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Polyurethane: Chemistry, Production, Applications, and Future Prospects—An Overview

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Abstract

Polyurethane (PU), a class of versatile polymers, has emerged as one of the most significant materials in modern industry owing to its remarkable mechanical strength, elasticity, durability, and resistance to abrasion, chemicals, and environmental degradation. Its wide range of tunable properties has made PU indispensable across multiple sectors, including fashion, automotive, manufacturing, biomedical, coatings, and construction. This review emphasizes the diverse applications of polyurethane and explores how its unique chemistry allows for the development of tailor-made materials suited to specific performance requirements. The mechanical, physical, biological, and chemical attributes of PU can be precisely tuned by manipulating the stoichiometric ratio of polyols and isocyanates, modifying catalysts, and adopting advanced polymerization and curing processes. The review also discusses how continuous innovations in synthesis strategies—such as solvent-free processes, waterborne systems, and bio-based formulations—are enhancing both the performance and sustainability of PU materials. Advanced characterization techniques have further contributed to understanding the structure–property relationships, facilitating the design of high-performance polyurethane materials with improved thermal, acoustic, and mechanical behavior. The study also outlines the classification of PU types, including thermoplastic, thermoset, and elastomeric variants, and provides insights into their specific advantages and limitations in different application domains. Furthermore, this article highlights significant research contributions related to novel synthesis routes, nanocomposite integration, and surface modifications that expand the functional landscape of PU-based systems. Finally, attention is given to environmental aspects, focusing on recyclability, biodegradability, and the development of green alternatives derived from renewable raw materials. Through an integrated approach combining chemistry, process engineering, and sustainability, the review underscores the evolving potential of polyurethane as a material of the future for high-performance and eco-conscious industrial applications.

Keywords: Polyurethane, hard and soft segments, Di isocyanate, polyol, PU foam

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INTRODUCTION

Polyurethane (PU) is a versatile polymer ever developed and finds applications in a wide range of industries, from automotive and construction to fashion and electronics. Due to its elasticity, toughness, durability, and resistance to abrasion and chemicals, polyurethanes have revolutionized material science and manufacturing. PU polymers exist in different forms, like rigid and flexible foams, coatings, adhesives, sealants, elastomers, and fibers as well, which allows their commercialization into numerous consumer and industrial products.

This review briefly explores the origins, chemistry, manufacturing processes, types, applications, environmental considerations, and the future of polyurethane materials.

HISTORY OF DEVELOPMENT

Polyurethane was developed in 1937 by Dr. Otto Bayer and his team at IG Farben in Germany [1, 2]. PU was initially developed as a substitute for rubber during World War II [3]. Polyurethane subsequently quickly attracted interest for usage in numerous industrial applications due to its unique properties and broad adaptability.

The commercial boom in polyurethane production was witnessed in the 1950s with the development of commercial polyurethane foams. As the material properties were better understood with continuous R&D, industrial use of PU expanded exponentially. The years 1950 to 1970s saw PU's introduction in insulation, footwear, automotive seats, and coatings, enhancing its status as a major industrial polymer class [4].

