Exploring the Potential of Chicken Feather-Reinforced Thermoplastic Polyurethane Composites for Sustainable Materials

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Abstract: This study explores the viability of chicken feather-reinforced thermoplastic polyurethane (TPU) composites as environmentally sustainable materials. Chicken feathers, an abundant keratin-rich biowaste generated by the poultry industry, were processed into both powder and fiber forms and subsequently subjected to chemical modification using (3-aminopropyl) triethoxysilane to enhance interfacial compatibility with the TPU matrix. Four composite formulations were produced via melt compounding, incorporating TPU-to-feather weight ratios of 90:10 and 85:15 for each morphological variant. Standardized test specimens were fabricated and evaluated through tensile, compressive, hardness, and density analyses. Among the formulations, the composite containing 85% TPU and 15% feather fiber exhibited the most favorable mechanical properties. The improved interfacial adhesion was attributed to the dual functional role of the silane coupling agent, which facilitated both covalent and hydrogen bonding at the filler–matrix interface. The findings underscore the potential of chemically treated feather waste as an effective and economical reinforcement for polymeric materials, advancing the development of high-performance, sustainable composites.

Keywords: Thermoplastic polyurethane, Chicken feather, Bio-composite, Sustainable materials, Silane coupling agent, Keratin biowaste, Mechanical properties, Interfacial adhesion.

1. INTRODUCTION

The global poultry industry generates several million tons of chicken feathers annually as a byproduct of meat production. These feathers are conventionally managed through incineration or landfilling, practices that present significant environmental and economic concerns due to the high protein content, resistance to biodegradation, and potential for microbial contamination [1, 2]. In light of increasing emphasis on sustainability and circular economy principles, such agricultural residues are gaining attention as renewable, value-added feedstocks for the development of bio-based composite materials.

Chicken feathers are predominantly composed of keratin a fibrous, sulfur-rich structural protein characterized by a high degree of cross-linking. Keratin offers advantageous material properties, including relatively high tensile strength, low density (~0.89–0.90 g/cm³), and inherent biodegradability [3], making it a promising candidate for use as a sustainable reinforcement in polymer matrices. However, the integration of keratin into hydrophobic synthetic polymers remains challenging due to incompatibilities at the filler matrix interface, primarily resulting from the hydrophilic nature of keratin.

Among commercially available thermoplastics, thermoplastic polyurethane (TPU) distinguishes itself by virtue of its mechanical resilience, abrasion resistance, thermal stability, and recyclability [4,9]. These characteristics have led to its widespread use in applications ranging from automotive components and sports gear to footwear and biomedical devices. TPU's versatile processing and structural properties also make it an attractive platform for natural fiber reinforcement. Prior studies have reported the incorporation of keratin-based fillers into polymer matrices such as polypropylene, polyethylene, and polylactic acid (PLA), yielding improved mechanical performance and reduced environmental impact [5-8].

While recent investigations have extended this approach to TPU-based systems, these studies often focus on a single feather morphology typically fibers and rarely examine the influence of chemical surface modifications on composite performance. For instance, Ali *et al*. [10] studied PLA reinforced with chicken feather fibers, reporting moderate gains in mechanical properties, while Soykan [11] evaluated turkey feather–TPU composites and documented improvements in mechanical, thermal, and morphological characteristics. However, these efforts did not systematically consider the role of filler morphology or chemical functionalization in enhancing interfacial interactions. Furthermore, the underlying molecular bonding mechanisms particularly those facilitated by silane coupling agents remain insufficiently explored.

Additional studies, such as those by Mutlu *et al*. [12] and Doğan *et al*. [13], have addressed other performance dimensions, including flame retardancy and mechanical reinforcement in keratin–TPU composites. Despite these contributions, key knowledge gaps persist regarding the morphology

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dependent behavior of feather-reinforced composites and the potential of chemical surface treatments to promote compatibility between keratin and TPU matrices.

