qualities over HPP, A decrease in crystalline homogeneity, which improves flexibility, clarity, and transparency, and a market share of 5% to 10%. Uses; In flexible containers that need clarity and transparent films (cast films) (Maddah, 2016).

2.2.3. Polypropylene Impact Copolymer (ICP)

Composition: A physical blend of random copolymer (RCP) and homopolymer (HPP), with a high ethylene concentration (45–65%) in the RCP phase, gives the material a rubbery phase. This type's properties include: the rigidity of HPP and extremely strong impact resistance, especially at low temperatures (below -20 °C). Applications are ideal for impact-prone containers and automotive uses, such as interior trim and TPO bumpers. In conclusion, polypropylene has various qualities that can be tailored by selecting the right type (HPP, RCP, or ICP) or through engineering techniques like branching, filling, and fiber reinforcement (Maddah, 2016).

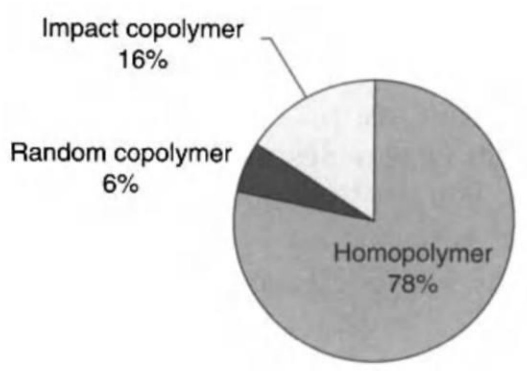

Fig.2. Categories of industrial polypropylene available in the market as of 2008. The overall market size in 2008 was approximated to be around 46 million metric tons (approximately 101 billion pounds) (Malpass and Band, 2012).

2.3. Chemical Constitution

2.3.1. Polymerization

Different arrangements of the methyl groups (CH_3) in polypropylene can occur during polymerization, and this variation impacts the material's density, melt flow behavior, and crystallinity. Polypropylene configurations can be classified as isotactic, syndiotactic, or atactic. Because all of the CH_3 groups in isotactic polypropylene are found on the same side of the polymer chain, the material has a strong crystallinity and a very uniform structure. Due to its superior mechanical qualities, this type is most frequently utilized in industrial settings.

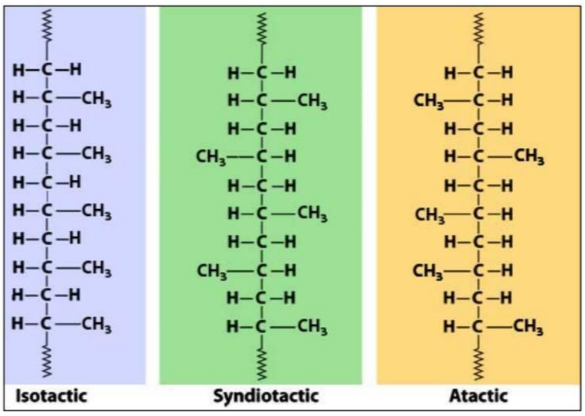

Fig.3. Three different configurations of polypropylene (Weckström, 2012).

Compared to the isotactic form, syndiotactic polypropylene has a slightly higher melting temperature and more flexibility because the CH_3 groups alternate consistently from one side to the other. However, because of its irregular CH_3 group arrangement, which results in an amorphous structure with poor mechanical strength, atactic polypropylene is rarely utilized in applications that call for endurance or rigidity. It is clear from comparing the three configurations that isotactic polypropylene has the highest density, tensile strength, and crystallinity. Whereas atactic polypropylene, which usually exists in an amorphous form, is the least ordered and has the lowest mechanical performance, syndiotactic polypropylene is more flexible (Weckström, 2012), can be seen in Figure 3.

3. POLYMER RECYCLING METHODS

3.1. Primary Recycling

Products made from waste plastic in this type of recycling have performance levels comparable to those of original products made from virgin plastics. Recycled waste or scrap is either mixed with virgin material or utilized as second-grade material to guarantee product quality. Other than the plant's trash being collected appropriately and cleanly, primary recycling is rather simple and doesn't require any safety precautions (Kumar et al., 2011).