Chemistry of Polyurethanes

The chemistry of PUs categorizes them to be grouped as reaction polymers or polycondensation polymers. Other polymers include phenolics, unsaturated polyesters, and epoxies [5]. Generally, PUs are synthesized from the condensation reaction between bifunctional isocyanate and polyol monomers in the presence of a catalyst or ultraviolet light activation [6]. Isocyanate and polyol molecules contain two or more isocyanate groups ($R-(N=C=O)n\geq2$) and hydroxyl groups ($R'-(OH)\ n\geq2$) to form a polymeric chain [7]. The PU polymeric properties are usually dependent on the types of polyols and isocyanates used from which they are made [8]. Typically, soft and elastic polymers can be produced from flexible long segments of polyols, while rigid and tough PU polymers are obtained by a higher extent of crosslinking. Stretchable PU polymers are obtained by long chains having low crosslinking, and hard polymers are produced with shorter chains with high crosslinkages. The combination of long chains and average crosslinking produces PU polymers, which are very suitable for foam application [9]. Crosslinking in PUs results in a polymer structure having infinite molecular weight with a network formation that is three-dimensional. That is why a small fraction of polymers (PUs) is referred to as a giant molecule, and also explains why PUs would not get soft or melt by heating. Compounding of virgin PUs with different additives along with the isocyanates and polyols, and modifications in processing conditions can alter the range of properties and performance features, which makes PUs suitable for various industrial applications [10]. Polyols used in PU synthesis normally consist of two or more –OH groups, and different kinds of polyols are commercially available, which can be prepared in various ways. Like polyether, polyols are obtained through copolymerization of propylene oxide and ethylene oxide with a polyol precursor [11], and polyester polyols are synthesized in a method similar to the polyester polymers are prepared. A novel polyether polyol, poly (tetramethylene ether) glycol, is prepared by polymerization of tetrahydrofuran for use in highly efficient elastomeric applications [12]. Preparation and characterization of isocyanate-terminated prepolymers using polytetrahydrofuran was reported by Rajendran *et al*. [13]. Polyols are commonly mixtures of molecules that are similar in nature but with different molecular weights. These molecules contain different numbers of hydroxyl groups. Therefore, it is essential to determine the average functionality or hydroxyl group per molecule of the polyols. Despite the complexity of polyol molecules, the industrial-grade polyols have controlled and consistent compositions during commercial production to obtain consistent properties of finished PUs necessary for producing PUs with desirable properties. Rigid PUs are made from low molecular weight polyols (<500), whereas flexible PUs are produced using high molecular weight polyols (~10000 or above) [13].

Isocyanates are used in PU synthesis along with hydroxyl group-containing compounds due to their high reactivity, though they exhibit slow reactivity at room temperature. The slow speed of PU reaction is attributed to the phase incompatibility of polar and less dense polyol and relatively nonpolar and denser isocyanate phase. Therefore, for an efficient reaction rate, suitable surfactants and catalysts are often required. The action of catalysts is based on the polarization of either the isocyanate or hydroxyl compound through polar interaction. Aromatic isocyanates like toluene diisocyanate (TDI) and diphenylmethane diisocyanate (MDI) are comparatively more reactive to their corresponding aliphatic counterparts, i.e., isophorone diisocyanate (IPDI) and hexamethylene diisocyanate (HDI). The isocyanates are generally bifunctional in nature (each molecule possesses two isocyanate groups), barring a few members like diphenylmethane diisocyanate, which comprises molecule mixtures containing either two or more isocyanate groups (the compound usually possesses an average functionality of 2.7). Alterations and changes to the types of raw materials and their ratio, and to the processing parameters during the synthesis of PU, determine the properties of the final product. Table 1 depicts the effect of ingredients on the final PU polymer [14].

Table 1. Role of different ingredients on the properties of the final polyurethane product.

Component	**Effect of Final PU**
Isocyanate	Reactivity during PU synthesis and cure properties
Polyol	Flexible segment and used for the synthesis of elastic PUs
Catalyst	Increase reaction rate even at room temperature.
Plasticizer	Reduce Hardness
Pigment	Aesthetic looks to the PUs (Pre-colored)

Chemical Structure and Composition

Polyurethanes are produced through a condensation polymerization reaction between a diisocyanate and a polyol. The basic chemical reaction is as shown in Figure 1:

