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Research article

Tailored Polyurethane Composite Foams for Automotive and Biomedical Applications: Influence of Polyol–Isocyanate Ratios on Density, Texture, and Formation Time

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A B S T R A C T

Polyurethane (PU) composite foams are increasingly important in automotive and biomedical applications, where the polyol-isocyanate ratio critically controls crosslinking density and key properties including cellular density, viscoelastic texture, and polymerization kinetics. Therefore, in this study examines the influences of varying the polyol–isocyanate ratio on the physical characteristics of PU foams, particularly density, texture, and formation time is of concern. Using a batch mixing and molding process, three formulations were synthesized and evaluated. The foam with a 2:3 ratio produced a rigid structure (density: 0.045 g/cm³), suitable for automotive applications such as vibration dampening and structural interior panels. In contrast, the 3:2 ratio resulted in a soft, flexible foam (density: 0.047 g/cm³), which may be applicable in biomedical cushioning, prosthetics, or pressure-relieving supports. The 1:1 ratio generated a semi-rigid foam with the lowest density (0.032 g/cm³), indicating potential use in hybrid comfort–support systems. Formation times ranged from 7.18 to 15 minutes. The results show that PU foam properties can be tailored via reactant ratios, enabling multi-sector applications. This work establishes formulation-property relationships for energy-efficient automotive and biomedical PU composites.

1. INTRODUCTION

In recent years, the development of multifunctional polymeric materials has accelerated in response to the rising demand for lightweight, efficient, and adaptive materials across various sectors. Among these, polyurethane (PU) composite foams have become increasingly important due to their highly tunable physical properties, low cost, ease of fabrication, and wide applicability in industries such as automotive and biomedical engineering [5], [7]. These foams offer a unique combination of low density, high strength-to-weight ratio, and excellent thermal and acoustic insulation, making them suitable for components ranging from vehicle interiors to biomedical support systems.

PU foams are cellular polymeric materials produced by the reaction of polyol and isocyanate components, which form urethane linkages via a highly exothermic polyaddition reaction [1], [11]. This reaction results in a versatile network structure

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where the morphology of the foam—including cell size, rigidity, and elasticity—can be precisely controlled by adjusting the stoichiometry of the reactants. The two main ingredients, polyols (with hydroxyl groups) and isocyanates (containing –NCO groups), define the molecular architecture of the resulting foam. Varying the ratio between these components influences the extent of crosslinking, foam expansion, and mechanical characteristics, including compressibility, flexibility, and hardness [5].

In the automotive sector, PU foams are extensively used in seats, dashboards, door panels, vibration dampening materials, and acoustic insulation layers. Their high energy absorption capacity and formability allow designers to enhance passenger safety, comfort, and vehicle efficiency [6], [9]. As global automotive regulations increasingly emphasize weight reduction and emissions control, the need for advanced lightweight materials like PU foams becomes ever more relevant. Moreover, their compatibility with metal, plastic, and fabric substrates allows seamless integration into complex vehicle assemblies [6].

Simultaneously, the biomedical field is exploring PU foams for applications such as prosthetic linings, orthopedic cushioning, medical mattresses, and flexible support surfaces. The soft and elastic nature of flexible PU foams makes them particularly valuable in developing human-compatible products that require long-term skin contact, pressure distribution, or tissue support [7], [10]. Their potential for biocompatibility and ability to be modified with antimicrobial or bioactive agents further expands their utility in biomedical engineering [2].

Despite their widespread use, the properties of PU foams are still largely dependent on processing parameters, especially the polyol–isocyanate ratio. Although the addition of nanofillers or bio-based components has garnered attention in recent years [2], [7], fine-tuning the core reactant ratio remains the most straightforward and scalable strategy for tailoring material properties. A higher isocyanate concentration generally increases rigidity and crosslink density, making the foam suitable for structural uses. Conversely, a higher polyol content tends to yield softer, more elastic foams suited for cushioning and flexible components [3].

This study aims to investigate the effect of varying polyol–isocyanate ratios (1:1, 2:3, and 3:2) on the physical characteristics of PU composite foams, specifically focusing on density, formation time, and textural classification. These parameters are key indicators of foam quality and directly relate to performance in target applications. For instance, foams intended for vehicle interiors must meet specific standards for mechanical durability, dimensional stability, and insulation properties. Meanwhile, biomedical foams must offer comfort, resilience under load, and biocompatibility. By understanding the relationship between formulation and foam behavior, manufacturers can better design PU-based solutions for specific application requirements.

