Characterization of Plastics and Polymers: A Comprehensive Study

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Abstract. Since the beginning of polymer synthesis, a huge modification and development have taken place in this field which resulted in a world where people cannot think of a single day without a polymer product. They are light in weight, affordable and have the potential to provide a similar strength like the traditional metallic objects. As the demand for polymer products is increasing rapidly, its characterization and evaluation of mechanical properties become essential for making a reliable, scientific and cost-effective product design. Recently the incorporation of biopolymers in the global market has made this industry more attractive to consumers and government bodies. But the main challenge lies in its characterization as plastics and polymers found in nature or synthesized artificially have a wide range of physical and chemical properties. So, a particular set of instruments that can evaluate the properties of a group of polymers, may not be usable for a different group with the same accuracy and technique. Researchers are working incessantly to find out effective methods for this purpose and many of them are successful in finding some crucial properties of polymers like strength, elastic modulus, viscosity, hardness etc. The present work briefly discusses the superiority of polymer materials and the research work that has been carried out so far for the characterization of the same. Study on the biopolymer, its characterization and necessity in the context of environmental sustainability are also included in this literature.

1. Introduction
In the advancement of civilisation, the role of plastic and polymers is too much to say in a few sentences. These two terms are interrelated, plastics are a special type of polymers having huge applications as raw materials for the manufacturing of various modern appliances while polymers form a big umbrella under which plastic exists. So all polymers cannot be termed as plastics. As the name indicates, a polymer is formed by the combination of monomer units that have a wide range of physical and chemical properties. From the small household application to the heavy industrial equipment, its presence is very much dominant. The reason behind it is its favourable properties i.e. lightness, durability, chemically inertness (in most cases) and many other desired mechanical properties like hardness, strength per unit weight, scratch resistance etc[1,2]. Even our body is full of natural polymers i.e. Polysaccharides, Polynucleotides (DNA), Proteins etc[3]. The applicability of polymers has now expanded beyond the common domestic applications. Like the polyurethanes can be used in multipurpose areas viz. furniture, automobile industry, coating, construction and even in biomedical engineering due to its antimicrobial properties[4]. All these things made it impossible to think of a world without polymer and its products but it has a very adverse impact too on the environment. So, it is reasonable to invest effort not only in replacing plastics products with other biodegradable material but also in the recycling of the same by the maximum possible extent. That is why this is one of the most demanded topics of research nowadays. Several works have been done so
far in this field and some of its fruitful results are advanced waste management processes, biopolymers, bioplastics (biodegradable), reinforced plastics and so on[5–7]. Polymers being a widely used material in many fields, their testing and characterization become an obvious thing for designing more reliable products with known or predictable material properties. The natures and properties of polymers are quite complicated to test and evaluate because of their wide range of physical states and unavailability of a unique testing methodology[8,9]. From a soft foam, viscous latex and rubber to a very hard and brittle thermoplast, all are different types and classes of polymers having different properties. Several unique physical testing methods are required for each unique class of polymers and that is the most challenging issue in this field of research[10]. Physical testing is mostly used to determine the mechanical properties of polymer namely hardness, tensile strength, flexural rigidity, scratch and wear resistance etc. Apart from that, a more detailed mechanical characterization can also be done for a sophisticated design of plastic products like creep, fatigue, fracture, impact strength, toughness, thermal stress etc and these data also plays a vital role in the failure analysis of the same[11,12]. Only the analysis of mechanical properties is not sufficient for the characterization of polymers as they can also be susceptible to chemical degradation, environmental corrosion, microbial(for biopolymers) and photolytic(due to sunlight) degradation, moisture-induced damage etc. These factors obviate the need for detailed chemical characterization of polymeric substances[13]. Properties of plastics and polymers are found to be highly influenced by functionalization, hydrocarbon chain length, incorporation of fibres, nanoparticles and different types of micro and nano fillers[14–18]. It has been found that the interfacial property of graphene oxide and a polymer matrix can be enhanced by controlling the functional group polarity of the polymer. Optimum polarity can increase the hydrogen bond density at the interface resulting in higher adhesion and superior strength[14]. Similarly, a study by Jian et al reveals that the interfacial shear strength and Young’s modulus of CNT-epoxy nanocomposite polymer are improved by chemical functionalization on CNTs[19]. In modern applications, the use of polymer coating has drawn the attention of many engineering industries due to its favourable surface properties. A significant portion of polymer coatings are used to increase the durability of the surface of the substrate which resulted in a rigorous study and research for the evaluation of the important surface properties like scratch, wear, hardness, corrosion resistance etc in recent years[20–24].

Due to the unique properties of plastics and polymers and its constant worldwide demand, it will continue to be an integral part of the civilisation in future and the research in this field will also go on in the search of new material with more flexibility and advanced properties which will be able to serve the need of the respective engineering industries in a better way. Present work is focused on the analysis and comparative study of different types of plastics and polymers. Specifically, the characterization processes of synthetic and biopolymers and the path towards sustainability are discussed in detail.

