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POLYPROPYLENE: A REVIEW OF PROPERTIES AND EMERGING APPLICATIONS

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ABSTRACT

One of the most popular thermoplastic polymers is polypropylene (PP), which has balanced tensile qualities, good chemical resistance, low density, and affordability. The basic characteristics of polypropylene, including its mechanical strength, crystallinity, rheological properties, and thermal behavior, are all well covered in this paper. A detailed discussion is given of how these qualities are affected by molecule structure, tacticity, and processing conditions. In order to overcome intrinsic drawbacks, including low impact resistance and subpar high-temperature performance, current developments in polypropylene modification through copolymerization, mixing, and nanocomposite reinforcement are also emphasized. The review also explores emerging applications of polypropylene in advanced fields such as automotive lightweight components, medical devices, sustainable packaging, fiber and textile engineering, and electrical insulation. Special emphasis is given to bio-based polypropylene, recyclable PP composites, and high-performance PP grades developed to meet modern sustainability and performance requirements. Overall, this review aims to provide a concise understanding of polypropylene is evolving role in both traditional and high-value engineering applications.

KEYWORDS: Crystallinity; Tacticity; Copolymerization; Sustainable materials; Recyclability; Bio- based polypropylene.

1.INTRODUCTION

Polypropylene is a clear, glossy film with high strength and puncture resistance. It has a moderate barrier to moisture, gas, and odours , which is not affected by change in humidity. Owing to its remarkable qualities, affordability, and ease of manufacturing, PP has become one of the most used thermoplastic polymers in recent decades. The development and application of PP have advanced significantly over time, resulting in its extensive use in a variety of sectors. In addition to examining the future prospects for PP research, this paper seeks to provide a thorough summary of the most recent developments in the field and its many applications [1]. The distinctive molecular structure of PP, which is made up of propylene monomers connected in an unbent chain, is the source of its adaptability. Increased crystallinity, better chemical resistance, lower density, and adequate mechanical strength are only a few advantages of this linear arrangement. Because of these characteristics, PP can be used in a wide range of applications, including consumer goods, automotive components, medical devices, and packaging materials [2]. Since 1957, polypropylene (PP) has been manufactured and utilized extensively. PP is currently the second-largest polymer produced globally. What is the key to this material's continuous success? It is a versatile polymer with a number of attributes that support its widespread use. PP's mechanical characteristics fall between those of engineering thermoplastics and commodity plastics. Its stereoregularity and polymorphism are additional characteristics that both academics and developers find fascinating. These characteristics, such as unusual crystallization, regulated beta PP formation, and the impact of processing conditions on the polymorphic structure, are associated with a considerable quantity of new research and numerous inventions [3]. Because of this, researchers view PP as the best model material to investigate various options for additional structure-property relationship adjustments. In this work, we aimed to review the current understanding of the structure- property relationship of PP and related systems. The tacticity, region and stereoregularity of PP, solid-state polymorphism of isotactic and syndiotactic PP, nucleation and crystallization of PP, morphology development and control, polypropylene copolymers, structure and properties of particulate-filled polypropylene, property control by polypropylene blends, PP composites, and foams are all covered in ten chapters in this book. Each chapter summarizes established knowledge and guidelines while also adding new information based on the most recent research findings [3]. Polyolefins are traditionally processed using shaping techniques such as melt extrusion, blow molding, injection molding, and compression molding. Subtractive manufacturing, which entails compression molding or extrusion followed by machining of the mold/extrudate, is another less common technique. These techniques are frequently characterized by great productivity [4].

