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A Systematic Review of Engineering Plastics and Their Viability in Conventional Industrial and Manufacturing Processes

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Abstract

The use of traditional materials such as metals and ceramics in industrial applications has limitations in terms of weight, cost, and design flexibility. Engineering plastics offer a promising alternative with their lightweight nature, cost-effectiveness, and ability to be molded into complex shapes. However, while their longevity is beneficial for industrial applications, it also implies that once they reach the end of their lifecycle, they can take hundreds of years to decompose. This poses a challenge for industries looking to adopt more sustainable practices and reduce their carbon footprint. Moreover, while some plastics can be recycled, the process is often complex and costly, making it less attractive for industrial applications. This results in a significant amount of plastic waste being disposed of in landfills or incinerated, further exacerbating the environmental impact of plastic production. To address this problem, a systematic literature review was conducted to gather information on the properties, carbon footprint, recyclability, challenges, opportunities and applications of engineering plastics in various industries. The findings revealed that engineering plastics exhibit excellent mechanical properties, including high tensile strength, impact resistance, and fatigue endurance. These properties make them suitable for a wide range of industrial applications, such as automotive components, electronic enclosures, and medical devices. The study further showed that engineering plastics can outperform traditional materials in terms of weight reduction, cost savings, and design flexibility. However, challenges such as limited temperature resistance and poor dimensional stability were identified as potential barriers to their widespread adoption. Additionally, the release of toxic fumes when exposed to high temperatures poses a health risk to workers in industrial settings. This highlighted the importance of implementing proper safety measures and regulations to protect workers from potential hazards associated with the use of engineering industrial plastics.

Keywords: Engineering plastics, Properties, Characteristics, Environmental sustainability, Applications.

1 | Introduction

Engineering plastics are a type of plastic material that is specifically designed to meet the demanding requirements of various industrial and manufacturing processes. These plastics are known for their high strength, durability, and resistance to heat, chemicals, and wear. They are widely used in a variety of

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applications, including automotive, aerospace, electronics, and medical devices [1], [2]. Engineering plastics are a subset of plastics that are used in engineering applications due to their superior mechanical properties, such as high strength, stiffness, and toughness. These plastics are typically used in applications where traditional plastics, such as Polyethylene (PE) and Polypropylene (PP), are not suitable due to their limited mechanical properties. The viability of engineering plastics in conventional industrial and manufacturing processes lies in their unique combination of properties, which make them ideal for a wide range of applications [3], [4]. These properties include high strength, stiffness, and toughness, as well as resistance to heat, chemicals, and wear [5]. Engineering plastics are also lightweight and can be easily molded into complex shapes, making them suitable for a variety of applications. Engineering plastics are highly versatile and can be easily molded into complex shapes. This flexibility allows for the production of custom parts and components that meet specific design requirements. This versatility makes engineering plastics a preferred choice for manufacturers looking to create innovative and efficient products [6]. Engineering plastics are a versatile and valuable material that plays a crucial role in modern industrial and manufacturing processes. Their unique combination of properties makes them ideal for a wide range of applications, and their viability in conventional processes is evident in their widespread use across various industries.

2 | Trends in Engineering Plastics

The trends of engineering plastics have been evolving rapidly in recent years, driven by advancements in technology and the increasing demand for lightweight, high-performance materials. The key trends in engineering plastics are as follows.

I. The development of new materials with improved properties, such as higher strength, stiffness, and heat resistance: these materials are being used in a wide range of applications, from automotive components to medical devices [7].

II. The increasing focus on sustainability and environmental impact: manufacturers are now developing bio-based plastics that are derived from renewable sources, such as corn or sugarcane. These materials offer a more sustainable alternative to traditional petroleum-based plastics, which are non-renewable and contribute to environmental pollution [8].

III. The use of engineering plastics in additive manufacturing, also known as 3D printing, is another emerging trend in the industry. This technology allows for the rapid prototyping and production of complex parts with high precision and accuracy. Engineering plastics are ideal for 3D printing due to their excellent mechanical properties and chemical resistance [9], [10].

The trends of engineering plastics are constantly evolving to meet the changing needs of various industries. From the development of new materials with improved properties to the focus on sustainability and the use of additive manufacturing, engineering plastics continue to play a crucial role in modern engineering applications.

3 | Characteristics of Engineering Plastics

Engineering plastics are a diverse group of materials that play a crucial role in various industrial and manufacturing processes. These materials are characterized by their high strength, durability, and resistance to heat, chemicals, and impact. They have the following characteristics:

I. Ability to withstand extreme conditions: for example, they can maintain their mechanical properties at high temperatures, making them ideal for use in automotive engines and other high-temperature applications. Additionally, engineering plastics are resistant to chemicals, making them suitable for use in chemical processing equipment and storage tanks [11], [12].

II. High strength-to-weight ratio: this property makes them lightweight yet strong, allowing for the design of lightweight components that can withstand heavy loads. This is particularly important in industries such as aerospace, where weight reduction is critical for fuel efficiency and performance [13].

III. Excellent dimensional stability: this means that they maintain their shape and size under various conditions, making them ideal for precision engineering applications. They also have good electrical insulation properties, making them suitable for use in electrical and electronic components [14].

Engineering plastics are a versatile group of materials that offer a wide range of benefits in industrial and manufacturing processes. Their high strength, durability, resistance to heat and chemicals, and other properties make them indispensable in various applications.