2. About plastics and polymers

Polymerization is a basic chemical process that is made by combining the monomer units(Ethylene, Propylene etc) in a chain or a complex network with the help of a specific chemical reaction mechanism basically, addition and condensation[25] (Fig 1). Polyethylene and polypropylene, the most used plastics in our everyday life are originated from crude oil and natural gas refinery. Firstly naphtha is separated from the by-products of the same and then passed through the cracking process at around 800 °C where the monomers i.e. ethylene and propylene are formed. It is then compressed and cooled to a liquid state and polymerisation is initiated by a free radical reaction with the help of an ‘initiator’ or ‘catalyst’ like organic peroxide.
Finally, they are collected as plastic pellets and sent to factories for casting into different products. These two are the example of addition or chain growth polymerisation which mainly takes place by a free radical exchange while the condensation polymerisation is one which gives water as a by-product by the substitution of Hydroxyl (OH−) radical. Polymerisation process is not limited to a small boundary. In fact, polymers were there from the creation of the universe and life and a wide range of natural polymerisation processes had taken place so far in our environment. In recent years, the increased demand for bio-based polymers has inspired chemists, microbiologists and process engineers to work on their synthesis in detail. Research has revealed that biopolymers can be produced from renewable resources or from organic substances like starch, cellulose, lactic acid, polysaccharide, polyamides etc which can be synthesized or degraded in the environment eco-friendly with the interaction of microorganisms[26,27]. Some basic types of biodegradable and non-biodegradable plastics are classified based on their source as shown in Table 1.

Table 1. Classification of some widely used plastics based on their source[28]

| Plastic Type          | Bio-based plastics (renewable resources)                  | Oil-based plastics (fossil resources)                  |
|-----------------------|-----------------------------------------------------------|-------------------------------------------------------|
| Biodegradable plastics| poly(lactic acid) (PLA)                                   | poly(e-caprolactone) (PCL)                            |
|                       | polyhydroxyalkanote (PHA)                                 | poly(butylene succinate/adipate) (PBS/A)              |
|                       | polysaccharide derivatives (low DS)*                      | poly(butylene adipate-co-terephthalate) (PBA/T)       |
|                       | poly(amo acid)                                            |                                                       |
| Non-biodegradable     | polyhydroxyalkanote (PHA)                                 |                                                       |
| plastics              | polyol–polyurethane                                       |                                                       |
|                       | bio-polyethylene (bio-PE)                                 |                                                       |
|                       | bio-poly(ethylene terephthalate) (bio-PET)                |                                                       |
|                       | poly(ethyylene terephthalate) (PET)                       |                                                       |
|                       | poly(e-caprolactone) (PCL)                                |                                                       |
|                       | poly(butylene succinate/adipate) (PBS/A)                  |                                                       |
|                       | poly(butylene adipate-co-terephthalate) (PBA/T)           |                                                       |

*DS- Degree of substitution

3. Characterization of traditional polymers and innovations in this field
In polymer science, the role of synthetic polymers extracted from fossil fuels has been significant from its beginning due to its available production method and desirable material properties. For this reason, the modern polymers synthesized from renewable resources have not been able to replace their position completely till now. In our modern applications the fossil-based plastics i.e. PE (polyethylene), PP(polypropylene), PET(Polyethylene terephthalate), PS(polystyrene), PVC(polyvinyl chloride) etc. are still dominating as they are light, cost-effective, available in different forms and meet the design criteria properly. Among them PE and PP are crystalline at room temperature and can be used as a moulded object, especially the PET has glass transition temperature well above the room
temperature which provides it higher hardness and dimensional stability. It is obvious that characterisation of any material requires proper testing methods to predict its physical and chemical properties which in fact, is the main requirement of engineering product design. There are several physical and chemical testing methods of polymers available today and many more are in the research stage[10,13]. Nowadays, as the use of recycled plastics has been emphasized worldwide as a part of sustainable development, its characterization becomes an important factor in design. As an example, the PET scrap is seen to be reusable after its separation from unwanted foreign particles, homogenization and heat treatment which gives it uniform mechanical properties. Its tensile properties, dynamic viscosity and thermo-oxidative stability are also studied for a detailed mechanical characterization[29]. PE and PP are widely abundant in domestic waste and there is a good possibility of recycling them if the waste is collected at the maximum extent by the municipality and other concerned authorities. There are many existing post-processing methods i.e. grinding, blending, homogenization, composite mixing, heat treatments which can make them reusable. It is found that the tensile properties improve if the plastic scrap mixture is finely milled to powder and also the possibility of alloy formation occurs among the polymers[30]. Researchers also suggest that the addition of waste rubber dust from the textile industry with the recycled PP blend elevates its bending, tensile and impact strength and damping characteristics[31]. Besides, PVC also contributes to plastic waste disposal significantly due to its heavy use in data, power transmission cable and fluid transmission pipes. A detailed mechanical characterization and composition analysis of the recycled PVC (r-PVC) reveals its reusability and processability after being separated from the waste. Due to some degradation in its mechanical properties over time researchers suggest the use of blended r-PVC with other recycled plastics or additives to improve its properties[32,33]. Research in the field of polymer science has been done extensively for the last few decades in the search of more effective polymers with superior mechanical and chemical properties and its demand is increasing day by day as it is benefitting the industries as well as our society a lot[34,35]. Polymer alloy can sometimes be a good replacement for the pure one i.e. PET/PP blend is more versatile than the individual polymers in many fields. It gives better stiffness, thermal and mechanical properties, favourable permeability etc[36]. Super polystyrene also is an example of modifying the existing polymer which is the copolymer of styrene and 1,1-Diphenylethylene. It exhibits long term service capability at elevated temperature and higher glass transition temperature due to the presence of bulky group DPE making it highly suitable in use as an insulating material, pump housing, fuse boxes, microwave dishes etc[2].