These methods enable the creation of products with the required qualities by adjusting different processing factors. Temperature, pressure, cooling rate, and melt residence time are some of these variables. Melt viscosity and shape are significantly influenced by the physical properties of the polymer, such as the density of entanglement, degree of polymerization, molecular weight distribution (MWD), and tacticity [4]. In order to improve the physical properties in comparison to composites containing micro-sized fillers, a great deal of research and development has been done on polypropylene (PP)-based nanocomposites using nanosized inorganic fillers. In many instances, the dispersion of nanofillers improves stiffness, but their presence significantly reduces toughness due to a decrease in elongation. Due to these materials' poor adherence, lower toughness can be partially explained by the filler's delamination from the matrix and cracking at the aggregated filler's grain boundaries. Therefore, improving interfacial interactions holds significant promise for improving nanocomposites' weak toughness. However, because PP is inert to inorganic fillers, which are frequently polar, improving interfacial interactions for PP nanocomposites continues to be a major difficulty. Here, we suggest combining the functionalization of PP with the use of mesoporous silica (MPS) filler as a unique solution to this technical issue, which together are expected to produce significant contact points.[5] Polyolefins are traditionally processed using shaping techniques such melt extrusion, blow molding, injection molding, and compression molding.

Subtractive manufacturing, which entails compression molding or extrusion followed by machining of the mold/extrudate, is another less common technique. These techniques are frequently characterized by great productivity. These methods enable the creation of products with the required qualities by adjusting different processing factors. Temperature, pressure, cooling rate, and melt residence time are some of these variables . Melt viscosity and shape are significantly influenced by the physical properties of the polymer, such as the density of entanglement, degree of polymerization, molecular weight distribution (MWD), and tacticity [6]. About 20% of all polyolefins produced worldwide are isotactic polypropylene (iPP), one of the most significant commodity thermoplastics [1]. Physical and mechanical features are balanced by its high isotacticity, improved mechanical qualities, narrow molecular weight distribution, and clarity. Its low cost and environmental friendliness (recyclability) provide an additional benefit. iPP is widely utilized in a variety of applications, including fibers, films for food packaging, the manufacture of bottles and tubes, etc., because of its low cost, low density, good thermal stability, and resistance to corrosion. The iPP matrix has a very high resistance to fracture initiation, but it has a very poor resistance to crack propagation. As a result, the matrix can shatter extremely readily when there is a crack or mechanical failure. This is particularly problematic in cold weather. As a result, a lot of work has been done to change its mechanical characteristics, such as mixing iPP with nanoparticle-based inorganic fillers. Additionally, these inorganic nano-fillers such as talc, silicon dioxide, carbon black, clay, and carbon nanotubes - act as nucleating agents for PP crystallization and improve its physical characteristics [7].

Engineering polymers have long been at the forefront of material engineering thanks to their special combination of mechanical qualities, robustness, and adaptability, opening the door for advances across a wide range of technological and industrial domains. These synthetic materials, which include a variety of plastics, elastomers, and fibers, are distinguished by their capacity to tolerate high levels of stress before failing. Each of these materials is designed for a particular use, from commonplace items to intricate parts in the automotive, aerospace, electronics, and biomedical industries. It is impossible to overestimate the importance of engineering polymers in material engineering; they provide unmatched design flexibility and cost- effectiveness, as well as improved performance over conventional materials like metal and glass. This has played a significant role in their historical development, which dates back to the first synthetic polymer's synthesis in the early 20th century, which signaled a radical break from natural materials and the beginning of a new era in material science. The field of engineering polymers is going through a paradigm transition in the twenty-first century, marked by quick developments in polymer science that could push the limits of material engineering. This paper examines these new developments, outlining how they signify a substantial shift in the creation, manufacturing, and use of materials [8].

2.Properties

One common semi-crystalline thermoplastic polymer in the polyolefin family is polypropylene (PP). PP has a wide range of uses in packaging, automotive, medical devices, textiles, and electrical components because of its low density, balanced mechanical performance, chemical resistance, and ease of processing. The molecular structure, tacticity, crystallinity, and processing conditions of PP all have a significant impact on its characteristics. Chemical Configuration Repeating propylene monomer units with the chemical formula $(C_3H_4)_n$ make up polypropylene, a hydrocarbon polymer. Chain packing, crystallinity, and thermal behavior are all greatly impacted by the presence of a methyl group ($–CH_3$) on each alternative carbon atom.