3.2. Mechanical Recycling (Secondary Recycling)

Involves cutting, shredding, washing, and other physical processes to turn waste plastic materials into new plastic goods. This method effectively separates the polymer from its associated impurities, allowing for easy reprocessing into granules through conventional melt filtration or extrusion. Waste plastic is processed straight into finished goods or flakes of constant quality that can be used to create other products once it has been sorted, cleaned, and dried. The waste plastic gets smaller as a result. The end-use and operation may determine the future recycling steps. Thermoplastics are the only materials that can be used in mechanical recycling since they can be remelted and processed into final goods (Jagtap et al., 2015). The fundamental polymer remains unchanged by the process. (Kumawat et al., 2015).

3.3. Chemical Recycling (Tertiary Recycling)

Polymers (plastics) can be broken down into their monomers and recycled using several methods, including hydrogenation, thermal treatment, the presence of an appropriate catalyst (like vinyl, ethylene, propylene, styrene, or benzene), and chemical depolymerization. This makes it one of the most important steps in recycling polymeric wastes. To produce different kinds of polymers, the monomer is then chemically polymerized (Coates and Getzler, 2020; Dimitris and Achilias, 2014).

3.4. Energy Recovery (Quaternary Recycling)

This technique is effective in reducing the quantity of organic chemicals. The most efficient way of lowering the volume of organic waste at the time is incineration with an energy recovery goal. The health hazards caused by airborne hazardous chemicals, such as dioxins (in the case of chlorine-containing polymers), make this strategy environmentally unsuitable even if it produces a considerable quantity of energy from polymers (Kumawat et al., 2015). An overview of the different pathways for recycling is shown in Figure 4, including where their respective end products re-enter the lifecycle of polymers (Ragaert et al., 2017).

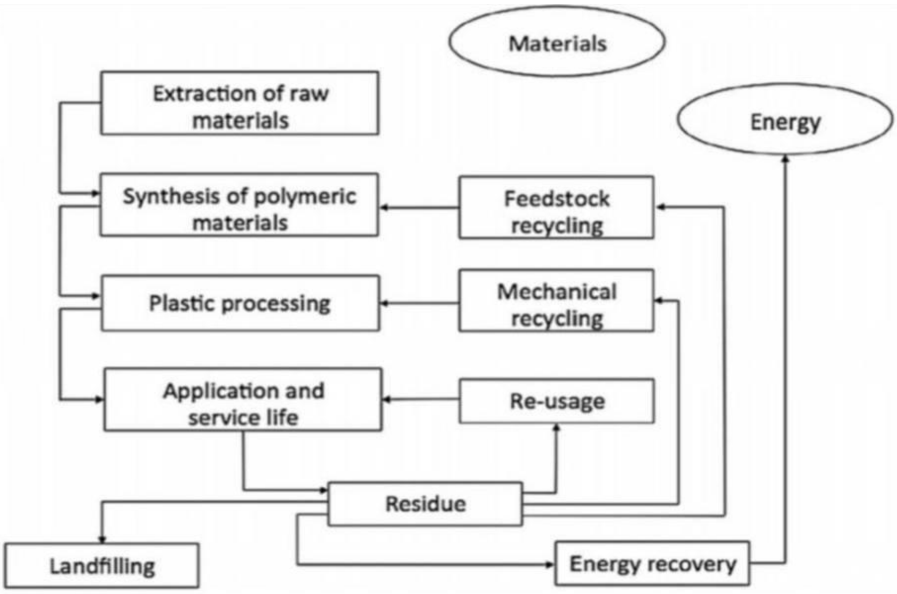

Fig. 4. Polymer Waste Management Options in Terms of the Life Cycle of Polymer Products (Ragaert et al., 2017).

4. STEPS OF RECYCLING OF POLYMER MATERIALS

Phases of Polymeric Material Recycling: Polymer waste needs to go through several steps to be recycled and utilized again, either for the same purpose or for a different one:

4.1. Collecting Stage

Collecting waste materials made of polymers, both directly and indirectly (from the manufacturer or the consumer). Customers and roadside polymer waste can be collected for recycling by setting up plastic waste containers in different areas for easy collection at a later time (Cook, 2015; Hopewell et al., 2009).