4 | Properties of Engineering Plastics

Engineering plastics are a type of material that has gained significant popularity in various industries due to their unique properties, which include the following:

I. Exceptional mechanical properties: these plastics have high strength-to-weight ratios, making them ideal for applications where weight reduction is critical. Additionally, engineering plastics have excellent impact resistance, allowing them to withstand heavy loads and harsh operating conditions [15], [16]. This makes them suitable for a wide range of applications, from automotive components to industrial machinery.

II. Engineering plastics offer superior chemical resistance compared to traditional materials such as metals and ceramics. This property makes them ideal for use in environments where exposure to corrosive substances is common [17]. For example, engineering plastics are commonly used in chemical processing plants, where they can withstand exposure to acids, bases, and solvents without degrading or losing their mechanical properties.

III. Ability to withstand extreme temperatures: unlike traditional plastics, which may soften or deform at high temperatures, engineering plastics can maintain their structural integrity even at temperatures exceeding 200°C. This makes them suitable for applications in industries such as aerospace, where components are exposed to extreme heat during operation [18].

IV. Engineering plastics also offer excellent electrical insulation properties: this makes them ideal for use in electrical and electronic applications, where insulation is critical to prevent short circuits and electrical failures [19], [20]. Engineering plastics are commonly used in the manufacturing of electrical connectors, insulators, and housings for electronic devices.

Overall, engineering plastics play a crucial role in modern industries by providing a wide range of benefits, including high strength, durability, chemical resistance, thermal stability, and electrical insulation. These properties make them essential for the advancement of technology and innovation in various sectors, from automotive and aerospace to electronics and healthcare.

Engineering plastics are a versatile and indispensable material that has revolutionized the way we design and manufacture products in modern industries. Their unique properties and capabilities make them essential for meeting the demanding requirements of engineering applications.

5 | Classifications of Engineering Plastics

Engineering plastics are a diverse group of materials that are used in a wide range of applications due to their unique properties and characteristics. These materials are specifically designed to meet the demanding requirements of various industries, including automotive, aerospace, electronics, and medical devices. There are several classifications/types of engineering plastics, each with its own set of properties and advantages. They are discussed as follows.

5.1 | Thermoplastics

Thermoplastics are a type of polymer that can be melted and reshaped multiple times through the application of heat without losing their properties. They are widely used in various industries due to their versatility, durability, and ease of processing [21]. The manufacturing process of thermoplastics involves the polymerization of monomers to form long chains of molecules. These chains can be linear or branched, depending on the specific type of thermoplastic being produced. Once the polymerization process is complete, the thermoplastic material is typically formed into pellets or granules for ease of transportation and storage. When it comes to shaping thermoplastics into final products, there are several common methods used in the manufacturing industry [22]. These include injection molding, Extrusion, blow molding, and thermoforming. Each of these processes has its advantages and limitations, depending on the specific requirements of the final product. There are numerous types of thermoplastics available in the market, with its unique applications as follows.

I. PE is a versatile plastic that is commonly used in packaging, construction, and automotive industries. It is known for its flexibility, durability, and resistance to moisture. Examples of products made from PE include plastic bags, bottles, and containers. It is commonly used in packaging materials, plastic bags, and containers [23], [24].

II. PP is another widely used plastic that is known for its high heat resistance and chemical stability. It is commonly used in food packaging, medical devices, and automotive parts. Examples of products made from PP include food containers, syringes, and car bumpers [25], [26].

III. Polyvinyl Chloride (PVC) is a durable plastic that is commonly used in construction, healthcare, and automotive industries. It is known for its resistance to chemicals, weathering, and fire. Examples of products made from PVC include pipes, window frames, and medical tubing [27], [28].

IV. Polystyrene (PS) is a lightweight plastic that is commonly used in packaging, electronics, and food service industries. It is known for its insulation properties and impact resistance. Examples of products made from PS include foam cups, packaging materials, and CD cases [29], [30].

V. Polyethylene Terephthalate (PET) is a strong and lightweight plastic that is commonly used in the packaging and textile industries. It is known for its clarity, barrier properties, and recyclability. Examples of products made from PET include soda bottles, food containers, and polyester fabrics [31]–[33].

VI. Polyether Ether Ketone (PEEK) is a specialty engineering semi-crystalline thermoplastic that belongs to the Polyaryletherketone (PAEK) family. It is known for its high-temperature resistance, excellent chemical resistance, low flammability, and high mechanical strength [34]. These properties make PEEK an ideal material for applications in industries such as aerospace, automotive, medical, and electronics. The manufacturing process of PEEK involves the polymerization of two monomers, 4,4'-difluorobenzophenone and hydroquinone, in the presence of a catalyst. The polymerization process results in the formation of a high molecular-weight polymer chain with repeating units of ether and ketone groups [35]. The polymer chain is then extruded into pellets or molded into various shapes using injection molding or compression molding techniques. PEEK is used in orthopedic implants, dental implants, and surgical instruments due to its biocompatibility and radiolucency. PEEK is also used in the automotive industry for components that require high-temperature resistance, such as fuel system components and electrical connectors [36].

VII. Liquid Crystal Polymers (LCPs) are a unique class of engineering thermoplastics that exhibit liquid crystal behavior in the molten state. These polymers possess a highly ordered structure, which gives them exceptional mechanical, thermal, and electrical properties. The manufacturing process of LCPs involves the polymerization of monomers containing rigid, rod-like molecular structures [37], [38]. These monomers are aligned in a specific orientation during the polymerization process, resulting in a highly ordered molecular structure.