To address these limitations, the present study investigates the combined effects of feather morphology (powder versus fiber) and chemical surface modification using (3-aminopropyl)triethoxysilane on the mechanical performance of TPU-based biocomposites. The feathers underwent a pretreatment sequence involving sodium hydroxide washing, silane immersion in ethanol, and controlled drying. The silane treatment introduces reactive –Si–OH and $–NH_2$ groups that are hypothesized to facilitate covalent and hydrogen bonding interactions with both the keratin filler and TPU matrix, thereby enhancing interfacial adhesion and improving stress transfer across the composite.

Four composite formulations were developed, varying in feather content (10 wt% and 15 wt%) and morphology (powder and fiber). The mechanical behavior of the resulting biocomposites was evaluated through tensile, compressive, hardness (Shore A), and density testing to elucidate structure–property relationships. This study aims to demonstrate that both feather morphology and interfacial chemistry play critical roles in determining the mechanical performance of keratin-reinforced TPU composites, and that chicken feather waste can be effectively transformed into functional materials through relatively simple processing and chemical modification techniques.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Materials

The following raw materials were used in this study:

- **Thermoplastic Polyurethane (TPU):** commercial-grade thermoplastic polyurethane elastomer (TPU) was used as the polymer matrix due to its excellent flexibility, chemical resistance, and mechanical properties.
- **Chicken Feathers (CF):** Waste chicken feathers were collected as a byproduct from a local poultry processing facility in the City. These feathers consist primarily of α-keratin, a tough, fibrous protein comprising about 90–91% of their total composition. The feathers were used in two physical forms
- **Silane Coupling Agent:** The coupling agent used for surface modification was (3-aminopropyl-triethoxysilane (APTES), purity ≥ 98%. APTES was selected due to its ability to introduce reactive silanol (Si–OH) and amine ($–NH_2$) groups onto the feather surface, enhancing chemical compatibility with the TPU matrix through covalent and hydrogen bonding.
- **Sodium Hydroxide (NaOH)** (1–2% solution): Used to degrease and clean the raw feathers.
- **Deionized Water**: Used for all cleaning and rinsing steps to avoid contamination.

2.1.1. Preparation of Chicken Feather Fillers

- **Initial Cleaning**

  Raw chicken feathers were thoroughly cleaned using a 1–2% sodium hydroxide (NaOH) solution mixed with mineral water to remove fats, dirt, and residual proteins. The feathers were soaked in this solution for 24 hours at room temperature to ensure maximum impurity removal.

- **Drying**

  After cleaning, the feathers were oven-dried at a controlled temperature of 40–50°C for 48 hours to eliminate moisture and prepare them for grinding.

- **Grinding and Forming Filler Types**

  Feather Powder: Dried feathers were milled at 35,000 rpm for 25 minutes using a high-speed grinder to obtain fine powder particles.

  Feather Fiber: For fiber form, feathers were milled at the same speed (35,000 rpm) but for a shorter duration of 4–5 minutes to retain fibrous structure.

- **Surface Treatment (Chemical Functionalization)**

  Feathers were immersed in an ethanol solution containing 3-aminopropyltriethoxysilane for 24 hours.

  After soaking, the treated fillers were oven-dried at 40–50°C.

  This silane treatment introduces silanol (-Si–OH) groups through hydrolysis, which react with keratin's hydroxyl groups, forming covalent Si–O–Keratin bonds. The silane's terminal $–NH_2$ groups form hydrogen bonds with the TPU's carbonyl (-C=O) groups.

  Figure **1.** Schematic representation of silane-treated chicken feather bonding with TPU.