4.2. Sorting Stage

The sorting stage is one of the most important stages in the recycling of polymeric materials. This phase requires careful waste sorting because impurities cause polymers to lose some of their properties. The sorting process can be done in several ways, including mechanical and manual (Schyns and Shaver, 2021; Abota, 2012).

4.3. Washing Stage

Polymer-based waste products are cleaned by putting them in large basins with hot water and adding caustic soda or detergents. For polymers to be recycled, they must be free of contaminants such as dust, oil, grease, paper, and other materials. The polymer wastes can be washed mechanically or manually in the washing tank, which makes it easy to remove the soiled water (Abota, 2012).

4.4. Drying Stage

To remove water and minimize moisture, the polymer waste is dried after washing. It is next transferred to drying basins where it is either mechanically dried, like in an oven, or exposed to direct sunlight. The polymer flakes are baked at 500 degrees Celsius for five to six hours (Abota, 2012; Harun, 2012).

4.5. Shredding Stage

The polymer waste is broken or sliced into smaller bits or volumes in shredding machines, depending on the type of polymeric material to be recycled. The required standards are followed while regulating the size of the crushing or cutting. Large plastic bottles should ideally be broken up into smaller pieces before being fed into the shredder (Harun, 2012; Ogunedo and Beneth, 2020).

4.6. Granulation Stage

After being sliced, these materials are sent in pieced or powdered form to the granulation machine. It is either granulated to create a raw material for the synthesis of new polymeric materials or produced as polymeric granules. Each sliced polymer type must be separated from the others to produce new products using only one type of polymer (Abota, 2012).

4.7. Stage of Formation

In this stage, polymers are formed into reusable objects. This process uses a variety of techniques, depending on the quality of the product, such as extrusion, injection, blow, injection blow molding, and others (Ogunedo and Beneth, 2020).

5. APPLICATIONS OF POLYPROPYLENE

5.1. Strapping

Slit film and strapping are comparable, however, the fabrics used here are thicker, roughly 20 mils. Either split sheets or direct extrusion is used to create fibers. Applications include holding stacks together and securing big boxes and parcels. (Karian, 2003).

5.2. Fibers and Fabrics

Different types of extrusion procedures are used to create fibers. Slit film and slit tape are examples of fibers. PP's benefits include strength, stain and chemical resistance, and low specific gravity, which results in more bulk per weight. Slit film, single fibers, nonwoven textiles, and monofilaments are among the several uses for fibers. A broad web extruded film is called slit film. Oil carpet backings are the main use for slit film. These days, PP is used to make carpet backings instead of just four natural jute fibers. This is because in high-moisture weather, the fiber deteriorates more quickly than PP fibers. Weather with high humidity will allow more water to be absorbed, which will lead to mold growth. Applications for slit film include tarpaulin, for textile prevention, woven fabrics for feed and fertilizer sacks, sand bags, and bulk container bags. Continuous filament fibers, which are more traditional than slit-film fibers, cannot be combined. (Karian, 2003).

5.3. Film

Through the extrusion technique, polypropylene (PP) film with a thickness of less than 10 mils can be created. It is frequently found in clothes, tobacco, and food product packaging. Cast films and biaxially oriented polypropylene (BOPP) films are the two primary categories into which PP films are often divided. Melted plastic is deposited onto a smooth surface, cooled, and then used to create the cast film. One to four mils are the usual thickness for this type. Cast films are frequently utilized in the manufacturing of bags, sheets, and pressure-sensitive labels because of their softness and flexibility.

BOPP Film Making Polypropylene however, is oriented by being extruded through a circular die followed stretching & followed by cooling to form BOPP Film. It is 0.25 to 2.5

mils in thickness, depending on the method of manufacture. BOPP film has excellent gloss, high transparency and good printability after surface treatment. As they can resist any moisture and keep product fresh, water-based inks have been widely used for flexible packaging—especially snack food and bakery products. Due to their attractive appearance and protective nature, BOPP films are often used to package chocolates, soaps as well as labels of beer bottles (Karian, 2003).