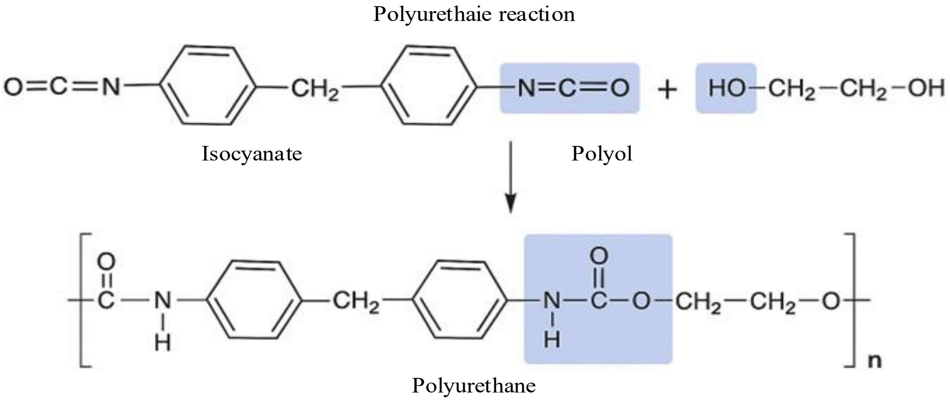

Figure 1. Chemical reaction for the synthesis of polyurethane.

Diisocyanate (-NCO) + Polyol (-OH) → Polyurethane (-NH-CO-O-)

Key raw materials (monomers): Di isocyanates: Aromatic (TDI, MDI) and Aliphatic (HDI, IPDI).

Polyols: Polyether and Polyester polyols.

Additives and catalysts: Blowing agents, surfactants, catalysts, fillers, flame retardants, and pigments influence the final properties [15].

Types of Polyurethane

Polyurethane polymers can be tailored for a vast range of industrial products, and are primarily grouped into [16]:

- *Flexible polyurethane foam:* Used for Furniture, automotive interiors, and bedding.
- *Rigid polyurethane foam:* Used for Insulation, refrigerators, and construction panels.

- *Polyurethane coatings:* Used for Industrial coatings, flooring, and automotive finishes.
- *Elastomers:* Used for Tires, seals, and sports equipment.
- *Adhesives and sealants:* Used for Footwear, construction, and electronics.
- *Thermoplastic polyurethanes (TPU):* Used for Medical devices, cables, and 3D printing.

Figure 2 depicts various ingredients, like Hard and Soft segments require different industrial grades of Polyurethane [17].

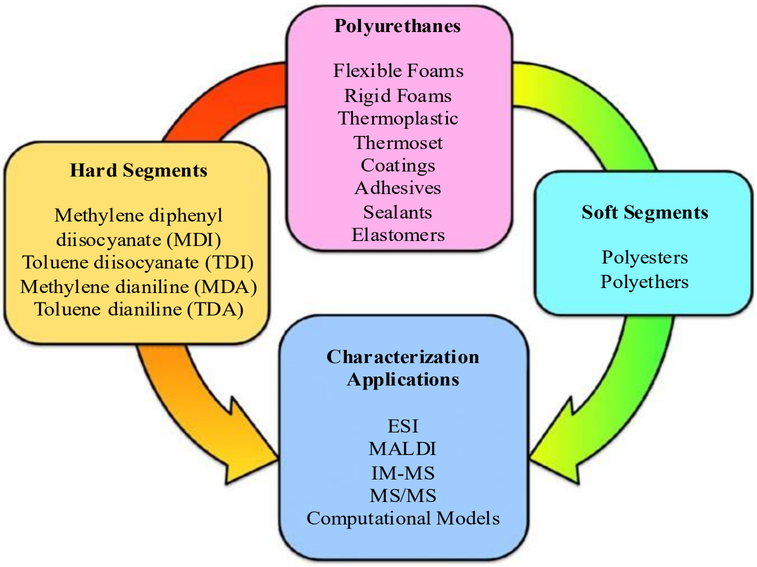

Figure 2. Ingredients and characterization of various industrial products of polyurethane.

General Manufacturing Processes for PU: Different Industrial Grades

There are several manufacturing processes to produce different grades of PU for various applications, as mentioned below [18]:

- *Foam production:* Mixing polyol, isocyanate, and blowing agents.
- *Molding and casting:* Used for automotive and footwear parts.
- *Spray applications:* For insulation and protective coatings.
- *Extrusion and injection molding:* For TPU and elastomers.