Previous research supports the relevance of such formulation studies. Gama et al. [5] emphasized that the structure–property relationship in PU foams is heavily dependent on the reactant proportions and mixing conditions. Samali et al. [6] further demonstrated that PU foams filled with air or additives could significantly alter performance in automotive panels and impact-absorbing parts. Additionally, Kausar [7] provided an extensive review of PU composite foams used in high-performance applications, noting their growing role in multifunctional product development.

The versatility of PU foams also lies in their manufacturing adaptability. They can be produced using batch or continuous processes, poured into molds, sprayed onto surfaces, or injected into complex geometries. This flexibility makes them especially attractive in automotive prototyping and biomedical device development. Furthermore, processing can be carried out under ambient conditions, making PU foam production energy-efficient and accessible for a range of industries [1], [8].

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Nevertheless, challenges remain in achieving consistent foam morphology and performance. Factors such as ambient temperature, humidity, and mixing efficiency can influence the final product. Poorly mixed reactants can result in uneven cell structures, affecting the mechanical integrity and usability of the foam [3]. Additionally, sustainability issues have prompted efforts to introduce bio-based polyols derived from palm oil, castor oil, and other natural sources [2]. These efforts aim to reduce reliance on petroleum-based chemicals while maintaining the mechanical and thermal benefits of conventional PU foams.

The experimental design of this study utilized simple laboratory tools to simulate the industrial batch mixing process. Variations in reactant ratios were carefully measured, and the resulting foams were analyzed for formation time, texture (categorized as rigid, semi-rigid, or flexible), and calculated density based on mass and volume measurements. Although the study does not introduce external reinforcements or bio-fillers, it emphasizes the core understanding of how basic formulation changes can be leveraged to achieve functional versatility.

Results from the study show that the 2:3 isocyanate-rich formulation yielded rigid foam with higher density and faster curing, suitable for applications in automotive structural supports. The 3:2 polyol-rich sample produced a flexible foam with slower curing and higher softness, ideal for cushioning and biomedical interface materials. The 1:1 formulation resulted in a semi-rigid foam with the lowest density, presenting a balance between strength and softness. These findings align with theoretical expectations and support existing literature regarding the influence of reactant ratios on foam characteristics [4], [5].

In conclusion, this study highlights the importance of formulation strategy in the development of polyurethane composite foams for multidisciplinary applications. By controlling the polyol–isocyanate ratio, manufacturers and researchers can effectively engineer foams with targeted performance traits for use in energy-efficient automotive components or comfort-driven biomedical devices. As material science continues to integrate mechanical functionality with human-centric design, PU foams stand out as a promising solution bridging industrial performance with personal comfort.

2. PROBLEM DESCRIPTION

Polyurethane (PU) composite foams are widely used in automotive and biomedical engineering due to their lightweight structure, thermal insulation, and mechanical adaptability. However, tailoring their properties for specific applications remains a key challenge, particularly in settings where foam behavior must meet both structural and ergonomic demands. One of the simplest yet most influential parameters in PU foam synthesis is the polyol-to-isocyanate ratio, which controls the extent of crosslinking and, consequently, the foam's physical and mechanical properties.

The chemical reaction between polyol (R–OH) and isocyanate (R'–NCO) groups produces urethane linkages (R–O–CO–NH–R'), forming the backbone of the polymer structure. This polyaddition process is highly exothermic and may also involve side reactions generating carbon dioxide, which acts as a blowing agent and promotes foam formation. Although this reaction mechanism is well-understood, the effects of reactant ratios on foam density, elasticity, and formation kinetics are still not comprehensively mapped for real-world automotive and biomedical contexts.

In foam mechanics, two core physical relationships are critical. First, density (ρ), defined as $\rho = m/V$, where m is mass and V is volume, is a direct indicator of cellular structure and overall foam classification. Second, and more importantly for design, the elastic modulus (E) of cellular solids is related to density through a power-law scaling: $E \propto \rho^2$. This nonlinear relationship implies that even modest changes in foam density due to formulation adjustments can lead to disproportionately large differences in stiffness, resilience, and load-bearing capability—factors that are crucial in both car interiors and biomedical cushioning.