5.4. Sheet / thermoforming

In the thermoforming process, a thermoplastic sheet is heated to its softening point, then mechanically formed into the required shape, and finally solidified into the intended shape. The extrusion method yields sheets that are thicker than 10 mils, with a typical thickness of 40 mils. Thermoformed containers for stiff packaging purposes are made from sheets. When it comes to creating stiff packages, PP and polystyrene differ in that PP resins withstand stress cracking when fatty goods are present, while polystyrene resins do not. Compared to polystyrene, PP is more robust and inflexible. Additionally, because PP has a lower specific gravity than polystyrene, we may create lighter containers with the same thickness and shape (Karian, 2003).

5.5. Blow Molding

The fundamental idea behind the blow molding process is to use hot air to blow a thermoplastic into a hollow shape. Before being blown, a heated thermoplastic hollow tube called a parison is inserted into a closed mold. After blowing, the parison takes on the shape of the mold and keeps it when it exits. The primary end products of the blow molding process are bottles and jars. (Karian, 2003).

5.6. Injection Molding

Polymer granules are heated to a melting point during this process. After that, a closed mold is filled with the molten substance. The mold typically comprises two sections that are secured together under pressure to counteract the force of the molten material. Subsequently, the injected substance is allowed to cool and solidify within the mold. The molding is then removed once
the two mold parts are opened. Mold shapes typically have extremely intricate geometries design. Applications for rigid packaging containers involve thin-wall injection molding. Water bottles come in a variety of shapes, including tall, flat, and square. The best option for quickly and efficiently creating containers with a variety of shapes is injection molding. Storage systems, toys, sporting goods, paintbrushes, and garden furniture are examples of household goods in use. Examples of closures made from PP include screw caps for bottles and jars. Additionally, injection molding can be used for many medical applications, including disposable syringes as well as hand tools. (Karian, 2003).

5.7. Automotive

Polypropylene is widely used in automobiles. Battery casings and AC ducts are two examples of its original use. Since PP has a low density of 0.9 g/mL, making it the lightest thermoplastic, it makes up a large portion of the plastics used in modern cars. This is because automakers often try to make their cars lighter overall to save consumers money on gas. Additionally, several external components and interior trim are entirely composed of PP or PP compounds. PP has been a popular material for vehicle exterior elements due to its ability to reduce weight. Car bumpers are made of thermoplastic olefin (TPO), a unique substance made from PP. (Karian, 2003). A 2005 study indicated that the predominant global use of polypropylene is for injection molding and fibers, Figure 5.

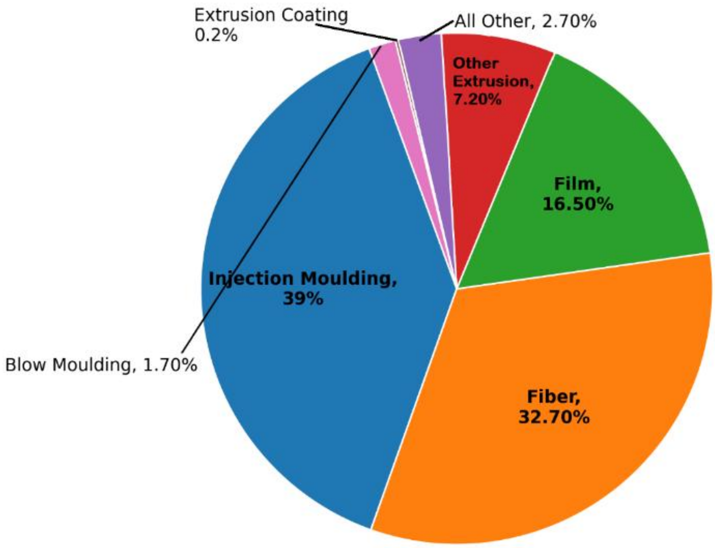

Fig. 5. Global consumption of polypropylene by end-use application (Maddah, 2016).

6. LITERATURE REVIEW

(Raj et al., 2013) In contrast to virgin material, polypropylene has structural alterations during recycling that influence its mechanical characteristics. This study examines the effects of degradation on the mechanical behavior of both virgin and recycled PP blends, taking into account the number of reprocessing cycles as well as the composition of the blend, As seen in the Tables 1,2,3.