A general process of production of MDI and Allied Grades is given in Figure 3 [19].

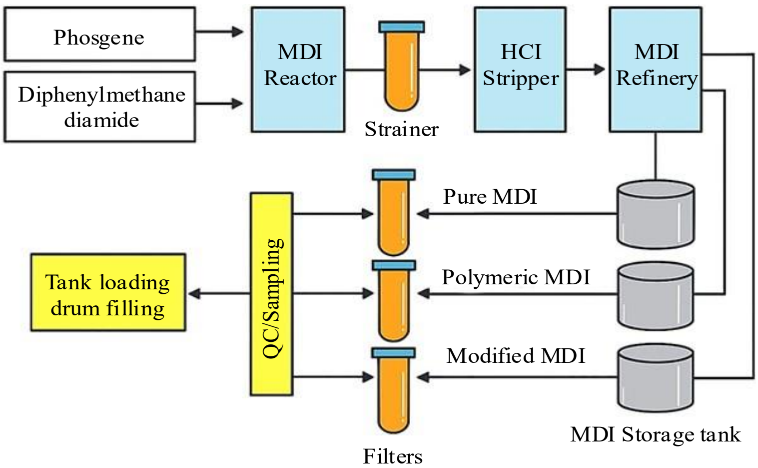

Figure 3. Production process of MDI, polymeric MDI, and modified MDI.

One-Step and Two-Step Synthesis of Polyurethane

Polyurethane polymers can be produced by the reaction between diisocyanates and polyols using one-step or two-step processes, depending on the target properties and application. A schematic diagram of both processes is given in Figure 4.

One-Step (One-Shot) Process

- In this process, all ingredients (i.e., polyol, diisocyanate, chain extender, catalysts, and additives) are added together and reacted in a single step.
- Polymerization of reactants and foaming process (if making foam products) occur together.
- This method is simple and more efficient for high-volume, continuous production. Flexible foams, coatings, adhesives, and insulation grades of PUs are commercially produced by this process in large volumes.

Two-Step (Prepolymer) Process

- *Step 1:* In this step, Diisocyanate and a portion of the polyol are reacted to form an intermediate (isocyanate-terminated prepolymer).
- *Step 2:* In this step, prepolymer prepared as above is reacted with a chain extender (typically remaining polyol) to the desired high molecular weight and properties of the finished PU product.
- This method allows better control over the reaction process and temperature as well as the properties of the final product, especially in uniform hard segments in PU polymer chain, and reduced side-product formation. This method allows reduced toxicity exposure from diisocyanates by allowing initial reaction in a controlled manner [20].