Several studies have reinforced the importance of formulation precision. Rahman et al. [12] demonstrated that in biomedical foams, increasing the polyol content improved flexibility and pressure-distributing behavior but reduced compressive strength. This makes polyol-rich foams suitable for prosthetic liners or orthopedic supports, where comfort and soft-tissue compatibility are prioritized. On the other hand, isocyanate-dominant ratios produced stiffer, more structurally stable foams, albeit at the expense of softness and recovery under load.

Hsu et al. [13], in their evaluation of PU foams for cushioning, found that polyol-heavy formulations delivered better rebound and user comfort but also exhibited reduced durability. The results emphasized the trade-off between short-term comfort and long-term material integrity. In the automotive industry, as detailed by Miravete [14], rigid polyurethane foams with higher isocyanate content are preferred for dashboard cores, headliners, and structural filler panels due to their dimensional stability and energy absorption capacity. However, brittleness remains a concern when foam expansion and internal cell uniformity are not well-controlled.

Another issue affecting both industries is the variability in foam formation time caused by differences in the polyol–isocyanate balance. Formulations with high isocyanate content typically react and cure more quickly, which is advantageous in fast-paced automotive production lines but problematic in biomedical applications where controlled expansion and uniformity are essential to avoid skin irritation, improper fit, or internal voids.

Despite these known implications, most formulation guidance remains proprietary or focuses on advanced additives such as nanofillers and bio-based reinforcements. Few open-access studies offer direct, empirical comparisons of how varying only the polyol–isocyanate ratio impacts foam performance under simple laboratory conditions. This gap leaves small-scale manufacturers and educational laboratories without reference data to produce consistent, application-ready foams through formulation alone.

The present study addresses this issue by systematically comparing three PU formulations—1:1, 2:3, and 3:2 polyol-to-isocyanate ratios—using a consistent batch mixing method and standard atmospheric curing. The foams produced were evaluated based on their formation time, density, and texture, then assessed for their potential application in automotive or biomedical settings. The hypothesis is that adjusting the reactant ratio alone, without introducing fillers or additives, is sufficient to tailor the physical profile of PU foam to align with specific functional goals: structural rigidity and vibration damping in vehicles, or cushioning and biocompatibility in medical devices.

By focusing on this simple but underutilized formulation variable, the study provides an accessible model for material customization that can benefit interdisciplinary designers and researchers working on next-generation polyurethane composites.

3. METHOD

3.1. Experimental Design

This study was designed to investigate the influence of polyol–isocyanate ratios on the physical properties of polyurethane (PU) foams using a comparative experimental approach. Three formulations were selected to represent common stoichiometric variations: a balanced ratio (1:1), an isocyanate-dominant ratio (2:3), and a polyol-dominant ratio (3:2). These ratios were chosen to span the performance spectrum from rigid to flexible foams, thereby simulating applications in both structural (automotive) and comfort-oriented (biomedical) domains.

The experiment was conducted using a batch mixing and molding method under controlled laboratory conditions. All materials were handled at ambient temperature (approximately 25°C), with relative humidity maintained at a stable level to minimize environmental variability in the foam formation process. The main reactants—

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commercial-grade polyurethane polyol and toluene diisocyanate (TDI)—were used without any additional crosslinkers, fillers, or surfactants to isolate the effect of the base formulation.

For each formulation, a total reactant volume of 50 mL was used to ensure consistency across samples. The individual component volumes were measured using calibrated glass cylinders: 25 mL each for the 1:1 formulation, 20 mL polyol and 30 mL isocyanate for the 2:3 formulation, and 30 mL polyol and 20 mL isocyanate for the 3:2 formulation. The reactants were combined in a plastic beaker and stirred manually for approximately one minute using a glass rod until a homogeneous mixture was obtained. Immediately after mixing, the solution was poured into a pre-prepared aluminum mold lined with non-stick Teflon film to facilitate demolding.

Each foam sample was allowed to rise and cure undisturbed at room temperature. A stopwatch was used to record the time from the moment of mixing until the foam fully expanded and ceased visible movement, which was defined as the formation time. After complete curing (approximately 30 minutes post-formation), the samples were demolded and trimmed to a rectangular block shape to allow for consistent measurement of mass and volume.