Mechanical Characteristics PPC's chemical makeup and chain length are related to its mechanical characteristics The PPC molecule's stiffness and rigidity are enhanced by the presence of carbonate groups. However, the length of the chain affects PPC's mechanical characteristics. The tensile strength is between 7 and 30 MPa, the elongation at break ranges from 600% to 1200%, and the reported Young's modulus of PPC shows a broad range of 200–1400 MPa. Furthermore, it has been demonstrated that PPC chain elongation through ternary or multicomponent polymerization can enhance its mechanical characteristics hydroxylated carbon nanotubes (CNTs) and polyvinyl alcohol (PVA) to PPC in consideration of the entanglement effect brought on by the high aspect ratio of one-dimensional fillers and intermolecular complexation. The hydrogen bonds between PPC, CNTs, and PVA were intended to limit the PPC chain's mobility. As a result, the mechanical strength of the final ternary composite (PPC/CNT)PVA increased significantly with the addition of CNTs and PVA, reaching 62.7 MPa of tensile strength more than four times greater than the average tensile strength reported for PPC (15 MPa) Wearable electronics and implantable materials can make advantage of these PPC-based composites with improved mechanical qualities.[9] Stiffness and ductility are well-balanced in PP. Excellent plastic deformation prior to failure is shown by the high elongation at break.

a. Thermal Characteristics

One crucial PPC index is the thermal property PPC typically has a low glass transition temperature (Tg), between 18 and 40 °C. At temperatures higher than 150 °C, PPC is vulnerable to thermal degradation . Because of this, PPC has a narrow temperature window for fusional processing and low thermal stability. The low Mw of PPC, which leads to comparatively weak intermolecular interactions, is the primary cause of its poor thermal stability. Furthermore, PPC is vulnerable to hydrolysis and pyrolysis during heating due to a large number of ester motifs in the backbone and the end hydroxyl groups. In general, PPC undergoes two different kinds of pyrolytic reactions: "unzipping" due to "hydroxyl backbite" and "irregular chain breaking [9].

b. Biodegradable Characteristics

PPC degrades naturally without releasing harmful gasses. PPC is hence regarded as "a green plastic." Our experience, however, indicates that PPC biodegrades mostly at the surface and is strongly influenced by its Mw and the quantity of microorganisms employed. Degradation will occur more quickly at lower Mw. For instance, research by Luinstra and colleagues demonstrates that fermentation with a large number of microorganisms at 60 °C may break down PPC sheets with a Mw of 5 × 104 g/mol in three months . On the other hand, after being buried in soil for six months, PPC films with a greater Mw of 4.63 × 105 g/mol can only decay by 8% . The enzymes produced by various microorganisms are likely another factor contributing to the variance in PPC biodegradation. A copolymer film of PPC and PCL, poly(propylene carbonate-co-ε- caprolactone), has been created and put in phosphate buffer with a panel of enzymes inorder to test this theory . It has been discovered that Rhizopus arrhizus lipase, ColoneZyme A, and Proteinase K can break down the film [9].

c. Biomedical Characteristics

PPC has a lot of promise for a variety of medical uses. In fact, PPC has been utilized in a number of medical goods, such as garbage bags for medical disposal, surgical gowns, masks, and insulating pads. Apart from these low-end uses, the majority of current research on PPC-based biomaterials is concentrated on implants, medical dressings, and drug carriers , particularly for biomodified PPC. We give a quick summary of the developments in the use of PPC as scaffolds, implants, medicinal dressings, and drug carriers [9].

d. Fiber-reinforced composite

PP is frequently blended with carbon, glass, or natural fibers to serve as the matrix material in fiber-reinforced composites. These composites are used in many different industries, such as the automotive, aerospace, and construction sectors, because of their high strength, low weight, and resistance to corrosion. Shen et al. examined the mechanical and acoustic properties of the PP composite reinforced with jute fibers. After jute's fiber content dropped, its mechanical qualities improved by as much as 50%. However, the 50% fiber content offers the optimum acoustic insolation performance [10].

e. Electrical Characteristics

Polypropylene is widely used in the electrical industry - especially in power capacitors and power cables because of its high breakdown strength, good dielectric properties, low density and excellent process ability. However, as modern power systems demand higher electrical performance, researchers have been exploring ways to improve PP by creating nanocomposites materials where nanoscale fillers are dispersed in the polymer matrix. This review provides a concise, systematic look at how polypropylene nanocomposites are being developed to meet the increasing electrical demands of power equipment, focusing on enhancements in dielectric properties through nanotechnology [11].