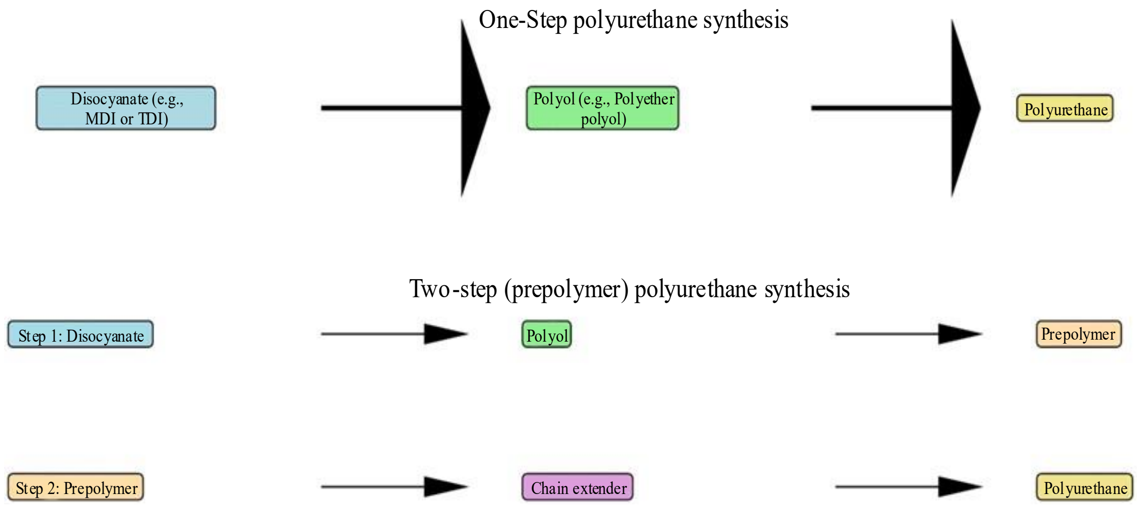

Figure 4. Schematic diagram of a step and two-step process for polyurethane production.

The differentiation shown in Table 2 is helpful in the selection of the appropriate method for the performance requirements of the final polyurethane product.

Table 2. Comparison of one-step and two-step synthesis of PUs.

Feature	One-step synthesis	Two-step synthesis
Reactants mixed	All Together	In Two Steps
Control over product	Lesser	Better
Processing	Simple	Complex
Applications	Foams and coatings	Elastomers and structural parts

General Applications of PU

The following are the various industrial applications of Polyurethanes, as shown in Figure 5:

- *Construction:* widely used in electrical insulation, sealants, and coatings.
- *Automotive:* PU finds numerous uses in automotives like seating, insulation, and bumpers.
- *Furniture and Bedding:* PU-based cushions, mattresses, and pillows are very popular.
- *Footwear:* Major applications of PU in the footwear industry are shoe soles and insoles.
- *Appliances:* In appliances, PU finds major use in thermal insulation and gaskets.
- *Textiles:* PU polymers are widely used in textile applications such as elastic fibers, waterproof coatings.
- *Medical:* Catheters, prosthetics.
- *Electronics:* Encapsulation, shock absorption [21].

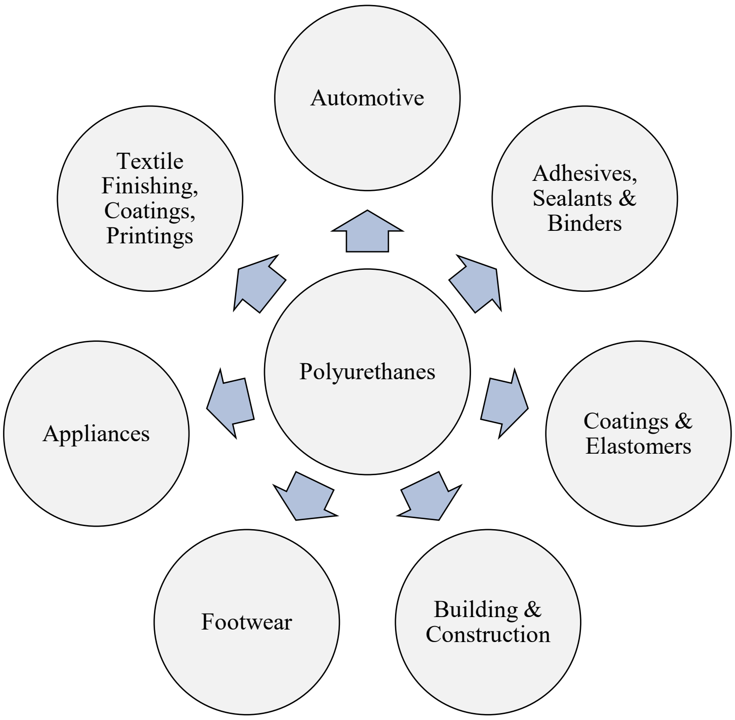

Figure 5. Different industrial applications of polyurethane.

Global Market Scenario for PU

- The global market for PU is estimated to exceed USD 90 billion by 2030.
- Asia-Pacific is expected to lead the consumption of PU in different commercial applications and followed by North America and Europe.
- Key players: Key global manufacturers of PU commercial grades are BASF, Dow, Covestro, Huntsman, Mitsui, and Wanhua.
- Growth drivers: Industrial drivers for PU market growth are insulation demand, automotive, and lightweight materials. A graph is presented in Figure 6 for the grade-wise global market for different PU products [22, 23].