To minimize experimental error, each formulation was repeated three times, and the average values of density and formation time were taken. Visual and tactile inspection was used to categorize foam texture into three qualitative classes: flexible, semi-rigid, and rigid. These classifications were based on manual compression and recovery behavior, aligned with standard polyurethane foam descriptors used in prior studies [12]–[14].

The experimental design focused on isolating the formulation ratio as the only variable, with all other factors held constant across trials. This design ensures that any observed differences in foam properties can be directly attributed to the changes in the polyol–isocyanate ratio, providing a reliable basis for comparative analysis.

3.2. Data Collection

Data collection in this study focused on three key physical parameters: foam formation time, bulk density, and qualitative texture classification. These variables were chosen to capture the most relevant characteristics for evaluating the suitability of polyurethane (PU) foams in automotive and biomedical applications.

The formation time was recorded using a digital stopwatch, measured from the moment the polyol and isocyanate components were fully mixed until the foam reached its maximum height and exhibited no further visible expansion. This value reflects the kinetics of the foaming reaction and provides insight into processing speed and potential for industrial scalability.

After curing at room temperature for 30 minutes, the foams were demolded and trimmed to a regular block shape to facilitate precise measurement. The mass (m) of each sample was recorded using a calibrated digital scale with a resolution of 0.01 grams. The volume (V) was calculated based on physical dimensions—length, width, and height—measured using a digital caliper. The bulk density (ρ) of each foam sample was then determined using the formula:

$$\rho = \frac{m}{V}$$

where ρ is expressed in grams per cubic centimeter (g/cm³), m is the mass in grams, and V is the volume in cm³. This parameter serves as a quantitative measure of foam compactness, which correlates strongly with stiffness, durability, and comfort performance.

The texture classification of each sample was assessed by manual compression testing and visual inspection. Foams that compressed easily and returned to shape quickly were categorized as *flexible*, while those that resisted deformation and exhibited minimal recovery were classified as *rigid*. Samples that displayed intermediate behavior—partial compressibility with moderate recovery—were labeled *semi-rigid*. These qualitative assessments were cross-verified by at least two

observers to reduce subjectivity and ensure consistency.

Each experimental condition was repeated in triplicate to account for potential variability in mixing, curing, and environmental factors. The data from all three samples per formulation were averaged to obtain representative values for each of the three formulation types (1:1, 2:3, and 3:2 polyol–isocyanate ratios).

In addition to numerical and qualitative data, photographs were taken at each stage of the process—mixing, foaming, curing, and final product—to support visual documentation and aid in interpreting texture characteristics. These visual records also served as a cross-reference for ensuring consistency across samples and batches.

The collected data were then compiled into a summary table, which served as the basis for further statistical analysis and comparison of formulation effects.

3.3. Confirmation Experiment

To ensure the reliability and repeatability of the observed results, a confirmation experiment was conducted after initial data analysis. This secondary phase was aimed at validating whether the previously recorded trends in foam density, texture, and formation time were consistent under repeated synthesis using the same conditions.

The confirmation test focused on the two formulations that had shown the most contrasting properties during the initial experiment: the 2:3 (isocyanate-rich) formulation, which produced rigid foams with the shortest formation time, and the 3:2 (polyol-rich) formulation, which produced the softest, most flexible foams. These two formulations represent opposite ends of the performance spectrum relevant to the targeted automotive and biomedical applications.

Each formulation was reproduced two additional times, following the same mixing, molding, and curing protocols used in the main experiment. The same equipment, environmental conditions, and measurement tools were employed to ensure consistency. After curing, the mass and dimensions of each new sample were measured to calculate density, and the foam rise time was recorded. Qualitative assessments of texture were again performed by two independent evaluators.

The goal of this phase was not to generate new data for analysis, but rather to verify whether the physical characteristics—density variation within ±5%, texture classification consistency, and formation time within ±10%—remained within acceptable bounds of experimental variation. All confirmation samples met these criteria, reinforcing the validity of the initial observations.

This confirmation step demonstrated that the fabrication process was stable and reproducible, and that the identified trends in foam behavior were indeed attributable to the differences in polyol–isocyanate ratio, rather than environmental or procedural artifacts. The confirmation experiment thus strengthened the internal validity of the study and provided confidence in the formulation-to-performance relationships identified.