Recently a detailed characterization of Polyvinylpyrrolidone, a new generation polymer, is done which revealed its usefulness and versatility in biomedical applications as it is biocompatible, chemically stable, non-toxic, highly soluble in different organic solvents and capable to form complex with both hydrophilic and hydrophobic substances. It has also good electrical properties, adhesiveness and high solubility in water which makes it suitable for use in many beyond medical applications[1]. Menčík et al[37] carried a detailed study on the characterization of viscoelastic plastics viz. polymethyl methacrylate, epoxy resin and tooth enamel. They successfully performed nanoindentation test on the said polymers to estimate their material properties like elastic modulus and surface hardness. Besides, a separate creep test over a period of 3700 seconds is performed using a Berkovich indenter for evaluating the creep data. The average value of hardness and elastic modulus is found to be 0.205GPa and 3.66GPa respectively. Nowadays the study and characterization of polymer and polymer composites are being done extensively in various research and development sectors. Its application is found to be useful in almost every industry like renewable energy, aircraft, automobile and electric equipment, biomedical application and even in the modern drug synthesis process[38]. Carbon nanotube (CNT) is one of the most promising materials for future innovation because of its many exceptional properties which include excellent mechanical, thermal and electrical properties. Requirement of high strength material with lighter weight in various engineering industries like automobile, aerospace, biomedical, defence etc. has resulted in a rigorous study on CNT based composite and nanocomposite materials[39,40]. Its outer surface is hydrophobic in nature and chemically inert which makes it suitable in many applications like, CNT-Polymer based film electrode can be successfully utilized to detect glucose in an aqueous system[41,42]. Not only that, it is also
found experimentally that anticancer drug-loaded multiwalled CNT has the ability to target and destroy the cancer cells more effectively[43]. Characterization of CNT reinforced epoxy composite is done by Dan et al using the finite element simulation to evaluate its mechanical properties like stress-strain relationship and tensile strength and the same has been validated by experimental data[44]. Advanced research suggests that the brake liner made of CNT reinforced epoxy and phenol-formaldehyde composite exhibits superior friction and wear characteristics as compared to the traditional asbestos liner[45]. Gupta et al conducted mechanical characterization on carbon fibre reinforced polycarbonate polymer composite using different techniques like universal testing machine, three point bending, compressive loading etc. They successfully found out the effect of carbon fibre on the tensile, compressive, flexural properties, toughness and ductility of the 3D printed polymer composite[11]. Due to the increasing health concern in our modern era synthesis and characterization of antimicrobial plastics and polymers are being done widely especially for biomedical applications[46]. Researchers found that the existing synthetic polymers can be made antibacterial by applying a layer of antimicrobial peptide(APM) on their surfaces. As it is expensive and complex in production, the synthesis of other cost-effective polymers is also being studied[47,48].