3.Emerging Applications

Many businesses worldwide currently develop metallocene-based polyolefin polymers, but BASF in Germany and ExxonMobile Chemical Co. in the United States are the primary manufacturers of PP based on metallocene. In 1960, Exxon started creating Escorene Polypropylene grades for nonwovens, and in 1995, it unveiled AchieveTM propylene polymers based on Exxpol catalyst technology. Compared to traditional polypropylene, this produced stronger and finer fibers at a reduced cost of manufacture, improving overall.

PP fiber applications in the textile and non-textile industries PP fiber is widely used in the industry due to its high-performance qualities and relatively inexpensive cost. nonwovens sector. PP dominates numerous nonwoven markets and is a crucial fiber in nonwoven processing. Nonwoven fabrics, especially absorbent product. Because of its low density, resilience to abrasion, and ability to drain away moisture, polypropylene fibers are used extensively in textiles, carpets, ropes, geotextiles, and nonwoven materials. PP nonwovens are utilized in disposable items like face masks, surgical gowns, and hygiene products in the medical textile industry. Its resistance to chemicals and microbes [12] further improves the material's potential for industrial and protective textile applications.

Automobile Sector despite a crisis in the automobile industry, the nonwovens industry in South America has been growing in an increasing number of automotive product categories. Over the previous year, 1.6 million units were made, a 24% decrease from 1997. Exports decreased 7.7% from 416,000 to 384,000 units throughout the year, while sales plunged 21%. Imports were a different story; the number of new cars imported increased by 13.8%, from 303,000 to 345,000. A number of factors, including rising unemployment, higher interest rates, tributary costs, and economic issues, contributed significantly to the unfavorable trends in 1998. Interior fabrics used in or on kick panels, package shelves, seat construction, truck liners, load decks; cabin air filters, etc. are the main uses for polypropylene nonwovens in automobiles [10].

Packaging Sector because of its low density, high strength-to-weight ratio, and chemical resilience, and outstanding processability, polypropylene is one of the most used polymers in the packaging sector. Food packaging, containers, bottles, caps, films, and flexible packaging materials all make substantial use of it. PP is appropriate for microwaveable and hot-fill packaging applications because to its strong moisture barrier qualities and thermal stability. Its significance in environmentally friendly packaging solutions is further increased by its non-toxic nature and recyclable nature [12].

Construction and Infrastructure Sector, in construction and infrastructure, polypropylene is used in pipes, fittings, insulation materials, roofing membranes, and concrete reinforcement fibers. PP fibers improve crack resistance, impact strength, and durability of concrete structures. Its resistance to moisture, corrosion, and chemicals makes polypropylene suitable for long-term structural applications in civil engineering [12].

Advanced Engineering and Industrial Sector, with the incorporation of nanofillers, fibers, and functional additives, polypropylene is increasingly used in advanced engineering applications such as high-performance composites, energy storage devices, and thermal and electrical insulation systems. These advanced PP materials offer improved mechanical, thermal, and functional properties, expanding their use beyond conventional commodity applications [12].

4.LIMITATIONS

Despite being widely used, polypropylene has a number of intrinsic drawbacks that limit its use in high-performance and specialized settings. Poor impact resistance at low temperatures, where the material becomes brittle due to decreased molecular mobility, is one of polypropylene's main disadvantages. This restricts its application in cryogenic and cold-climate settings. Furthermore, polypropylene's low surface energy leads to poor printability and stickiness, making coating, painting, bonding, and additive manufacturing procedures more difficult without surface modification. In comparison to engineering plastics, polypropylene exhibits comparatively low heat distortion temperatures and limited thermal resistance. Dimensional instability, mechanical strength loss, and thermal deterioration can result from extended exposure to high temperatures. Additionally, PP requires the addition of flame-retardant chemicals for usage in electrical and construction applications because to its high flammability and weak intrinsic flame retardancy. Its vulnerability to ultraviolet (UV) radiation and oxidative degradation, which results in embrittlement, discoloration, and a shorter service life when exposed to outdoor conditions, is another important drawback. Particularly in molded and additively made components, polypropylene's high crystallinity can cause shrinkage, warpage, and anisotropic mechanical characteristics. Lastly, even though polypropylene may be recycled, mechanical recycling can deteriorate its qualities, and the material's non-biodegradable nature poses environmental issues that call for continued study into sustainable modification and recycling techniques.