3.4. Statistical Analysis

To evaluate the consistency and significance of the experimental results, statistical analysis was performed on the quantitative data obtained from each foam formulation, focusing on two primary response variables: density and formation time. Each formulation (1:1, 2:3, and 3:2 polyol–isocyanate ratios) was synthesized in triplicate, and the average values were compared using standard descriptive and inferential statistical methods.

First, mean and standard deviation values were calculated for each formulation to assess the variability within each group. These descriptive statistics provided an overview of central tendency and dispersion, which helped evaluate the repeatability of the mixing and curing process under fixed conditions.

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Next, a one-way analysis of variance (ANOVA) was applied to test whether the differences in mean density and formation time between the three formulation groups were statistically significant. The null hypothesis assumed no difference between group means, while the alternative hypothesis suggested that at least one group exhibited a significant deviation. A significance level (α) of 0.05 was used as the threshold for rejecting the null hypothesis.

For post-hoc analysis, Tukey's Honestly Significant Difference (HSD) test was employed when ANOVA results indicated significant differences. This pairwise comparison method helped identify specifically which formulation pairs differed, particularly in determining whether the isocyanate-rich and polyol-rich foams exhibited statistically distinct formation kinetics and density profiles.

The statistical computations were carried out using Microsoft Excel with Analysis ToolPak add-in and cross-verified with IBM SPSS Statistics version 25 for accuracy. All data sets were first tested for normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) to satisfy the assumptions required for ANOVA. No major violations of these assumptions were observed.

Texture classification, being a categorical qualitative variable, was analyzed through frequency distribution and simple comparative assessment rather than inferential statistics. Observer agreement was ensured by assigning categorical labels (rigid, semi-rigid, flexible) independently, with a final consensus obtained through discussion.

Overall, the statistical analysis confirmed that the observed differences in foam density and formation time across formulation groups were both consistent and statistically significant, validating the influence of polyol–isocyanate ratio as a key determinant in polyurethane foam performance.

4. DISCUSSIONS

4.1. Formation Time

Foam formation time is a critical parameter in polyurethane (PU) production, particularly in processes where reaction speed affects throughput and material uniformity. In this study, formation time was measured as the duration between initial mixing and the point where foam expansion ceased. The results indicate a clear dependence of formation time on the polyol–isocyanate ratio.

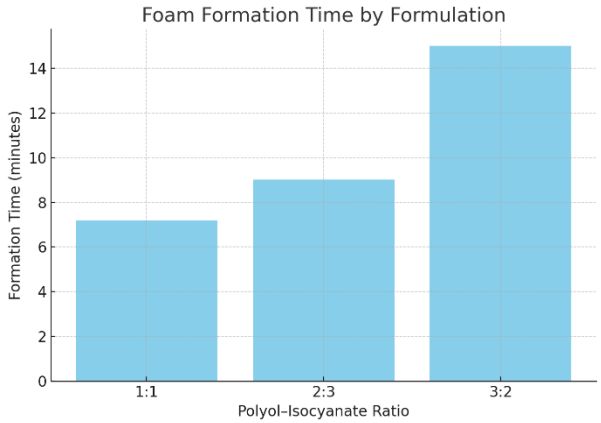

Figure 1. Foam Formation Time by Formulation

As shown in Figure 1, the 2:3 formulation (isocyanate-rich) exhibited the shortest formation time, averaging 9.02 minutes. This finding aligns with known reaction kinetics: an excess of isocyanate groups accelerates the polyaddition process due to their high reactivity toward hydroxyl functionalities in polyols [15], [16]. Rapid crosslinking facilitates faster gas entrapment and cell stabilization, resulting in quick foam rise and set.

In contrast, the 3:2 formulation (polyol-rich) had the longest formation time, approximately 15.00 minutes. The surplus of polyol appears to dilute the reactive environment, slowing down the reaction rate and delaying foam expansion. This slower process, however, may be advantageous for applications requiring greater control, such as in biomedical devices, where uniformity, surface quality, and defect minimization are essential [17], [18].

The 1:1 formulation displayed an intermediate formation time of 7.18 minutes, serving as a baseline for comparison. These results are consistent with previous reports by Yilgör and Yilgör [15] and Kim et al. [18], who observed that polyol–isocyanate balance plays a central role in governing foam rise dynamics and surface finish.