PE, PP, PVC, PS, and PET are all important thermoplastics with unique properties that make them suitable for a wide range of applications. These materials are known for their high strength, toughness, and chemical resistance, making them ideal for applications that require durability and reliability.

5.2 | Thermosetting Plastics

Thermosetting plastics are a type of polymer that undergoes a chemical reaction during the manufacturing process, which results in a permanent change in their structure. This change makes them resistant to heat and chemicals, making them ideal for a wide range of applications in various industries [39], [40]. The manufacturing process of thermosetting plastics involves the polymerization of monomers to form long chains of molecules. These chains are then cross-linked through the addition of a curing agent, which creates a three-dimensional network that is rigid and cannot be melted or reshaped once it has been set. This process is irreversible, unlike thermoplastics, which can be melted and reshaped multiple times. In other words, thermosetting plastics are a type of polymer that, once cured, cannot be reshaped or melted [41]. This property makes them ideal for applications where durability and heat resistance are required. Examples of thermosetting plastics are as follows.

I. Epoxy resin: epoxy resins are widely used in the construction industry for bonding materials together. They are also used in the aerospace industry for their high strength and resistance to heat and chemicals [42], [43].

II. Phenolic resin: phenolic resins are commonly used in the production of circuit boards and automotive parts due to their excellent electrical insulation properties [44], [45].

III. Polyurethane: polyurethanes are used in a wide range of applications, including furniture, insulation, and adhesives. They are valued for their flexibility, durability, and resistance to abrasion [46], [47].

IV. Melamine formaldehyde: melamine formaldehyde resins are commonly used in the production of kitchenware and laminate flooring due to their heat resistance and durability [48].

V. Polyester resins are a type of synthetic resins that are created through the reaction of dibasic organic acids and polyhydric alcohols, resulting in a thermosetting polymer that is known for its durability, strength, and resistance to corrosion. However, they can be prone to cracking under high stress or impact, and their curing process can be sensitive to temperature and humidity [49], [50]. They are commonly used in the manufacturing of tanks, pipes, and other equipment that require resistance to harsh environments. They can be easily molded into complex shapes, making them a popular choice for the production of decorative items, furniture, and consumer goods.

Thermosetting plastics play a crucial role in various industries due to their unique properties. Epoxy resin, phenolic resin, polyurethane, and melamine formaldehyde are just a few examples of thermosetting plastics that are widely used in different applications. Their heat resistance, durability, and strength make them indispensable in industries such as construction, aerospace, electronics, and automotive.

5.3 | Acrylonitrile Butadiene Styrene

Acrylonitrile Butadiene Styrene (ABS) is a thermoplastic polymer that is composed of three monomers: 1) acrylonitrile, 2) butadiene, and 3) styrene. It is known for its high impact resistance, toughness, and heat resistance [51], [52]. ABS is commonly used in the automotive industry for making bumpers, interior trim, and dashboard components. It is also used in the electronics industry for making computer keyboards, printer housings, and other electronic components. The manufacturing process of ABS involves the polymerization of the three monomers in the presence of a catalyst. The polymerization process can be carried out using different methods, such as emulsion polymerization, solution polymerization, or bulk polymerization [53]. Once the polymerization is complete, the ABS resin is extruded into pellets or molded into various shapes using injection molding or extrusion processes.

5.4 | Polycarbonate

Polycarbonate is another thermoplastic polymer that is known for its high impact resistance, optical clarity, and heat resistance. It is commonly used in the manufacturing of eyeglass lenses, safety goggles, and automotive headlight lenses [54]. Polycarbonate is also used in the electronics industry for making compact discs, DVDs, and smartphone screens. The manufacturing process of polycarbonate involves the reaction of bisphenol A and phosgene to form a polymer chain. The polymerization process can be carried out using different methods, such as melt polymerization, solution polymerization, or interfacial polymerization [55]. Once the polymerization is complete, the polycarbonate resin is extruded into pellets or molded into various shapes using injection molding or extrusion processes.

5.5 | Polyamide Plastics

Polyamide (PA) plastics, commonly known as nylon, are a versatile group of synthetic polymers that are widely used in various industries due to their excellent mechanical properties, chemical resistance, and thermal stability [56]. PA plastics are a type of thermoplastic polymer that contains recurring amide groups in their molecular structure. These polymers are known for their high strength, toughness, and abrasion resistance, making them ideal for applications that require durable and lightweight materials. PA plastics are commonly used in the production of textiles, nylon tubing, upholstery, automotive parts, electrical components, and consumer goods. The manufacturing process of PA plastics involves the polymerization of monomers such as adipic acid and hexamethylenediamine [57]. These monomers are reacted together under controlled conditions to form long chains of PA molecules. The resulting polymer can then be processed into various forms, such as fibers, films, and molded parts, using techniques like extrusion, injection molding, and compression molding.

6 | Molecular Structure of Thermoplastic Materials

PE, PP, PVC, PS, PET, PEEK, and LCPs are all important types of polymers with unique molecular structures that contribute to their distinct properties and applications (see *Fig. 1*). The molecular structures of the following thermoplastics are crucial for designing engineering materials with specific properties for various industrial and commercial uses:

I. PE is a widely used polymer with a simple molecular structure consisting of repeating ethylene units $(-CH2 - CH2-)$. The linear arrangement of these units results in a flexible and relatively low-density polymer, making PE suitable for applications such as packaging materials, plastic bags, and containers [58].