In recent years, the use of wood plastic composite (WPC) in automobile, aerospace and building structure components has been incorporated significantly due to its low production cost, desired strength and sustainability as compared to glass fibre composites. WPC can be manufactured by the recycled plastic blend separated from construction and demolition waste[49]. It is found from the mechanical characterization that it is less strong than the reference material made with low-density PE(LDPE) but shows more stiffness than the reference. A similar kind of study and characterization is performed for the WPC where it is manufactured by recycled PE/PP blend reinforced with external fibre material which is a more effective and advanced method to meet the required strength criteria of design[50]. Modern high-performance engineering plastics can be a better option for the future because of their many favourable properties compared to the traditional ones but their synthesis cost is too high. Aromatic polyimino ether(PIE) is one of them which shows a promising future because of its low synthesis cost, high thermal stability and higher decomposition temperature[51]. Semicrystalline polymers also playing an important role in materials synthesis because its exceptional thermomechanical properties which are desirable in many applications. So its characterization also becomes necessary for further product development. Voyiadjiset al[52] conducted nanoindentation test on poly(ether-ether-ketone)(PEEK) to study its localized nanomechanical properties. Several other studies are also going on in this field like avoidance of density variation caused by the chain termination on the surface of semicrystalline polymers. Chain termination and dangling of fibres at the end surfaces can reduce the density by 17% of the average density[53]. Research done in this field is quite vast and multipurpose. Newer methods and techniques are yet to come for the study and characterization of plastics and polymers which will certainly enrich science and technology and consequently the human civilization.

4. Biopolymer, its characterization and sustainability

The journey of plastics and polymers started a long time ago in the second half of the 19th century when humans developed celluloid from cellulose fibre which is a natural polymer extracted from wood or straw[54]. From then a tremendous development has been done in this field for satisfying the need of our civilisation which resulted in a world full of plastics and polymers. Consequently, the dependence on artificial plastics has increased which has been affecting our environment and ecosystem for a long time. Microplastic is one of the most dangerous plastic derivatives found mainly in soil and water. They are tiny plastic particles produced by the gradual decay of plastic molecules from various sources viz tube, tire, waste container, textile, packaging industries etc[55]. Hence, the study, synthesis and characterization of alternate polymers i.e. the biopolymers has been the epicentre of research for the last few decades[56–58]. Biopolymers are those types of polymers that are produced from renewable and natural resources while biodegradable polymers are another type of biopolymer that dissolve or degrade easily in the environment producing non-toxic compounds or gases[26,59]. Bioplastics/polymers may be biobased(from biomass), biodegradable or can possess...
both the characters. So a fully bio-based plastic may not be biodegradable and a fully oil-based (fossil) plastic may be completely biodegradable. Degradation of these polymers is also highly dependent on the sink it finally ends up in like seawater, marine water, soil etc. Haider et al[56] gave a detailed review on the biodegradation characterization of polymers and suggested the need for practical experimental study apart from laboratory experiments so that all the random factors in the environment can be taken into account. Several microorganisms like aerobes, anaerobes, photosynthetic bacteria, archaeabacteria etc are responsible for the biodegradation of bioplastics which are mainly abundant in soil and compost[40]. Hydrolysis is one of the most important biodegradation processes which is capable of decomposing polyesters, polyethers, cellulose derivatives, starch etc[58]. It is already discussed that the demand for biopolymers has been increasing gradually and consequently the modification of existing biopolymers are also being done by composite blending, fibre reinforcement, addition of external functional groups etc in the existing hydrocarbon chain. These processes are seen to be effective in achieving superior properties as compared to the existing ones. When polyvinyl alcohol (PVA) is blended with corn starch and lignocellulosic fibre its thermal stability, water permeability and biodegradation rate improves which are suitable for specific application based product design[60]. Research suggests that potato and yam can be good raw materials for starch-based polymer synthesis due to their high starch content and excellent biodegradability in soil. Besides the resulting polymer shows moderate thermal stability which is confirmed by thermogravimetric analysis (TGA) and a workable tensile strength (0.6-1.9 MPa) suitable for low strength applications[61,62].