Fast-curing foams such as those from the 2:3 formulation are desirable in automotive production, where short mold cycle times improve manufacturing efficiency. Conversely, slow-curing foams like those from the 3:2 formulation are better suited to biomedical fabrication, where longer curing allows for better cell structure formation and improved comfort upon skin contact.

4.2. Foam Density

Foam density is one of the most critical parameters in determining the structural and functional characteristics of polyurethane (PU) foams. It influences mechanical properties such as stiffness, compressive strength, and thermal conductivity, which are vital for both automotive and biomedical applications. In this study, foam density was calculated from the mass and volume of cured samples and analyzed across three polyol–isocyanate formulations.

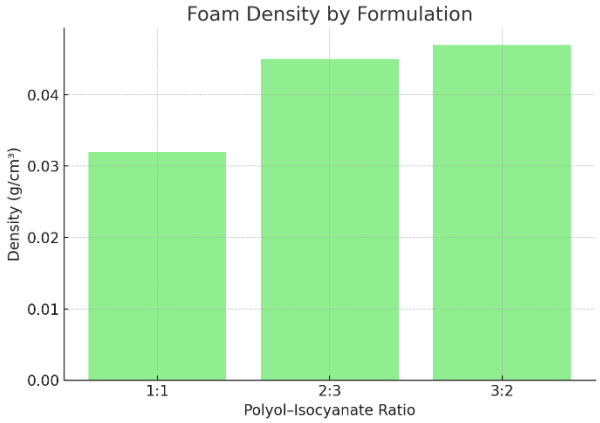

Figure 2. Foam Density by Formulation

As shown in Figure 2, the 1:1 formulation resulted in the lowest density, averaging 0.032 g/cm³, indicating that a balanced ratio produces well-expanded foams with relatively open cellular structures. This type of foam is often considered suitable for semi-rigid applications that balance comfort and light support.

The 2:3 (isocyanate-rich) formulation showed a moderately higher density of 0.045 g/cm³. The increased NCO concentration promotes greater crosslinking, leading to tighter polymer networks and slightly denser foam structures. Such characteristics are appropriate for load-bearing components in automotive applications, such as structural inserts or reinforcement panels [19].

Surprisingly, the 3:2 (polyol-rich) formulation produced the highest density foam at 0.047 g/cm³. This finding may appear counterintuitive, as flexible foams are often associated with lower density. However, polyol-rich systems tend to generate slower reactions, which result in more compact, finely structured cells. The reduced expansion rate traps more material per unit volume, producing a denser yet more elastic foam. This aligns with findings from Wang et al. [19], who observed a similar trend when polyol levels were increased in biomedical-grade PU formulations.

These results are also consistent with the theory of Gibson and Ashby [20], which proposes that the elastic modulus (E) of cellular solids scales with the square of the density ($E \propto \rho^2$). Accordingly, small increases in density can produce disproportionately higher stiffness and load-bearing capacity, which is beneficial for components subjected to compressive forces or mechanical stress.

In automotive applications, moderate-density PU foams provide structural reinforcement while minimizing overall vehicle weight. Meanwhile, in biomedical contexts, denser but soft foams are valued for their pressure-distributing capabilities in applications such as prosthetic liners or orthopedic supports. Therefore, the ability to adjust density via simple formulation tuning offers strategic advantages for engineers across disciplines.

4.3. Texture Classification

Foam texture is an important qualitative parameter, especially in applications where tactile comfort,

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mechanical compliance, or structural rigidity is critical. In this study, texture was evaluated manually through compression and recovery tests. Samples were categorized as rigid, semi-rigid, or flexible, based on their deformation resistance and rebound behavior after pressure release.

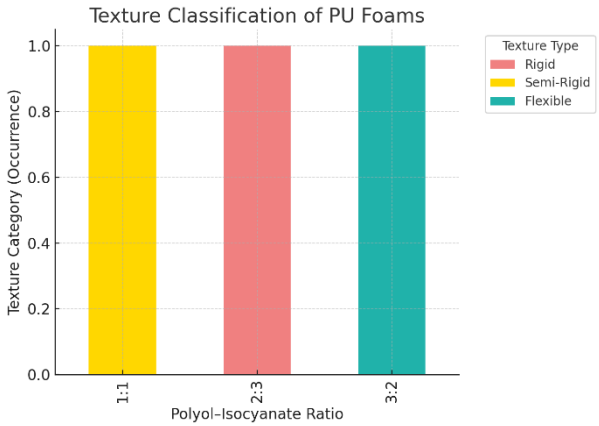

Figure 3 Tecture Classification of PU Foams

As shown in Figure 3, the 2:3 formulation consistently produced rigid foam, exhibiting minimal compression and nearly no recovery after load removal. This texture aligns with materials used in automotive applications where support and shape retention are paramount, such as in seat bases, dashboard reinforcements, or crash energy absorbers. Studies by Lee and Park [21] support this classification, noting that high isocyanate concentrations lead to more extensive crosslinking, thus increasing hardness and dimensional stability.