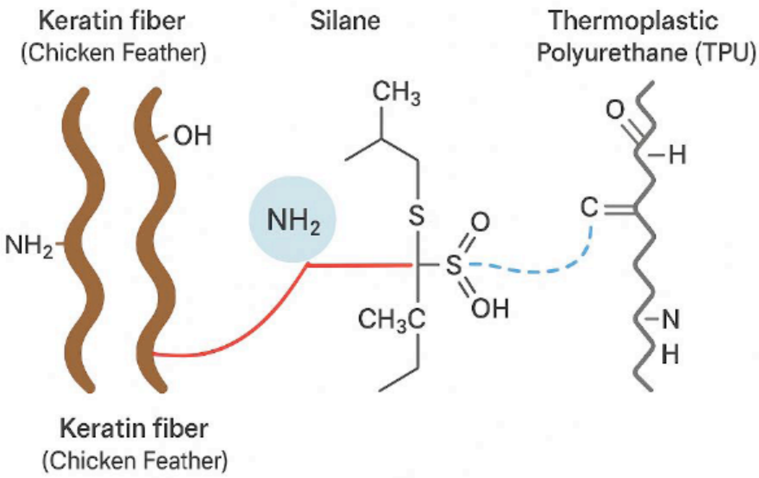

Figure 1: Schematic representation of silane-treated chicken feather bonding with TPU.

Red lines indicate covalent Si–O–Keratin bonds; blue dashed lines represent hydrogen bonding between silane's $–NH_2$ and TPU's carbonyl groups.

2.2.2. Composite Preparation

1. Mixing Process (Melt Compounding):

- The treated feather fillers were compounded with TPU using a laboratory-scale kneader (Figure **2**).

The compounding parameters were as follows:

- **Temperature:** 190°C
- **Mixing Speed:** 40 rpm
- **Total Mixing Time:** 5–6 minutes, the TPU was first pre-melted for 2.5 minutes, after which the filler (either feather powder or fiber) was gradually introduced and mixed until a homogeneous blend was achieved.

2. Mold Design:

- The study utilized a Dog bone shape plate (Figure no. **3**) with measurements of 115 mm×10 mm×5 mm.

3. Sample Fabrication:

- The mixed composites were molded into standardized dog-bone-shaped (Figure **3**) specimens using hot compression molding. The molding process was conducted at 190°C under 30 bar pressure for 5–6 minutes, followed by controlled cooling to ensure dimensional stability.

2.2.3. Composite Formulations

- Four different composite formulations were prepared based on the feather type and concentration:

Figure 2: Kneader.

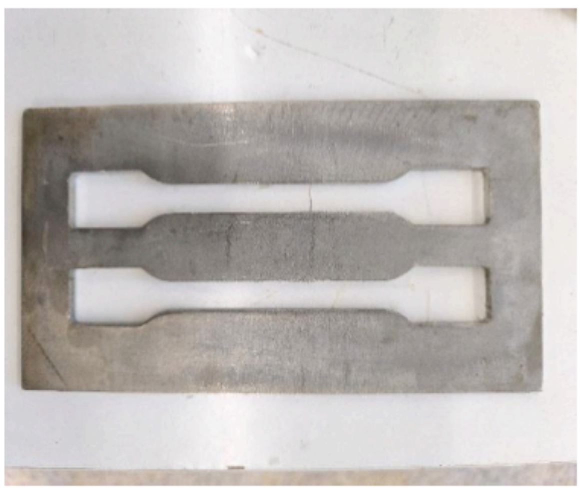

Figure 3: Mold.

Figure 4: Sample.

Table 1: Composition of TPU and Chicken Feather Samples in wt%

Sample Code	TPU (%)	Feather Powder (%)	Feather Fiber (%)
S1	90	10	-
S2	85	15	-
S3	90	-	10
S4	85	-	15

2.2. Experimental Method

2.2.1. Tensile Test

- Tensile tests (Figure **5**) were to evaluate the behaviour of the composite materials under uniaxial tension. The procedure adhered to the DIN EN ISO 527 standard using a Zwick Roell universal testing machine, with a crosshead speed set at 50 mm/min. Young's modulus was determined within a strain range of 0.05% to 0.25%. For each composite formulation, five specimens were tested, and the average values were recorded. Throughout the testing process, force and displacement data were continuously monitored to generate corresponding stress–strain curves. All test specimens were fabricated to standardized dimensions of 115 × 10 × 5 mm.