Composite blending is a widely accepted modern polymerisation process and blending of synthetic polymers with biopolymers is a part of that. Its objective is to find the resulting characteristics of the composite polymer and whether it is more beneficial than the virgin ones or not. As an example, the mixture of low density polyethylene (LDPE) with corn starch has been studied which reveals that it exhibit reduced melt flow index (MFI) and increased elastic modulus[63]. Among biopolymers, the edible film is showing an increasing demand in the food processing industry as they are digestible and possess no threat to the human body. An edible film is a thin layer of edible polymer that can be placed over or between food components and plays a vital role in food preservation and distribution[64,65]. There are many processes of production of edible film and still, research is continuing for finding a more efficient and cost-effective synthesis process. Edible film produced from grass pea flour in the presence of transglutaminase enzyme has good potential because of its desired properties. It is found experimentally that the presence of microbial transglutaminase makes it mechanically resistant and gives a better digestive property. Besides, the scanning electron microscopy (SEM) study confirms its homogeneous structure obtained by enzyme treatment[66]. It’s a matter of deep concern that the earth’s mineral oil source is limited and it will be completely depleted in a few decades. So, the human civilisation cannot be fully dependent on traditional synthetic polymers for a long time. Researchers are trying to find alternate sustainable resources for its replacement and polyhydroxyalkanoates (PHAs) can be used quite satisfactorily for the same purpose. They are fully biodegradable, immunologically inert, highly suitable for biomedical applications and exhibits many desirable properties like mineral-based polymers[67]. PHAs are one type of polyesters that are produced from microbial fermentation. Because of its low production yield, the overall cost of PHAs increases causing a big barrier to its large scale use in the polymer industry[68]. Besides, proteins, lipids, fibres and polysaccharides are also widely available biopolymers obtained from plant and animal sources[69]. Efforts have been made to utilize these polymers in product synthesis by suitable modification and homogenization techniques. Among them, proteins have many available sources based on plants and animals like oilseeds, eggs, milk etc and most importantly, the wastes and surpluses from the food processing industry contribute the most. A detailed characterization of protein-based polymers reveals that the protein collected from these sources can be made usable by suitable mixing and other thermomechanical treatments. Experiments show that the addition of plasticizer, degree of blending and moulding process improve the value of young modulus, tensile strength, water uptake capacity and other properties of the polymer significantly[70]. The diverse properties of polymers and their composites along with the help of additive manufacturing have
brought phenomenal changes in the biomedical field. They are capable of providing required strength, corrosion resistance and antimicrobial properties which make them the perfect raw material to produce customized biodevices, scaffolds for tissue culture, artificial bone replacements, heart valves, drug carriers and so on[71–73]. The wide availability, easy processibility and many other impressive properties of plant-based cellulose fibre is also a good replacement for the synthetic polymer. It possesses higher mechanical strength as compared to the protein-based polymers and even, the natural fibre reinforced composite polymer has the potential to compete with the existing metals and ceramics[74].

5. Conclusion
The modern civilisation which we are living in is indeed nothing but the result of incessant innovation and advancement in the field of science and technology. The prime objective of any scientific research is to understand the way the universe works and to utilize our available resources for the welfare of mankind in the most efficient manner. It is discussed many times in this article that the role of plastics and polymers in our life is huge. From our body to every corner of the outer world, there is the existence of polymers that we often do not realize. Due to its immense importance, research in this field is still going on on a large scale. In most cases, plastics are proven to be more flexible, user-friendly, lightweight and have a higher strength to weight ratio as compared to metals. Not only that, plastic products are aesthetically and ergonomically far superior to traditional metals. The inventions of newer synthesis processes resulted in the creation of innovative polymers with excellent properties which had never existed before. Due to its increasing demand, there is tough competition among the manufacturers and day by day newer plastic and polymer products are being launched in the market with better performance and reliability. Characterization helps to know the actual nature and characteristics of the polymer which in fact, determines the capability of that material to perform in a specific application. Detailed knowledge about a particular material also improves the design methodologies and safety of the designed product. However, the characterization and testing procedures of polymers are not standardized, unlike the metals because of their widely available physical and chemical states. In the past few decades, due to the rising consciousness of the sustainable exploitation of natural resources, the emphasis on biopolymers have been increased significantly. Undoubtedly, the biopolymer is going to replace the traditional mineral oil-based polymer soon and it is the only way to make a habitable planet for our future generations. The advancement in the field of biopolymers done so far is promising and the future scope of study in this field is widening day by day as the whole world is trying to move towards a greener and cleaner environment with minimal wastage. The main advantages of biopolymers are that they are made from renewable resources and most of them can be made fully biodegradable in a suitable medium(sink). So finally, it can be concluded that the characterisation of plastics and polymers is one of the prime requirements for product design, development and quality assurance. More innovations are yet to occur in this field which will hopefully be able to serve the need of human civilisation in a better way.

References
[1] Teodorescu M and Bercea M 2015 Poly(vinylpyrrolidone) – A Versatile Polymer for Biomedical and Beyond Medical Applications Polym. Plast. Technol. Eng. 54 923–43
[2] Gausepohl H, Oopen S, Knoll K, Schneider M, McKee G and Loth W 2000 Super-polystyrene: a new class of engineering plastics with versatile properties Des. Monomers Polym. 3 299–315
[3] Olatunji O 2016 Classification of Natural Polymers Natural Polymers (Cham: Springer International Publishing) 1–17
[4] Rusu L C, Ardelean L C, Jitariu A A, Miu C A and Streian C G 2020 An Insight into the Structural Diversity and Clinical Applicability of Polyurethanes in Biomedicine Polymers (Basel) 12 1197
[5] Siddique R, Khatib J and Kaur I 2008 Use of recycled plastic in concrete: A review Waste Manag. 28 1835–52
[6] Sharma P V 2020 Polymers and Microplastics: Implications on Our Environment and
Sustainability Emerging Technologies, Environment and Research for Sustainable Aquaculture (IntechOpen)

[7] Folino A, Karageorgiou A, Calabrò P S and Komilis D 2020 Biodegradation of Wasted Bioplastics in Natural and Industrial Environments: A Review Sustainability 12 6030