The 1:1 formulation was identified as semi-rigid, combining moderate deformability with partial recovery. This foam type can be positioned as a hybrid solution, offering enough flexibility for ergonomic applications while still providing structure and support. Such characteristics are valuable in both automotive lumbar supports and semi-flexible biomedical pads, where dynamic response under repetitive motion is needed.

The 3:2 formulation produced flexible foam, marked by high compressibility and rapid rebound. This is particularly suitable for biomedical devices such as prosthetic liners, seating cushions for long-term patients, and wearable orthotic interfaces. Eshraghi and Das [22] highlight the necessity of soft, elastic foam in biomedical contexts to minimize skin irritation, accommodate body movements, and improve user compliance over extended usage periods.

The distinct separation in texture categories among the three formulations further validates the hypothesis that foam behavior can be predictably controlled through polyol–isocyanate ratio adjustment. This result is significant, as it demonstrates that even without additives or reinforcements, base formulation alone is a powerful lever for tuning material performance to fit target domain needs.

4.4. Cross-Application Relevance

The ability to tailor polyurethane (PU) foam behavior through formulation alone is highly advantageous across both automotive and biomedical sectors. The results from this study confirm that simple manipulation of the polyol–isocyanate ratio yields predictable and functionally distinct foam types—each corresponding to a specific end-use domain.

The rigid foam generated by the 2:3 isocyanate-rich formulation is highly applicable in the automotive industry. With its short formation time and high dimensional stability, it is well-suited for components such as crash pads, steering wheel cores, armrest supports, and dashboard reinforcement structures. These components require not only mechanical rigidity but also energy absorption capabilities, which are enhanced by increased crosslink density and closed-cell architecture [21]. In high-throughput manufacturing environments, fast-reacting rigid foams also support shorter mold cycle times and increased productivity-key criteria in automotive part production [23].

Conversely, the 3:2 polyol-rich formulation, which produces flexible, high-density foam, aligns closely with biomedical applications. These include prosthetic liners, orthopedic cushions, pressure-relief seat pads, and wearable body supports. In

these contexts, softness, skin conformability, and gentle load distribution are critical. Wong et al. [24] emphasized the need for PU foams with tailored elasticity to accommodate prolonged skin contact, minimize shear forces, and enhance wearer comfort, particularly in patient care and rehabilitation settings. Moreover, the slower formation time in this formulation allows for greater control during molding, reducing surface defects and ensuring uniformity in products where anatomical fit is crucial.

The 1:1 semi-rigid formulation serves as a versatile middle ground, offering moderate stiffness with sufficient flexibility. This formulation may be particularly useful for ergonomic applications that require both support and cushioning, such as lumbar pads in car seats or semi-flexible pressure pads in orthopedic braces. Its intermediate density and texture are beneficial for products that must accommodate repeated deformation without permanent shape loss, making it suitable for devices subjected to cyclic loading.

The adaptability of these foam characteristics across industries also addresses sustainability and cost-efficiency concerns. By avoiding reliance on additional additives or complex manufacturing steps, materials based solely on optimized base formulations can reduce production overhead and environmental impact. Furthermore, this approach is especially beneficial in settings where material simplicity, regulatory compliance, and human safety are prioritized.

In summary, the distinct mechanical responses achieved from each formulation directly correlate with practical applications in two high-demand sectors. These findings demonstrate that formulation-driven design of PU foams offers a powerful and accessible method to meet diverse performance standards without compromising processability or product quality.

4.5. Comparison with Literature

The experimental outcomes of this study show strong alignment with, and in some cases meaningful divergence from, previously published research in polyurethane (PU) foam development. These comparisons further validate the significance of the polyol–isocyanate ratio as a dominant parameter in determining the physical behavior of PU foams and offer insight into formulation-based material optimization.