Table 1
Tensile Properties of Virgin Polypropylene and Recycled Polypropylene

Sr. No.	Ratio Virgin PP: Recycled	Tensile Strength KgF/cm^2			Elongation at Break KgF/cm^2			Youngs Modulus KgF/cm^2		
		Batch I	Batch II	Batch III	Batch I	Batch II	Batch III	Batch I	Batch II	Batch III
1	90:10	313.07	317.24	306.84	18	26	26	1739.32	1220.15	1180.15
2	80:20	315.06	304.71	284.24	26	24	18	1211.76	1159.05	1134.25
3	70:30	308.49	301.69	277.96	22	22	16	1402.13	1105.15	1100.00
4	60:40	319.44	305.55	250.00	26	20	14	1228.61	1005.63	961.53

Source: (Raj et al., 2013).

Table 2
Flexural Properties of Virgin Polypropylene and Recycled Polypropylene

Sr. No.	Ratio Virgin PP: Recycled	Flexural Strength KgF/cm^2			Flexural Modulus KgF/cm^2		
		Batch I	Batch II	Batch III	Batch I	Batch II	Batch III
1	90:10	627.94	549.75	500.00	4490.34	3525.25	3300.52
2	80:20	502.94	505.50	475.25	4434.91	3450.00	3350.25
3	70:30	470.58	475.00	460.65	3855.95	3400.00	3300.00
4	60:40	450.60	450.00	425.25	3760.80	3350.25	3250.80

Source: (Raj et al., 2013).

Table 3
Izod Impact Strength & Melt Flow Index (MFI) of Virgin Polypropylene and Recycled Polypropylene

Sr. No.	Ratio Virgin PP: Recycled	Izod Impact Strength Joule/cm			Melt Flow Index (MFI) gm./10 min.		
		Batch I	Batch II	Batch III	Batch I	Batch II	Batch III
1	90:10	0.538	0.520	0.510	2.17	2.18	2.18
2	80:20	0.524	0.485	0.460	2.19	2.20	2.22
3	70:30	0.490	0.460	0.410	2.21	2.21	2.23
4	60:40	0.461	0.416	0.390	2.23	2.25	2.26

Source: (Raj et al., 2013).

Based on the aforementioned information and all interpretations, we deduce that blends of neat and recycled fractions in 90:10 ratios best demonstrate the required tensile strength. The ideal ratio for achieving good flexural strength is 60:40. The ratio that is found to have the best impact strength is 90:10. Additionally, it is determined that this is the most effective method of using polypropylene waste without sacrificing any of its qualities.

