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POLYURETHANE FOAM: VERSATILITY AND SUSTAINABILITY

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ABSTRACT

Polyurethane (PU) foam has established itself as a highly versatile material with broad applications across engineering sectors, ranging from construction and automotive to packaging and insulation. This review provides a brief examination of the functionality, versatility, and sustainability of PU foam systems. It begins with a general overview of PU foams, including their processing routes and structural characteristics. Subsequent sections analyze in detail the performance of PU foams. Finally, the paper concludes with perspectives on future research directions and potential industrial applications of PU foams.

KEYWORD

Polyurethane foam, review, environmental-friendly

INTRODUCTION

Since Otto Bayer's discovery of polyurethanes (PU) in the 1930s [1], they have been utilized in a wide variety of applications, ranging from simple uses like furniture, cushioning, and shoe insoles to high-end applications in maritime and aerospace industries [2–5]. Apart from inherent characteristics such as high chemical and thermal resistance, as well as enhanced mechanical properties [1,4], PU's versatility is another significant trait: by adjusting the amount and types of processing materials, the soft and hard segments and cross-linking ability of PU can be modified. This, in turn, determines the final PU products, such as coatings, adhesives, foams, and elastomers [6]. As a material that has been claimed to "*combine the toughness of metal with the elasticity of rubber,*" [1] it is no surprise that the demand for this unique polymer is growing in the global market.

PU is a versatile step-growth polymer formed through an exothermic reaction between diols and diisocyanates, resulting in urethane (–NH–COO–) linkages without by-product formation, as shown in Figure 1. Its chemistry involves two main reaction types: primary reactions, where isocyanates react with hydrogen-containing groups, and secondary reactions, such as self-addition or reactions with water to produce carbamic acid, which decomposes into amines that form substituted urea. Further reactions between isocyanates and urethane or urea groups yield allophanates and biurets, introducing various functional moieties into the polymer network. The resulting PU structure comprises alternating soft and hard segments derived from polyols and polyisocyanate. By adjusting this ratio, a wide range of materials—from flexible foams to rigid insulation—can be tailored. Chain extenders and processing methods such as the prepolymer route further refine molecular organization, enabling enhanced mechanical and thermal performance [7,8].

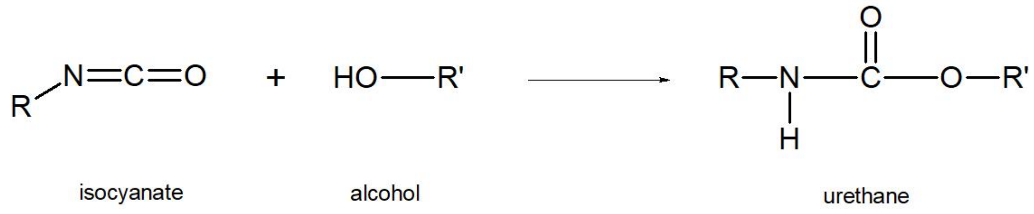

Figure 1: PU chemistry

VERSATILITY

PU foams, classified as cellular polymers, are produced by introducing gas bubbles into the polymer matrix through physical or chemical blowing processes. Physical blowing agents vaporize during polymerization, while chemical blowing involves water reacting with isocyanates to generate carbon dioxide that drives foam expansion. The resulting foams can be open- or closed-cell, corresponding to flexible or rigid morphologies, respectively. Rigid foams possess low density, strong insulation capability, and superior moisture resistance, whereas flexible foams offer better impact absorption but are more flammable. These qualities of rigid foams make it a viable candidate in structural and insulation applications. Flexible foams on the other hand offer better energy absorption capabilities but at the cost of higher combustibility. Flexible foams are therefore often utilised in cushioning, bedding, and packaging applications for many domestic and consumer-level products [1,4]. Foam properties are strongly influenced by raw material selection—short-chain polyols produce rigid foams, whereas long-chain polyols yield flexible ones. Additives like siloxane-based surfactants are also essential for stabilizing the cell structure, reducing surface tension, and preventing foam collapse.

SUSTAINABILITY

While properties such as strength, density, thermal stability, flame retardancy, chemical resistance, and energy absorption are vital in polyurethane (PU) foam design, sustainability has become equally important. Growing environmental concerns have driven the need to replace petroleum-based components with renewable alternatives. One effective strategy is to substitute conventional petrochemical polyols with bio-based ones, either partially or fully. This trend is reflected in the actions of major companies like Shell, Dow, and BASF, as the global bio-polyol market was valued at around USD 4.4 billion in 2021 and is projected to reach USD 6.9 billion by 2027 [9].

Polyols—compounds containing multiple hydroxyl groups (–OH)—are essential in PU synthesis, typically reacting with isocyanates to form the polymer network. However, most commercial polyether and polyester polyols are derived from petroleum-based sources, such as glycerol or propylene oxide. To reduce dependence on these feedstocks, researchers have turned toward natural alternatives [10]. While both polyols and isocyanates rely on petroleum precursors, efforts have mainly focused on developing bio-based polyols because greener replacements for isocyanates remain challenging. Among various renewable sources, plant and vegetable oils have emerged as promising raw materials for PU foam production due to their abundance, lower cost, biodegradability, and reduced toxicity. Table 1 shows selected researches focusing on nature-based PU foams.

FUTURE PROSPECT

Recent studies have showed an interesting trend for PU foam, focusing on a few specific applications. Among these are on energy harvesting - several groups of researchers have reported the success of turning PU foam into a piezoelectric-like material, which can generate electricity upon application of force [28,29]. Another future application is towards oil spill absorption, where the PU foam could be modified to increase its hydrophobicity for better oil absorption [30, 31].

Table 1: Selected research on PU foams from bio-based polyol

Polyol Source	Polyol Substitution	Filler/Additives	Ref.
Palm oil	Full	Montmorillonite nanoclay	[11]
	Full	Montmorillonite organoclay	[12–14]
	Full	Rockwool fiber	[15]
	Partial	-	[16]
Rapeseed	Partial/Full	-	[17]
	Partial	Nanosilica	[18]
	Partial	Waste paper sludge	[19]
	Full	Fire retardants	[20]
Castor	Partial	Tetra-pak Waste	[21]
	Partial	Nanoclay + Silica	[22]
	Partial	Fire retardants	[23]
	Full	-	[24]
Soybean	Partial	Fire retardants	[25]
	Full	-	[26]
	Partial	Feathers	[27]

SUMMARY

In this paper, a brief review of the PU foam was provided. It was shown that PU foam is a versatile engineering material that can be tailored in accordance with end-user applications. Continuous research on this material is a must to make it always relevant in today's global applications.

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