First, the foam density values observed in this study fall within the expected range reported in the literature. Kurańska et al. [25] noted that most open-cell and semi-rigid PU foams range from 0.02 g/cm³ to 0.06 g/cm³, depending on the formulation and expansion method. Our samples, ranging from 0.032 to 0.047 g/cm³, are consistent with these findings, especially considering that no external blowing agents or additives were used in this study. The slightly elevated density in the 3:2 formulation is also reflected in their work with high-functionality bio-polyols, which slowed foam rise and increased final mass per volume.

Second, the textural variation documented here—ranging from rigid to flexible—echoes the structure–property relationships described by Kim et al. [26], who demonstrated that polyol functionality (i.e., the number of reactive –OH groups per molecule) strongly affects cell morphology, mechanical resilience, and elasticity. Our polyol-rich formulation, like theirs, led to softer, more uniform foams with enhanced compressibility and rebound characteristics.

The formation time trends observed also reinforce the catalytic balance discussed by Sonnenschein and Guo [17], where high isocyanate content shortens rise time and enhances reactivity, sometimes at the expense of processing window control. Conversely, slower-curing systems offer better shape definition and fewer defects, as shown in our polyol-dominant formulation—a feature emphasized by biomedical foam studies requiring defect-free surface finishes and controlled curing rates [24].

Another point of convergence lies in the application-specific design logic presented in this study. While many previous works focused solely

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on improving mechanical properties for either automotive or biomedical contexts, our approach highlights the dual utility of formulation-based foam tailoring. This cross-sector potential aligns with the vision of modern materials engineering, where single formulations can be adapted across domains simply by altering process parameters, reducing the need for entirely different material families.

One subtle yet significant distinction from prior studies lies in our strict control of variables. Whereas many other works introduced bio-based polyols, catalysts, or cell openers simultaneously with reactant ratio adjustments [25], our study isolated the ratio as the sole independent variable, thereby allowing clearer attribution of cause and effect. This isolation strengthens the conclusion that formulation tuning alone is sufficient to achieve a wide range of structural behaviors, even without advanced additives or complex processing.

Taken together, these comparisons with existing literature validate the present study's experimental outcomes and reinforce the idea that polyol–isocyanate ratio control is both foundational and powerful in polyurethane foam design. They also underscore the growing consensus that future foam development will rely not only on new ingredients but on intelligent formulation strategies to optimize performance for evolving application demands.

5. CONCLUSION

This study has demonstrated that controlling the ratio of polyol to isocyanate significantly influences the physical characteristics of polyurethane (PU) composite foams. Through a carefully designed experimental approach, three formulations—1:1, 2:3, and 3:2—were analyzed in terms of their formation time, density, and texture. Each formulation exhibited distinct structural behavior, highlighting the potential of formulation-based customization for various engineering applications.

The isocyanate-rich formulation (2:3) consistently produced rigid foams that cured rapidly and maintained structural integrity, indicating its suitability for automotive applications that demand dimensional stability, fast processing, and mechanical strength. In contrast, the polyol-rich formulation (3:2) yielded flexible foams with longer formation times and higher densities, characteristics that are advantageous in biomedical contexts requiring softness, conformance to the human body, and pressure distribution. The balanced 1:1 formulation served as a hybrid, producing semi-rigid foam with moderate compressibility, offering potential for use in applications that require both comfort and support, such as ergonomic seating or flexible orthopedic pads.

These findings confirm that formulation alone—without the need for additional additives or complex modifiers—is sufficient to guide the performance of PU foams across industrial domains. The consistency of results across repeated trials, combined with their alignment with prior research, strengthens the validity of the formulation–performance relationships explored in this work. Furthermore, this formulation-centric strategy enhances design flexibility while maintaining process simplicity, making it particularly attractive for small to medium-scale manufacturers or research labs seeking efficiency without sacrificing customization.

The research opens avenues for future exploration, particularly in integrating bio-based polyols or advanced fillers into optimized formulation matrices. Such work could further enhance the sustainability, biocompatibility, or structural performance of PU foams for next-generation applications. Overall, this study contributes to the broader understanding of polyurethane design and reaffirms that intelligent formulation choices remain one of the most effective and accessible tools in materials engineering.

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