2.2.2. Compression Test

- A compression test (Figure **7**) is a standard mechanical characterization method used to evaluate the behavior of materials when subjected to compressive loading. This test provides critical data regarding the strength, stiffness, and deformation response of materials, which are essential for assessing their structural integrity and suitability for various engineering applications. Compression testing is widely applicable to a broad range of materials, including polymers, foams, paper, composites, and metals. In this study, the test was conducted in accordance with the DIN EN ISO 604 standard. Test specimens were prepared with dimensions of 5 mm × 5 mm × 8 mm to ensure consistency and compliance with the testing protocol.

2.2.3. Hardness Test (Shore A)

- The Shore A hardness test was employed with help of durometer (Figure **6**) to evaluate the material's resistance to permanent surface deformation, which serves as an indicator of its surface strength and wear resistance. The test was conducted using a Shore A durometer, which measures hardness by pressing a standardized indenter into the surface of the specimen under a specific load. The resulting indentation depth is used to determine the hardness value. This method is particularly suitable for soft to medium-hard polymeric materials.

2.2.4. Density Test

- Density testing (Figure **8**) was carried out to determine the mass per unit volume of the composite materials, providing insight into their structural composition and potential for lightweight applications. The measurements were conducted by accurately weighing each specimen and calculating the density using standardized volume measurements. A total of

Figure 5: Tensile testing machine.

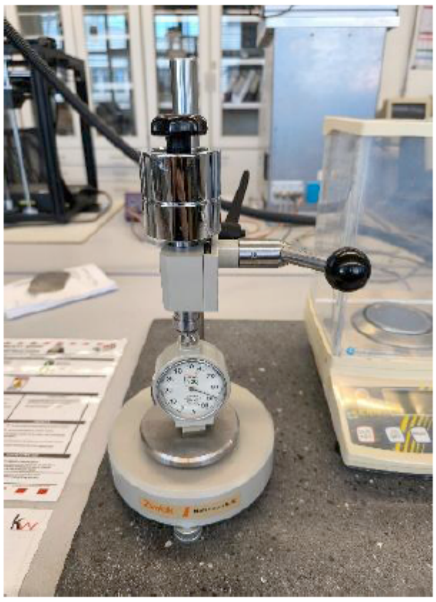

Figure 6: Durometer.

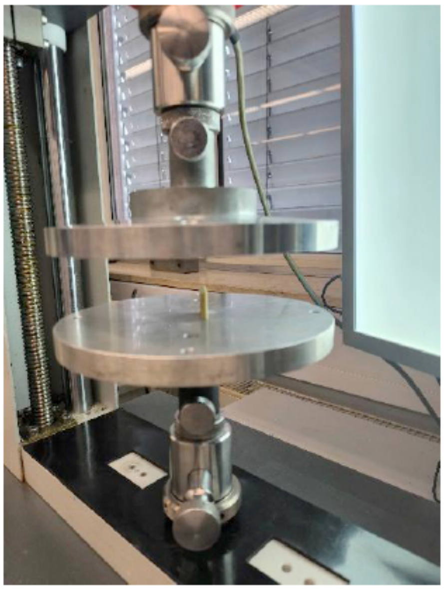

Figure 7: Compression testing machine.

Figure 8: Scale for density measurement.

12 specimens, representing four different composite formulations, were tested, and the average values were used to ensure reliable and consistent results.

3. RESULTS

3.1. Tensile Test

- The tensile strength values for the composite samples with varying filler contents are presented in Figure **9**. Among the tested formulations, the composite containing 15 wt% feather fiber exhibited the highest tensile strength, reaching 15.3 MPa, followed by the 15 wt% feather powder composite, which achieved a value of 13.1 MPa. In contrast, the unfilled (neat) TPU sample demonstrated significantly lower tensile strength, ranging from 9 to 10 MPa. These results indicate that the incorporation of feather-based fillers, particularly in fibrous form, leads to a notable enhancement in tensile strength, with performance increasing alongside filler content.