[8] Wanasinghe D, Aslan F, Ma G and Habibi D 2020 Review of Polymer Composites with Diverse Nanofillers for Electromagnetic Interference Shielding Nanomaterials 10 541

[9] Yu Y, Yuh H, Parada G A, Wu Y, Liu X, Nabdzyk C S, Youcef-Toumi K, Zang J and Zhao X 2019 Multifunctional “Hydrogel Skins” on Diverse Polymers with Arbitrary Shapes Adv. Mater. 31 1807101

[10] Brown R 1999 Handbook of Polymer Testing: Physical Methods (CRC press)

[11] Gupta A, Fidan I, Hasanov S and Nasirov A 2020 Processing, mechanical characterization, and micrography of 3D-printed short carbon fiber reinforced polycarbonate polymer matrix composite material Int. J. Adv. Manuf. Technol. 107 3185–205

[12] Brandtner-Hafner M H 2020 Fracture Mechanical Characterization of Adhesively Bonded Wood-Ceramic Interfaces for Mode I Loading J. Test. Eval. 48 20180256

[13] Lampman S 2003 Characterization and Failure Analysis of Plastics ISBN: 978-0-87170-789-5

[14] Zhang Y, Zhang Q, Hou D and Zhang J 2020 Tuning interfacial structure and mechanical properties of graphene oxide sheets/polymer nanocomposites by controlling functional groups of polymer Appl. Surf. Sci. 504 144512

[15] Ehlert G J, Lin Y and Sodano H A 2011 Carboxyl functionalization of carbon fibers through a grafting reaction that preserves fiber tensile strength Carbon N. Y. 49 4246–55

[16] Nilagiri Balasubramanian K B and Ramesh T 2018 Role, effect, and influences of micro and nano-fillers on various properties of polymer matrix composites for microelectronics: A review Polym. Adv. Technol. 29 1568–85

[17] Liu J, Shen J, Gao Y, Zhou H, Wu Y and Zhang L 2014 Detailed simulation of the role of functionalized polymer chains on the structural, dynamic and mechanical properties of polymer nanocomposites Soft Matter10 8971–84

[18] Yan P, Zhao W, Zhang B, Jiang L, Pether S, Smith J A, Parker D J, Cooper A I, Lei J and Hasell T 2020 Inverse Vulcanized Polymers with Shape Memory, Enhanced Mechanical Properties, and Vitrimer Behavior Angew. Chemie Int. Ed. 59 13371–8

[19] Jian W and Lau D 2020 Understanding the effect of functionalization in CNT-epoxy nanocomposite from molecular level Compos. Sci. Technol. 191 108076

[20] Bertrand-Lambotte P, Loubet J ., Verpy C and Pavan S 2001 Nano-indentation, scratching and atomic force microscopy for evaluating the mar resistance of automotive clearcoats: study of the ductile scratches Thin Solid Films 398–399 306–12

[21] Wong M, Lim G ., Moyse A, Reddy J . and Sue H-J 2004 A new test methodology for evaluating scratch resistance of polymers Wear 256 1214–27

[22] Charitidis C, Gioti M, Logothetidis S, Kassavetis S, Laskarakis A and Varsano I 2004 Comparison of the nanomechanical and nanoscratch performance of antiscratch layers on organic lenses Surf. Coatings Technol. 180–181 357–61

[23] Pelletier H, Mendibide C and Riche A 2008 Mechanical characterization of polymeric films using depth-sensing instrument: Correlation between viscoelastic-plastic properties and scratch resistance Prog. Org. Coatings 62 162–78

[24] Baranwal R K, Hassan T, Agarwal G, Sarkar S and Majumdar G 2019 Optimization of the stress discontinuity value at the interface of a cylindrical stainless steel substrate and electroless Ni-P coating Mater. Res. Express 6 116421

[25] Flory P J 1946 Fundamental Principles of Condensation Polymerization. Chem. Rev. 39 137–97

[26] Breuer U 2009 Book Reviews: Microbial Production of Biopolymers and Polymer Precursors: Applications and Perspectives. Edited by Bernd H. A. Rehm CLEAN - Soil, Air, Water 37 414

[27] Mohan S, Oluwafemi O S, Kalarikkal N, Thomas S and Songca S P 2016 Biopolymers – Application in Nanoscience and Nanotechnology Recent Advances in Biopolymers (InTech)