5. CONCLUSION

Because of its low density, superior mechanical strength, outstanding chemical resistance, ease of production, and affordability, polypropylene has become one of the most significant and versatile thermoplastic polymers. The basic qualities of polypropylene, such as its mechanical, thermal, electrical, and chemical properties, which make it appropriate for a variety of typical applications, have been highlighted in this review. However, its usage in high-performance situations has historically been limited by inherent constraints such low impact resistance at low temperatures, poor UV stability, limited flame resistance, and surface inertness. The potential applications for polypropylene have been greatly increased by recent developments in materials science. Polypropylene-based composites and nanocomposites with improved mechanical, thermal, electrical, and functional properties have been developed through the addition of fillers, fibers, nanoparticles, and compatibilizers. Polypropylene has evolved from a commodity polymer to a multipurpose engineering material, as evidenced by new uses in fields including electrical insulation, additive manufacturing, filtration membranes, medicinal devices, automobile light weighting, and environmental technology. Notwithstanding these developments, issues with long-term durability, sustainability, recyclability, and nanofillers dispersion continue to be significant research priority. Future research should concentrate on creating eco-friendly modification methods, increasing recycling effectiveness, and creating multipurpose polypropylene systems that strike a compromise between environmental responsibility and performance. All things considered, polypropylene is still a very versatile material, and future study is anticipated to increase its use in cutting-edge industrial and technical applications.

REFERENCES

1. Nature (Hossain, M.T., Shahid, M.A., Mahmud, N. et al. Research and application of polypropylene: a review. Discover Nano 19, 2 (2024). https://doi.org/10.1186/s11671-023-03952-z
2. Maurya AK, Manik G. Advances towards development of industrially relevant short natural fiber reinforced and hybridized polypropylene composites for various industrial applications: a review. J Polym Res. 2023;30(1):47.
3. Karger-Kocsis, József, and Tamás Bárány. "Polypropylene handbook." Switzerland: Springer 2019).
4. Karaki, A. Hammoud, E. Masad, M. Khraisheh, A. Abdala & M. Ouederni, Polymer, 307, Article 127333 (2024). https://doi.org/10.1016/j.polymer.2024.127333

5. Watanabe, R., Hagihara, H. & Sato, H. Structure-property relationships of polypropylene-based nanocomposites obtained by dispersing mesoporous
6. Silica into hydroxyl-functionalized polypropylene. Part 1: toughness, stiffness and transparency. Polym J 50, 1057–1065 (2018). https://doi.org/10.1038/s41428-018-0095
7. Bikiaris D. Microstructure and Properties of Polypropylene/Carbon Nanotube Nanocomposites. Materials. 2010; 3(4):2884-2946. https://doi.org/10.3390/ma3042884
8. Harun-Ur-Rashid M, Imran AB. Emerging Trends in Engineering Polymers: A Paradigm Shift in Material Engineering. Recent Progress in Materials 2024; 6(3): 024; doi:10.21926/rpm.2403024.
9. Wang, L.; Li, Y.; Yang, J.; Wu, Q.; Liang, S.; Liu, Z. Poly(Propylene Carbonate)-Based Biodegradable and Environment-Friendly Materials for Biomedical Applications. Int. J. Mol. Sci. 2024, 25, 2938. https://doi.org/10.3390/ijms25052938
10. HS Mohapatra, A Chatterjee, P Kumar - IJ of Adv. and Nano Technol, 2013 - ijaent.org
11. Liu, W., Cheng, L., & Li, S. (2018). Review of electrical properties for polypropylene-based nanocomposite. Composites Communications, 10, 221–225. https://doi.org/10.1016/j.coco.2018.10.007
12. Walter, P., Mäder, D., Reichert, P., & Mülhaupt, R. (1999). Novel polypropylene materials. Journal of Macromolecular Science, Part A, 36(11), 1613–1639. https://doi.org/10.1081/MA-100101617