II. PP is another common polymer with a molecular structure similar to PE but with a methyl group $(-CH3)$ attached to every other carbon atom in the polymer chain. This structural difference gives PP a higher melting point and stiffness compared to PE, making it suitable for applications such as automotive parts, medical devices, and food packaging [59], [60].

III. PVC is a polymer with a molecular structure containing chlorine atoms along the polymer chain. This chlorine content gives PVC its unique properties, including flame resistance, chemical resistance, and durability. PVC is commonly used in construction materials, pipes, and medical devices [61], [62].

IV. PS is a polymer with a molecular structure consisting of a benzene ring attached to a linear chain of styrene units. This structure gives PS its rigid and transparent properties, making it suitable for applications such as food packaging, disposable cups, and insulation materials [63], [64].

V. PET is a polymer with a molecular structure that consists of repeating units of ethylene glycol and terephthalic acid, which are linked together through ester bonds. This structure gives PET its high strength and stiffness, as well as its excellent resistance to heat and chemicals [65], [66].

VI. PEEK is a high-performance polymer with a molecular structure containing alternating ether and ketone groups along the polymer chain. This unique structure gives PEEK its exceptional mechanical, thermal, and chemical resistance properties, making it ideal for demanding applications in aerospace, automotive, and medical industries [67], [68].

VII. LCPs are a class of polymers with a molecular structure containing rigid and rod-like molecules that can form liquid crystal phases. This unique molecular arrangement gives LCPs their exceptional strength, stiffness, and heat resistance properties, making them suitable for high-performance applications in electronics, automotive, and aerospace industries [69], [70].

By understanding these molecular structures, researchers and engineers can design and develop new materials with tailored properties for specific industrial and commercial uses.

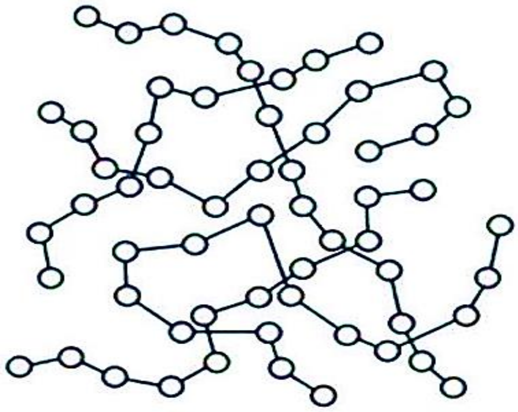


Fig. 1. Molecular structure of thermoplastic materials [71].

7 | Molecular Structure of Thermosetting Plastics

Epoxy resins, phenolic resins, polyurethane, melamine formaldehyde, and polyester resins are all important classes of thermosetting polymers (which typically have the molecular structure in *Fig. 2*) used in various industrial applications. Each of these resins has the following molecular structures that contribute to their specific properties and performance characteristics.

I. Epoxy resins are formed by the reaction of epichlorohydrin and bisphenol A, resulting in a linear polymer with a three-membered cyclic ether group. This structure provides epoxy resins with excellent adhesion, chemical resistance, and mechanical properties, making them ideal for applications such as coatings, adhesives, and composites [72].

II. Phenolic resins, on the other hand, are synthesized by the condensation of phenol and formaldehyde, leading to a cross-linked polymer network with phenolic rings as the repeating units. This structure imparts phenolic resins with high heat resistance, flame retardancy, and dimensional stability, making them suitable for use in high-temperature applications such as automotive parts and electrical components [73].

III. Polyurethane resins are produced by the reaction of isocyanates and polyols, resulting in a polymer with urethane linkages in the backbone. This structure gives polyurethanes flexibility, toughness, and abrasion resistance, making them versatile materials used in coatings, foams, and elastomers [74].

IV. Melamine formaldehyde resins are synthesized by the condensation of melamine and formaldehyde, forming a cross-linked polymer with melamine rings as the repeating units. This structure provides melamine formaldehyde resins with high heat resistance, chemical resistance, and dimensional stability, making them suitable for use in laminates, coatings, and molded parts [75].

V. Polyester resins are formed by the condensation of diacids and diols, resulting in a linear polymer with ester linkages in the backbone. This structure gives polyester resins good weatherability, corrosion resistance, and electrical insulation properties, making them commonly used in marine applications, automotive parts, and construction materials [76].

Understanding these structures is essential for designing and selecting the most appropriate resin for specific applications in various industries.

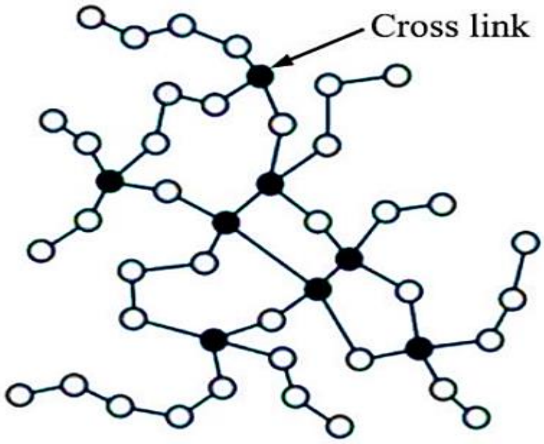


Fig. 2. Molecular structure of thermosetting plastics [77].