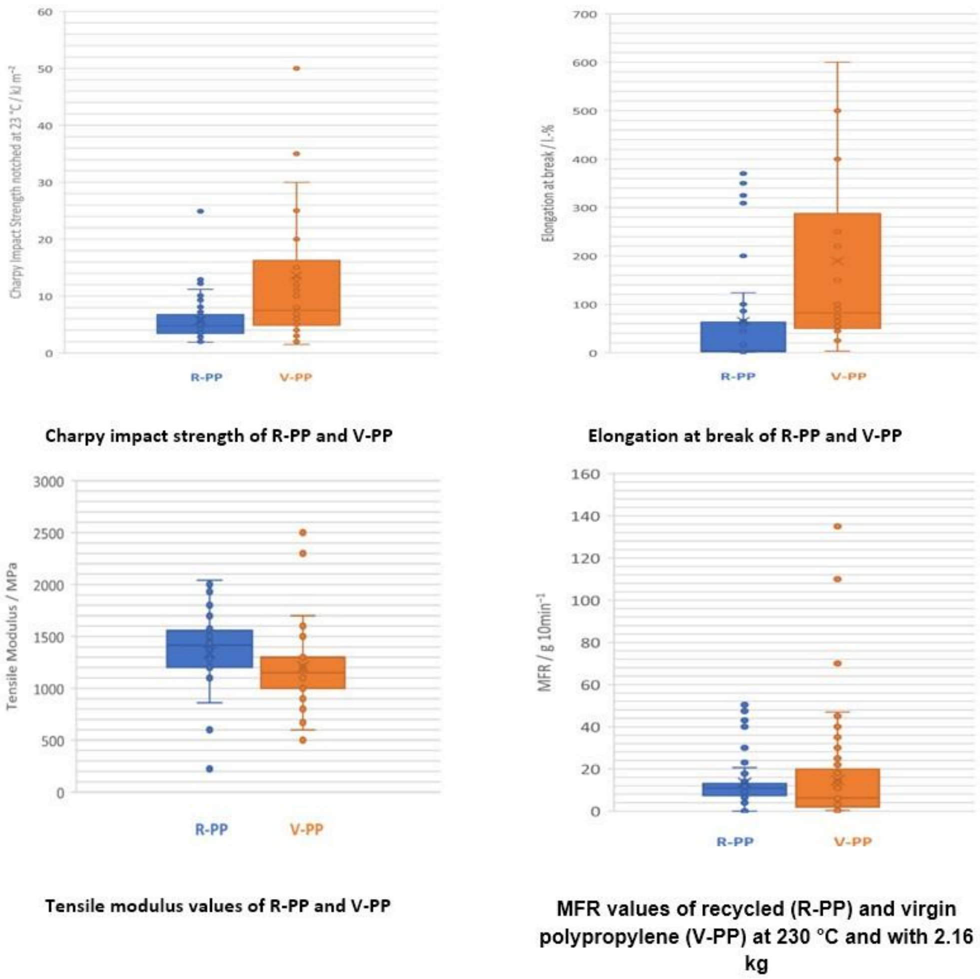

Fig. 6. Illustrate various test of R-PP and V-PP (Ladhari et al., 2021).

(Ladhari et al., 2021) conducted a comparative analysis of the characteristics of recycled polypropylene (R-PP) and virgin polypropylene (V-PP) utilizing data sourced from recyclers and suppliers. Their findings indicated that the attributes of recyclates did not have a direct correlation with those of virgin polymers or the recycling methodologies employed. R-PP exhibited a higher melt flow rate (MFR), with a median value of 11 g/10 min, in contrast to V-PP's 6.3 g/10 min. In terms of mechanical properties, R-PP was frequently observed to be stiffer and more brittle, demonstrating a higher Young’s modulus (1400 MPa for R-PP compared to 1200 MPa for V-PP), diminished elongation at break, and reduced impact strength. This study underscores the variability present in the characteristics of recycled polypropylene within the marketplace.

(Weckström, 2012) have studied the effect of recycling on the mechanical properties of polypropylene attention to tensile strength modulus and melt Index through a thesis. This investigation consisted in comparing virgin and recycled (14 times), polypropylene mechanical properties to determine any changes. All tensile strength and Young’s modulus were measured using a testometric tensile testing machine, melt flow index was determined by the melt flow index machine. The material was ground with a plastic milling apparatus. In addition, (Hamad et al., 2013) review progress on recycling of conventional polymers based on articles (constituted by polyethylene, polypropylene and polystyrene), discussing both the mechanical and chemical methods. They emphasized that mechanical recycling would be preferred because of its ease compared to chemical processes which involve very complex apparatus. The study showed that when low amounts of new polymers were added to recycled materials and compatibilizers were used, material characteristics could be enhanced substantially. For instance, PLA in combination with PET waste exhibited an increased thermal stability, and PC residuals with ABS wastage and compatibilizers presented better mechanical performances. These results suggest that mechanical recycling can improve the material properties.

7. CONCLUSIONS

Polypropylene (PP) is a crucial thermoplastic polymer utilized in various industrial sectors, owing to its distinctive attributes of lightness, strength, thermal stability, and resistance to chemicals. This study emphasizes that the structural variations of PP namely homopolymer, random copolymer, and impact copolymer allow manufacturers to customize its mechanical and physical characteristics for a wide array of applications, including packaging, textiles, and automotive parts. The recycling of polypropylene is essential for conserving natural resources and mitigating environmental pollution. Specifically, mechanical and chemical recycling techniques present promising methods for recovering high-quality materials and reducing plastic waste. Nonetheless, issues such as polymer degradation and contamination need to be tackled to enhance recycling efficiency and material performance.

In summary, the progress of recycling technologies and the growth of closed-loop systems can greatly improve the sustainability of polypropylene production and utilization. Encouraging the reuse and recycling of PP not only aids in environmental conservation but also plays a significant role in the global shift towards a circular economy and energy-efficient manufacturing.

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