- The observed improvements in mechanical performance can be attributed to two key factors: (1) the fibrous morphology of the chicken feathers, which provides a higher aspect ratio and greater surface area, facilitating more effective stress transfer within the composite, and (2) the chemical surface modification using (3-aminopropyltriethoxysilane). The APTES

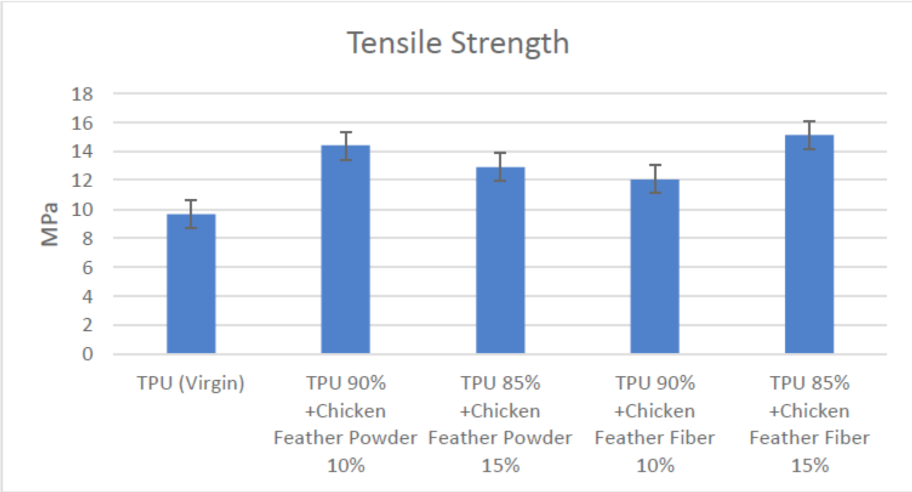

Figure 9: Comparison of the Tensile Strength of TPU + Chicken feather samples with varying filler content.

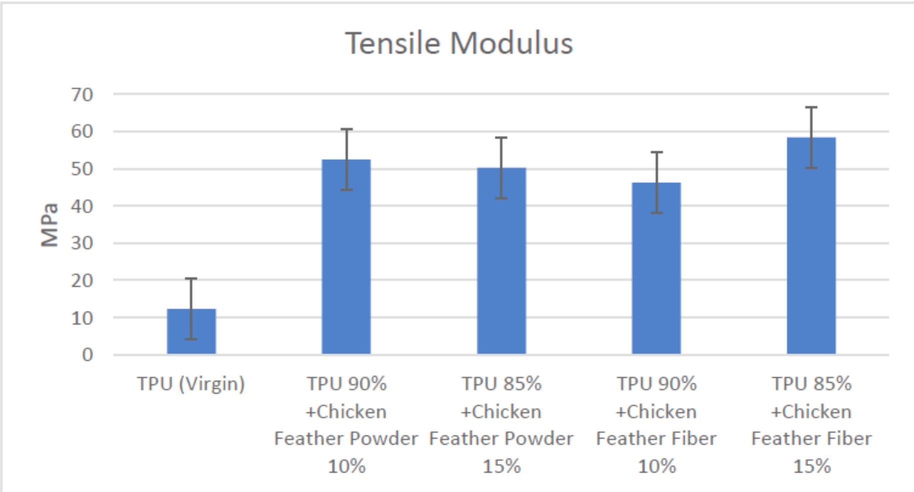

Figure 10: Comparison of Tensile modulus of TPU + Chicken feather samples with varying filler content.

treatment promotes interfacial bonding through the formation of covalent interactions between silanol-functionalized feather surfaces and hydroxyl groups present in keratin, while the terminal amine groups are capable of forming hydrogen bonds with the carbonyl groups in the TPU matrix. These chemical interactions enhance interfacial adhesion, minimize void formation, and enable more uniform load distribution throughout the polymer matrix.