8 | Molecular Structure of Acrylonitrile Butadiene Styrene

ABS is a thermoplastic polymer that is widely used in various industries due to its excellent mechanical properties and chemical resistance. The molecular structure of ABS (see *Fig. 3*) consists of three main monomers: 1) acrylonitrile, 2) butadiene, and 3) styrene.

I. Acrylonitrile, also known as vinyl cyanide, is a synthetic monomer that contributes to the chemical resistance and heat resistance of ABS. It is a polar molecule with a nitrile group($-C\equiv N$) that enhances the strength and rigidity of the polymer. The presence of acrylonitrile in ABS also improves its resistance to chemicals such as acids, alkalis, and oils [78], [79].

II. Butadiene is a conjugated diene monomer that provides ABS with its toughness and impact resistance. The presence of butadiene in the polymer chain allows for flexibility and resilience, making ABS suitable for applications that require durability and impact resistance [80]. The presence of butadiene also enhances the overall toughness of ABS, making it a preferred material for products that undergo mechanical stress.

III. Styrene is a monomer that contributes to the rigidity and processability of ABS. It is a non-polar molecule with a phenyl group that enhances the flow properties of the polymer during processing. The presence of styrene in ABS also improves its dimensional stability and surface finish, making it a versatile material for a wide range of applications [81].

The molecular structure of ABS is a copolymer of acrylonitrile, butadiene, and styrene, with each monomer contributing to the unique properties of the polymer. The combination of these monomers results in a material that exhibits a balance of strength, toughness, and processability, making ABS a popular choice for applications in industries such as automotive, electronics, and consumer goods.

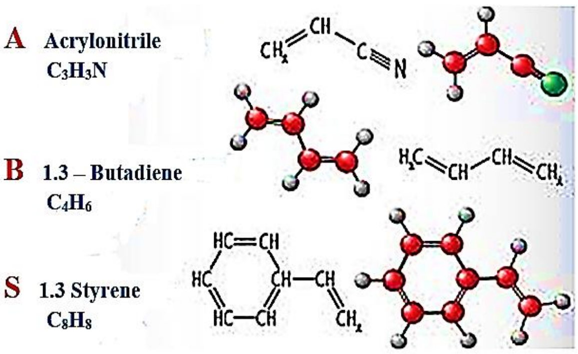


Fig. 3. Molecular structure of acrylonitrile butadiene styrene [82].

9 | Molecular Structure of Polycarbonate

Polycarbonate molecular structure is composed of repeating carbonate groups, which are linked together through ester bonds. The molecular formula of polycarbonate can be represented as $(C16H14O3)n$, where n represents the number of repeating units in the polymer chain [83]. The molecular structure of polycarbonate plays a crucial role in determining its physical and chemical properties. The presence of carbonate groups in the polymer chain imparts high-impact resistance and transparency to polycarbonate. The ester bonds in the molecular structure provide flexibility and toughness to the material, making it suitable for a wide range of applications. The presence of aromatic rings in the carbonate groups enhances the thermal stability of polycarbonate, allowing it to withstand high temperatures without deforming or degrading [84]. The transparency of polycarbonate structure is a result of the arrangement of the carbonate groups in the polymer chain, which allows light to pass through with minimal.

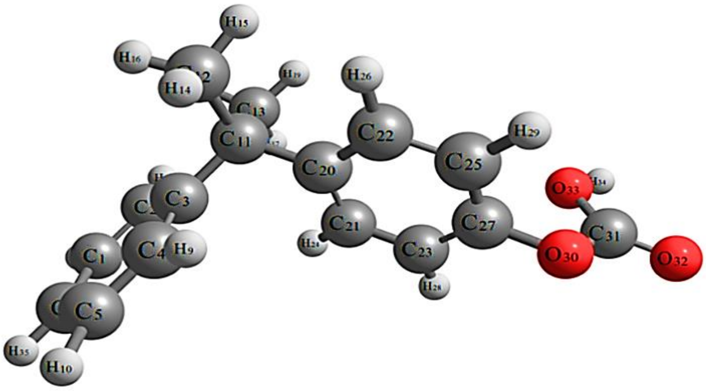
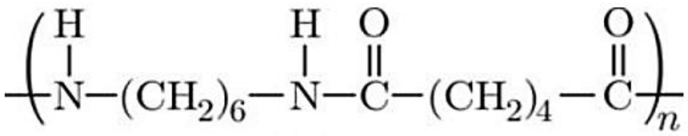


Fig. 4. Molecular structure of polycarbonate [85].

10 | Molecular Structure of Polyamides

PAs are formed by the reaction of a diacid with a diamine, resulting in the formation of amide linkages $(-CONH-)$ along the polymer chain. The repeating unit in a PA chain consists of a carbonyl group $(C = O)$ and an amine group (NH), connected by a single bond. This structure gives PAs their characteristic toughness and flexibility, as the amide linkages allow for rotation around the bond axis [86]. The arrangement of the amide linkages in the polymer chain also plays a significant role in determining the properties of PAs. In general, PAs with a more regular and symmetrical arrangement of amide linkages exhibit higher crystallinity and mechanical strength. This is because the regular arrangement allows for closer packing of polymer chains, leading to stronger intermolecular interactions. On the other hand, PAs with a more random and irregular arrangement of amide linkages tend to have lower crystallinity and mechanical strength [87]. This is because the irregular arrangement disrupts the packing of polymer chains, leading to weaker intermolecular interactions, as shown in *Fig. 5*. However, these PAs often exhibit higher flexibility and impact resistance due to the presence of amorphous regions in the polymer chain. The length of the polymer chain also influences the properties of PAs. Therefore, longer polymer chains tend to exhibit higher tensile strength and thermal stability, as the increased chain length allows for more extensive intermolecular interactions. However, longer chains can also lead to decreased flexibility and impact resistance as the polymer becomes more rigid.