[28] Iwata T 2015 Biodegradable and Bio-Based Polymers: Future Prospects of Eco-Friendly Plastics Angew. Chemie Int. Ed. 54 3210–5
[29] Pawlak A, Pluta M, Morawiec J, Galeski A and Pracella M 2000 Characterization of scrap poly(ethylene terephthalate) Eur. Polym. J. 36 1875–84
[30] Jonna S and Lyons J 2005 Processing and properties of cryogenically milled post-consumer mixed plastic waste Polym. Test. 24 428–34
[31] Jose J, Satapathy S, Nag A and Nando G B 2007 Modification of Waste Polypropylene with Waste Rubber Dust from Textile Cot Industry and its Characterization Process Saf. Environ. Prot. 85 318–26
[32] Suresh S S, Molhanty S and Nayak S K 2017 Composition analysis and characterization of waste polyvinyl chloride (PVC) recovered from data cables Waste Manage. 60 100–11
[33] Güney A, Özdişek C, Kangal M O and Burat F 2015 Flotation characterization of PET and PVC in the presence of different plasticizers Sep. Purif. Technol. 151 47–56
[34] Hotta A, Cochran E, Ruokolainen J, Fredrickson G H, Kramer E J, Shin Y-W, Shimizu F, Cherian A E, Hustad P D, Rose J M and Coates G W 2006 Semicrystalline thermoplastic elastomeric polyolefins: Advances through catalyst development and macromolecular design Proc. Natl. Acad. Sci. 103 15327–32
[35] Andrade A L and Neal M A 2009 Applications and societal benefits of plastics Philos. Trans. R. Soc. B Biol. Sci. 364 1977–84
[36] Papadopoulou C P and Kalfoglou N K 2000 Comparison of compatibilizer effectiveness for PET/PP blends: their mechanical, thermal and morphology characterization Polymer (Guildf). 41 2543–55
[37] Menčík J, He L H and Němeček J 2011 Characterization of viscoelastic-plastic properties of solid polymers by instrumented indentation Polym. Test. 30 101–9
[38] Gupta B, Ghosh A K, Suzuki A and Rattan S 2018 Advances in Polymer Sciences and Technology (Singapore: Springer Singapore)
[39] Ali F, Ishfaq N, Said A, Nawaz Z, Ali Z, Ali N, Afzal A and Bilal M 2021 Fabrication, characterization, morphological and thermal investigations of functionalized multi-walled carbon nanotubes reinforced epoxy nanocomposites Prog. Org. Coatings 150 105962
[40] Soni S K, Thomas B and Kar V R 2020 A Comprehensive Review on CNTs and CNT-Reinforced Composites: Syntheses, Characteristics and Applications Mater. Today Commun. 25 101546
[41] Gopal N, Shukla P and Sahney R 2018 Development of CNT–Polymer Film-Based Electrode for the Detection of Glucose Advances in Polymer Sciences and Technology Springer 177–86
[42] Gergeroglu H, Yildirim S and Ebeoglugil M F 2020 Nano-carbons in biosensor applications: an overview of carbon nanotubes (CNTs) and fullerenes (C60) SN Appl. Sci. 2 603
[43] Mangla B, Patel K S, Kumar P and Kohli K 2018 Anticancer Drug-Loaded Folate-Conjugated Multiwalled Carbon Nanotubes 197–210
[44] Li D, LiDing, Liu Z, Li Q, Guo K and Cao H 2020 Simulation Analysis on Mechanical Property Characterization of Carbon Nanotubes Reinforced Epoxy Composites Comput. Model. Eng. Sci. 125 145–71
[45] Sridhar B S, George R and Shashikala A R 2021 Synthesis and characterization of carbon nanotube reinforced polymer brake liner material Mater. Today Proc.
[46] Anjum S, Gupta A, Kumari S and Gupta B 2020 Preparation and biological characterization of plasma functionalized poly(ethylene terephthalate) antimicrobial sutures Int. J. Polym. Mater. Polym. Biomater.69 1034–42
[47] Majhi S, Arora A and Mishra A 2018 Antibacterial Activity of Antimicrobial Peptide (AMP) Grafted Polystyrene Surface pp 39–46
[48] Arora A, Zheng W, Liang H and Mishra A 2018 Synthesis of Lysine Mimicking Membrane Active Antimicrobial Polymers 29–37
[49] Turkı I, Keskiçaarı A, Kärki T, Puurtinen A and Marttila P 2017 Characterization of wood plastic composites manufactured from recycled plastic blends Compos. Struct. 161 469–76
[50] Taufiq M J, Mansor M R and Mustafa Z 2018 Characterisation of wood plastic composite manufactured from kenaf fibre reinforced recycled-unused plastic blend Compos. Struct. 189510–5
[51] Al-Hussaini A S 2014 Synthesis and characterization of new thermally stable polymers as new high-performance engineering plastics High Perform. Polym. 26 166–74
[52] Voyiadjis G Z, Samadi-Dooki A and Malekmotiei L 2017 Nanoindentation of high performance semicrystalline polymers: A case study on PEEK Polym. Test. 61 57–64