Environmental and Health Considerations for PU

- *Health Risks:* PU polymers may create respiratory issues due to residual isocyanate exposure.
- *Environmental Concerns:* PU is non-biodegradable and creates severe disposal challenges.
- *Recycling:* There is a strong need to develop mechanical and chemical methods and designs for recycling.
- *Bio-based Polyurethanes:* R&D efforts are in progress for bio-based PU made from castor oil, soy, sugarcane [24].

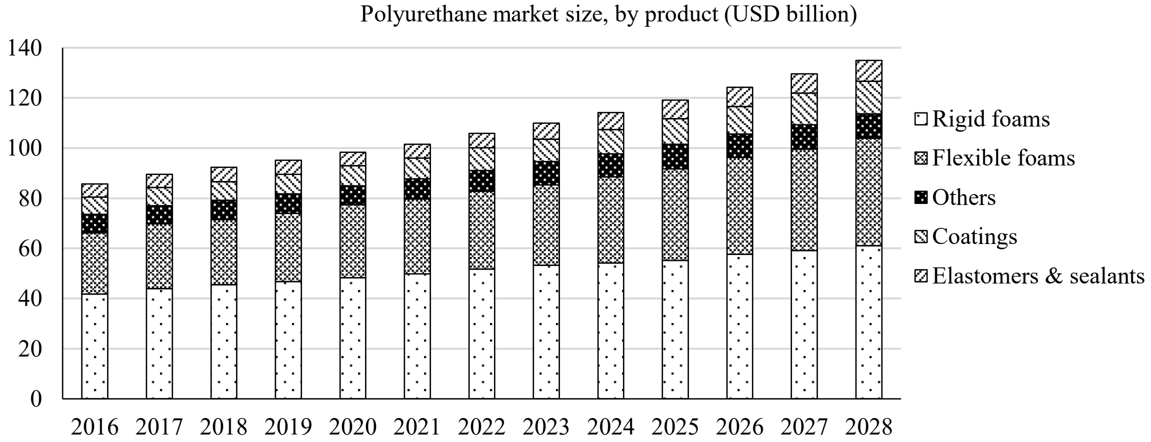

Figure 6. Projected global market for various PU grades.

Innovations and Future Trends

- *Green polyurethanes:* New age PU are being developed, which are bio-based, VOC-free, lifecycle analysis.
- *Advanced applications:* Newer applications like self-healing, smart materials, and aerogels are being developed.
- *Circular economy:* PU new grades are being developed keeping in mind closed-loop systems, carbon capture.
- *AI in manufacturing:* Usage of Artificial Intelligence and Machine Learning is being explored in commercial production of PU Predictive maintenance, and quality control [25].

Challenges

- Major challenges for PU production are petrochemical dependence for raw materials, where RM prices are very volatile.
- Also, regulatory pressure on TDI, MDI is another big hurdle in the market growth of PU.
- Recycling complexity of PU is also a roadblock for PU market growth.
- Being non-biodegradable, PU usage is limited due to public perception regarding plastic waste [26].

CONCLUSION

Polyurethane is an engineering and performance polymer due to its diverse properties, performance, and adaptability in several industrial applications, which make it a key raw material in the global industrial sectors. From comfort and insulation to advanced electronics and biomedical devices, polyurethane has gained a prominent place across all industrial sectors. However, it may be highlighted that the industry is being pivotal point for growth for any country. Environmental sustainability, responsible sourcing, and waste management are also necessary and mandatory for future growth.

Industries and governments are pushing for greener solutions globally, and the PU industry is now gearing up by developing bio-based alternatives, advanced recycling technology, and circular models. It can be concluded that by sustained research, innovation, and regulatory alignment, PU is poised to see exponential market growth in the years to come as an even more sustainable and essential material.

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