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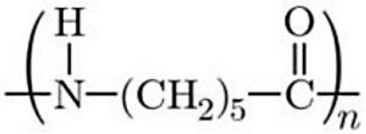


Nylon 6

Fig. 5. Molecular structure of polyamides [88].

11 | Amorphous Plastics

Amorphous plastics are a type of polymer material that lacks a crystalline structure, resulting in a transparent or translucent appearance. These plastics are widely used in various industries due to their unique properties, such as flexibility, impact resistance, and thermal stability. The term amorphous refers to the lack of a regular, repeating molecular structure in the material [89]. Unlike crystalline plastics, which have a highly ordered arrangement of molecules, amorphous plastics have a random arrangement of molecules, resulting in a more flexible and transparent material. This lack of crystallinity gives amorphous plastics their unique properties, such as high impact resistance and thermal stability. The manufacturing process of amorphous plastics involves the polymerization of monomers to form long chains of molecules. These chains are then cooled and solidified to form the final plastic material [90]. The lack of a crystalline structure in amorphous plastics allows for easier processing and shaping of the material, making it ideal for a wide range of applications. The molecular structure of amorphous plastics is characterized by long chains of molecules that are randomly arranged. This random arrangement gives the material its flexibility and transparency, as light is able to pass through the material without being scattered by a crystalline structure [91]. The molecular structure of amorphous plastics also contributes to their high impact resistance and thermal stability, making them suitable for use in a variety of applications. Amorphous and crystalline regions of a polymer (plastics) are presented in *Fig. 6*.

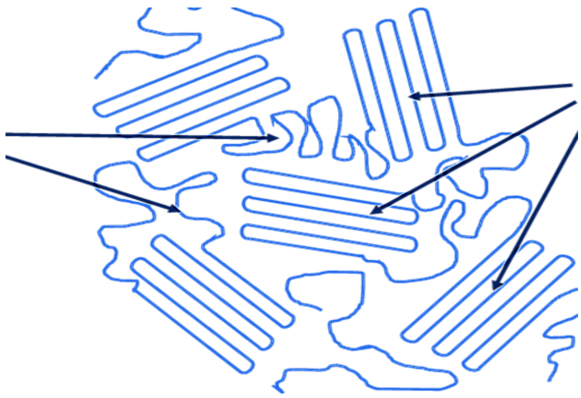
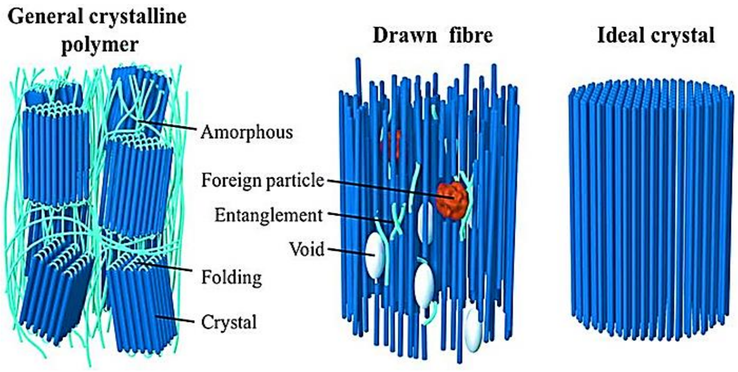


Fig. 6. Amorphous and crystalline regions of a polymer (plastics) [92].

12 | Crystalline Plastics

Crystalline plastics, as shown in *Fig. 7*, are a type of polymer that exhibits a highly ordered molecular structure, resulting in a regular arrangement of atoms or molecules in a repeating pattern. This organized structure gives crystalline plastics distinct properties that set them apart from their amorphous counterparts [93]. One defining characteristic of crystalline plastics is their transparency and high tensile strength. This is due to the tight packing of molecules in a crystalline lattice, which allows for efficient transmission of light and resistance to deformation. Additionally, crystalline plastics tend to have a higher melting point compared to amorphous plastics, making them suitable for applications requiring heat resistance. The manufacturing process of crystalline plastics involves the polymerization of monomers to form long chains of repeating units. These chains then undergo a process called crystallization, where the molecules align themselves in an ordered fashion to form a crystalline structure [94]. This process can be controlled by adjusting factors such as temperature, pressure, and cooling rate, which ultimately determine the degree of crystallinity in the final product. The molecular structure of crystalline plastics is characterized by the presence of regular repeating



units arranged in a three-dimensional lattice. This arrangement gives rise to distinct physical properties, such as high stiffness, hardness, and thermal stability. The crystalline structure also influences the mechanical properties of the material, including its resistance to impact and fatigue.

Fig. 7. Crystalline plastics [95].

13 | Applications of Engineering Plastics

Engineering plastics are a versatile group of materials that have found widespread applications in various industries due to their unique combination of properties. These materials, also known as high-performance plastics, are specifically designed to meet the demanding requirements of industrial, chemical, physical, biological, technological, and structural applications. The key applications of engineering plastics are as follows.