[53] Fritzsching K J, Mao K and Schmidt-Rohr K 2017 Avoidance of Density Anomalies as a Structural Principle for Semicrystalline Polymers: The Importance of Chain Ends and Chain Tilt Macromolecules 50 1521–40
[54] Trescott M M 1984 Pioneer Plastic: The Making and Selling of Celluloid. By Robert Friedel. (Madison: University of Wisconsin Press) Bus. Hist. Rev. 58 284–5
[55] Rochman C M, Brookson C, Bikker J, Djuric N, Earn A, Bucci K, Athey S, Huntington A, McIlwrath H, Munno K, De Frond H, Kolomijec A, Erdle L, Grbic J, Bayoumi M, Borrelle S B, Wu T, Santoro S, Werbowski L M, Zhu X, Giles R K, Hamilton B M, Thaysen C, Kaura A, Klasios N, Ead L, Kim J, Sherlock C, Ho A and Hung C 2019 Rethinking microplastics as a diverse contaminant suite Environ. Toxicol. Chem. 38 703–11
[56] Haider T P, Völker C, Kramm J, Landfester K and Wurm F R 2019 Plastics of the Future? The Impact of Biodegradable Polymers on the Environment and on Society Angew. Chemie Int. Ed. 58 50–62
[57] He D and Luo Y 2020 Microplastics in Terrestrial Environments 95 (Cham: Springer International Publishing)
[58] Amass W, Amass A and Tighe B 1998 A review of biodegradable polymers: uses, current developments in the synthesis and characterization of biodegradable polyesters, blends of biodegradable polymers and recent advances in biodegradation studies Polym. Int. 47 89–144
[59] Bhagabati P 2020 Biopolymers and biocomposites-mediated sustainable high-performance materials for automobile applications Sustainable Nanocellulose and Nanohydrogels from Natural Sources (Elsevier) 197–216
[60] Imam S H, Cinelli P, Gordon S H and Chiellini E 2005 Characterization of Biodegradable Composite Films Prepared from Blends of Poly(Vinyl Alcohol), Cornstarch, and Lignocellulotic Fiber J. Polym. Environ. 13 47–55
[61] Ismail N A, Mohd Tahir S, Norihan Y, Abdul Wahid M F, Kairuddin N E, Hashim I, Rosli N and Abdullah M A 2016 Synthesis and Characterization of Biodegradable Starch-Based Bioplastics Mater. Sci. Forum 846 673–8
[62] Emadian S M, Onay T T and Demirel B 2017 Biodegradation of bioplastics in natural environments Waste Manag. 59 256–36
[63] Rosa D S, Grillo D, Bardi M A G, Cali M R, Guedes C G F, Ramires E C and Frollini E 2009 Mechanical, thermal and morphological characterization of polypropylene/biodegradable polyester blends with additives Polym. Test. 28 836–42
[64] Porta R, Di Pierro P, Rossi-Marquez G, Mariniello L, Kadivar M and Arabestani A 2015 Microstructure and properties of bitter vetch (Vicia ervilia) protein films reinforced by microbial transglutaminase Food Hydrocoll. 50 102–7
[65] Falguera V, Quintero J P, Jiménez A, Muñoz J A and Ibarz A 2011 Edible films and coatings: Structures, active functions and trends in their use Trends Food Sci. Technol. 22 292–303
[66] Giosafatto C, Al-Asmar A, D’Angelo A, Roviello V, Esposito M and Mariniello L 2018 Preparation and Characterization of Bioplastics from Grass Pea Flour Cast in the Presence of Microbial Transglutaminase Coatings 8 435
[67] Keshavarz T and Roy I 2010 Polyhydroxyalkanoates: bioplastics with a green agenda Curr. Opin. Microbiol. 13 321–6
[68] Amache R, Sukan A, Safari M, Roy I and Keshavarz T 2013 Advances in PHAs production Chem. Eng. Trans. 32 931–6
[69] Avérous L 2004 Biodegradable Multiphase Systems Based on Plasticized Starch: A Review J. Macromol. Sci. Part C Polym. Rev. 44 231–74
[70] Felix M, Perez-Puyana V, Romero A and Guerrero A 2017 Production and Characterization of Bioplastics Obtained by Injection Moulding of Various Protein Systems J. Polym. Environ. 25
91–100

[71] Pekkanen A M, Mondschein R J, Williams C B and Long T E 2017 3D Printing Polymers with Supramolecular Functionality for Biological Applications Biomacromolecules 18 2669–87

[72] Seppälä J, van Bochove B and Lendlein A 2020 Developing Advanced Functional Polymers for Biomedical Applications Biomacromolecules 21 273–5

[73] Puertas-Bartolomé M, Mora-Boza A and García-Fernández L 2021 Emerging Biofabrication Techniques: A Review on Natural Polymers for Biomedical Applications Polymers (Basel). 13 1209

[74] Thakur V K and Thakur M K 2014 Processing and characterization of natural cellulose fibers/thermoset polymer composites Carbohydr. Polym. 109 102–17