I. In industrial applications, engineering plastics are used for their excellent mechanical properties, chemical resistance, and thermal stability. These materials are commonly used in the manufacturing of components for machinery, equipment, and tools that are subjected to high temperatures, corrosive environments, and heavy loads [96]. For example, PEEK is a popular engineering plastic that is widely used in the aerospace, automotive, and medical industries due to its exceptional strength, stiffness, and resistance to chemicals and high temperatures.

II. In chemical applications, engineering plastics are chosen for their resistance to a wide range of chemicals, including acids, bases, solvents, and fuels. These materials are commonly used in the construction of storage tanks, pipes, valves, and fittings for handling corrosive substances [97]. For instance, Polyvinylidene Fluoride (PVDF) is a highly chemical-resistant engineering plastic that is commonly used in the chemical processing industry, as shown in *Fig. 8*. This is due to its structures of α, β, and γ phase which exhibits excellent resistance to a wide range of aggressive chemicals.

III. In physical applications, engineering plastics are valued for their excellent impact resistance, toughness, and durability. These materials are commonly used in the manufacturing of protective gear, sports equipment, and consumer electronics that require high levels of impact resistance and durability [98]. For example, polycarbonate is a popular engineering plastic that is commonly used in the production of safety glasses, helmets, and smartphone cases due to its exceptional impact resistance and toughness.

IV. In biological applications, engineering plastics are chosen for their biocompatibility, sterilizability, and resistance to harsh cleaning agents. These materials are commonly used in the medical, pharmaceutical, and food processing industries for the manufacturing of implants, medical devices, and packaging materials [99]. For instance, PET is a widely used engineering plastic that is commonly used in the production of medical devices and packaging materials due to its excellent biocompatibility and resistance to sterilization processes.

V. In technological applications, engineering plastics are valued for their electrical insulation properties, flame retardancy, and dimensional stability. These materials are commonly used in the manufacturing of electronic components, electrical connectors, and housings for electronic devices [100]. For example, PA is a popular engineering plastic that is commonly used in the electronics industry for its excellent electrical insulation properties and flame retardancy.

VI. In structural applications, engineering plastics are chosen for their high strength-to-weight ratio, stiffness, and fatigue resistance [101]. These materials are commonly used in the construction of lightweight structures, automotive components, and aerospace components that require high levels of strength and durability. For instance, Carbon Fiber-Reinforced Polymers (CFRPs) are advanced engineering plastics that are commonly used in the aerospace and automotive industries for their exceptional strength-to-weight ratio and fatigue resistance.

Engineering plastics have revolutionized various industries by providing innovative solutions to complex engineering challenges. These materials offer a unique combination of properties that make them ideal for industrial, chemical, physical, biological, technological, and structural applications.

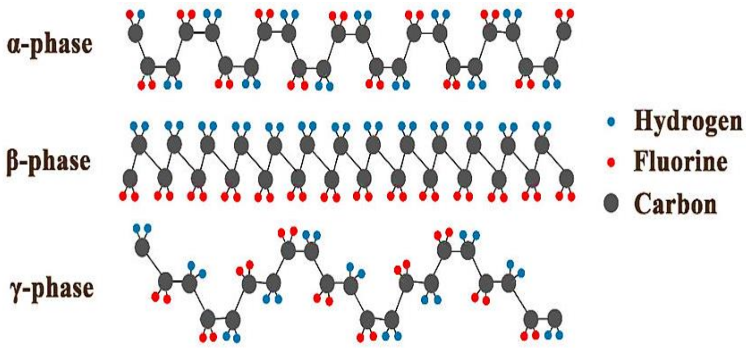


Fig. 8. Structures of *α*, *β*, and *γ* phase polyvinylidene fluoride [102].

14 | Environmental Sustainability of Engineering Plastics

Environmental sustainability is a critical consideration in the field of engineering, particularly in the production and use of plastics. As the demand for plastics continues to rise in various industrial and manufacturing processes, there is a growing need to assess the environmental impact of these materials and explore more sustainable alternatives [103]. Engineering plastics, which are high-performance polymers used in a wide range of applications, have the potential to offer a more environmentally friendly option compared to traditional plastics. The key factors that contribute to the environmental sustainability of engineering plastics are as follows.

I. Their production process: unlike traditional plastics, which are derived from fossil fuels, engineering plastics can be produced from renewable sources such as plant-based materials. This reduces the reliance on non-renewable resources and helps to lower the carbon footprint of the production process. Additionally, engineering plastics are often designed to be more durable and long-lasting, which can help to reduce the amount of waste generated over time [104], [105].

II. Their use in industrial and manufacturing processes: engineering plastics offer several advantages that contribute to their environmental sustainability [106]. These materials are known for their high strength-to-weight ratio, which allows for the production of lighter and more fuel-efficient products. This can help to reduce energy consumption and greenhouse gas emissions during transportation and use. Furthermore, engineering plastics are often recyclable, which means that they can be reused or repurposed at the end of their life cycle, further reducing waste and environmental impact [107].

III. Despite these benefits, there are still challenges to overcome in order to realize the environmental sustainability of engineering plastics fully. One of the main issues is the recycling and disposal of these materials [108]. While many engineering plastics are technically recyclable, the infrastructure for collecting and processing them is still limited. This can result in a significant amount of engineering plastics ending up in landfills, where they can take hundreds of years to decompose [109]. In order to address this issue, more investment is needed in recycling technologies and infrastructure to ensure that engineering plastics can be effectively recycled and reused.

Engineering plastics have the potential to offer a more environmentally sustainable option in conventional industrial and manufacturing processes. Their production from renewable sources, durability, and recyclability make them a promising alternative to traditional plastics. However, more efforts are needed to improve the recycling and disposal of engineering plastics in order to realize their environmental benefits fully.

15 | Advantages of Engineering Plastics

Engineering plastics have become increasingly popular in industrial and manufacturing processes due to the advantages and benefits they offer in conventional industrial and manufacturing processes. Some of the key advantages of engineering plastics include:

I. Their high strength and durability: these materials are known for their ability to withstand extreme temperatures, chemicals, and mechanical stress, making them ideal for use in demanding industrial environments [110]. Additionally, engineering plastics are lightweight, which can help reduce the overall weight of a product or component, leading to improved fuel efficiency and lower transportation costs.

II. Their excellent resistance to corrosion and wear: unlike traditional metals, engineering plastics do not rust or corrode, making them ideal for use in applications where exposure to harsh chemicals or environmental conditions is a concern [111].

III. Engineering plastics have low friction coefficients, which can help reduce wear and tear on moving parts, leading to longer service life and reduced maintenance costs [112].

IV. Engineering plastics offer excellent dimensional stability and precision, making them ideal for use in manufacturing processes that require tight tolerances and high accuracy. These materials can be easily molded and machined to create complex shapes and designs, allowing for greater design flexibility and customization [113]. Additionally, engineering plastics are available in a wide range of colors and finishes, making them suitable for a variety of aesthetic applications.

V. Engineering plastics also offer excellent electrical and thermal insulation properties. These materials are non-conductive and can withstand high temperatures, making them ideal for use in electrical and electronic applications. Furthermore, engineering plastics are resistant to flame and heat, making them suitable for use in high-temperature environments [114].

The advantages and benefits of engineering plastics make them a viable option for a wide range of industrial and manufacturing processes. These materials offer a unique combination of properties that make them highly versatile and cost-effective, making them an attractive alternative to traditional materials such as metals and ceramics.

16 | Disadvantages of Engineering Plastics

Despite the numerous advantages of engineering plastics, they also come with the following disadvantages that can hinder their viability in conventional industrial and manufacturing processes: Some of the main disadvantages of engineering plastics include:

I. Their high cost compared to traditional materials such as metals: the production of engineering plastics involves complex manufacturing processes and specialized equipment, which can significantly increase the overall cost of the final product. This high cost can be a major deterrent for industries looking to adopt engineering plastics in their manufacturing processes [115].

II. Their limited temperature resistance: while engineering plastics are known for their high strength and durability, they often have a lower temperature resistance compared to metals. This can be a significant drawback in industrial processes that involve high temperatures, as engineering plastics may deform or degrade under extreme heat conditions [116].

III. Engineering plastics are prone to wear and tear over time, especially in high-stress applications. Unlike metals, which can be easily repaired or replaced, engineering plastics may require more frequent maintenance and replacement, leading to increased downtime and production costs [117].

IV. Engineering plastics are not as easily recyclable as traditional materials such as metals. The recycling process for engineering plastics is often complex and costly, making them less environmentally friendly compared to other materials [118]. This can be a major concern for industries looking to reduce their carbon footprint and adopt more sustainable manufacturing practices.

While engineering plastics offer several advantages in terms of strength and durability, their disadvantages, such as high cost, limited temperature resistance, susceptibility to wear and tear, and lack of recyclability, can pose challenges to their viability for conventional industrial and manufacturing processes. Industries must carefully weigh the pros and cons of using engineering plastics in their processes and consider alternative materials that may be more cost-effective and sustainable in the long run.

17 | Conclusion and Recommendations

Engineering plastics have been widely reviewed in this study for their potential applications in conventional industrial and manufacturing processes. The findings from this study suggest that engineering plastics are a viable alternative to traditional materials in industrial and manufacturing processes. Their excellent mechanical properties, chemical resistance, and thermal stability make them suitable for a wide range of applications. However, it is important for manufacturers to carefully consider the cost and dimensional stability of engineering plastics before incorporating them into their processes. Engineering plastics have the potential to revolutionize the industrial and manufacturing sectors, offering innovative solutions to complex challenges. In light of this, the following recommendations are suggested for the improvement of engineering plastics.

I. Continued research and development to improve the performance of engineering plastics: this includes exploring new formulations, processing techniques, and additives that can enhance the properties of these materials and make them more suitable for a wider range of applications.

II. Investment in training and education for engineers and technicians who work with engineering plastics: these materials can be more challenging to work with than traditional plastics, and it is essential that personnel have the knowledge and skills necessary to handle them safely and effectively.

III. It is also recommended that companies consider the environmental impact of using engineering plastics in their manufacturing processes: while these materials offer many benefits, they can also have a negative impact on the environment if not handled properly. Companies should strive to minimize waste and emissions associated with the production and use of engineering plastics and explore sustainable alternatives where possible.

By exploring research and development, training and education, and environmental sustainability, companies can ensure that they are able to take full advantage of the unique properties of engineering plastics and stay ahead of the competition in today's rapidly evolving industrial landscape.

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Data Availability

The data used in this research can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest related to this study.

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