- A similar trend was observed in the tensile modulus results (Figure **10**). The composite reinforced with 15 wt% feather fiber achieved the highest modulus value at 58 MPa, followed by the feather powder composite at 52 MPa, whereas the neat TPU exhibited a much lower modulus in the range of 12–12.5 MPa. These findings further underscore the importance of both filler morphology and surface functionalization. The fibrous reinforcements, due to their rigidity and elongated structure, not only provide higher intrinsic stiffness but also facilitate more efficient stress transfer to the matrix when chemical compatibility is enhanced through silane treatment. Collectively, the results demonstrate that both tensile strength and stiffness increase proportionally with filler content, with optimal performance observed in fiber-reinforced, chemically modified systems.

3.2. Compression Test

- Among all the mechanical properties obtained, the most crucial one is the compression strength, as depicted in Figure **11**. In the case of 15% of fiber filler samples, this led to a decrease in compressive strength from 15.9 to 16.9 MPa. The 10% fiber filler results were 17.9 and 17 MPa, respectively, which were higher than the 15% samples. The compressive strength increased for 15% powder content and reached 20.6 MPa. Meanwhile, for 10% powder filler, the compressive strength was 20.5 MPa,

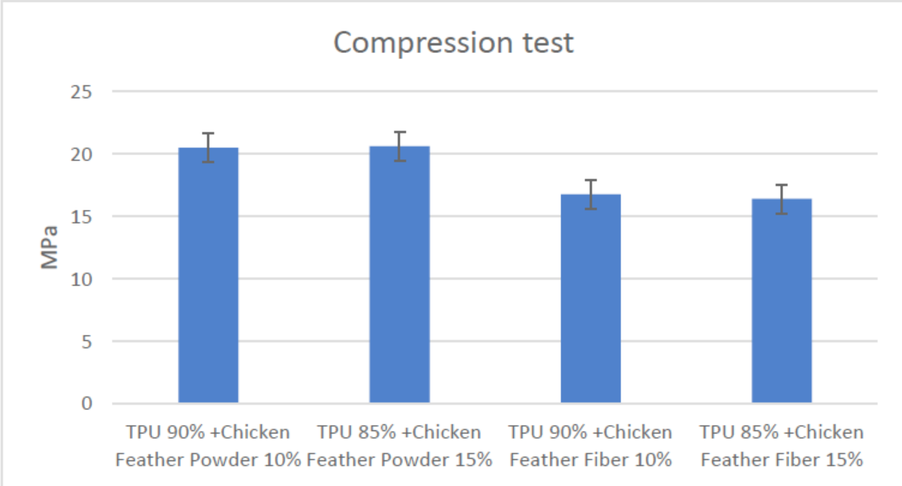

Figure 11: Comparison of Compression test of TPU + Chicken feather samples with varying filler content.

respectively. Notably, the compressive strength for powder filler samples was higher than fiber fillers.

3.3. Hardness Test (Shore A)

- The Shore A hardness values of the TPU-based composites exhibited a modest but consistent increase with the incorporation of both feather powder and fiber fillers, as illustrated in Figure **12**. This enhancement in hardness reflects a slight elevation in the surface rigidity of the material upon filler addition.

- The observed increase in hardness can be primarily attributed to the incorporation of keratin-based fillers, which possess inherently higher rigidity compared to the TPU matrix. Furthermore, the presence of the silane coupling agent is likely to have contributed to this effect by strengthening the interfacial adhesion between the filler and matrix. The chemical bonding facilitated by the (3-aminopropyltriethoxysilane) treatment promotes a more cohesive filler–matrix interface, allowing the treated feathers to behave as structurally integrated components. As a result, the composites exhibit greater resistance to localized deformation under indentation, thereby leading to improved hardness characteristics.

3.4. Density Test

- The density measurements of the TPU + chicken feather revealed values of 1.126, 1.029, 1.092, 1.014 g/cm^3 for fiber 10% & 15% through powder 10% & 15%, respectively. These densities were a bit lower compared to virgin material, as illustrated in Figure **13**.

4. DISCUSSION

The mechanical performance data clearly demonstrate that both the morphology of the feather filler and its concentration play critical roles in determining the overall behavior of the TPU-based

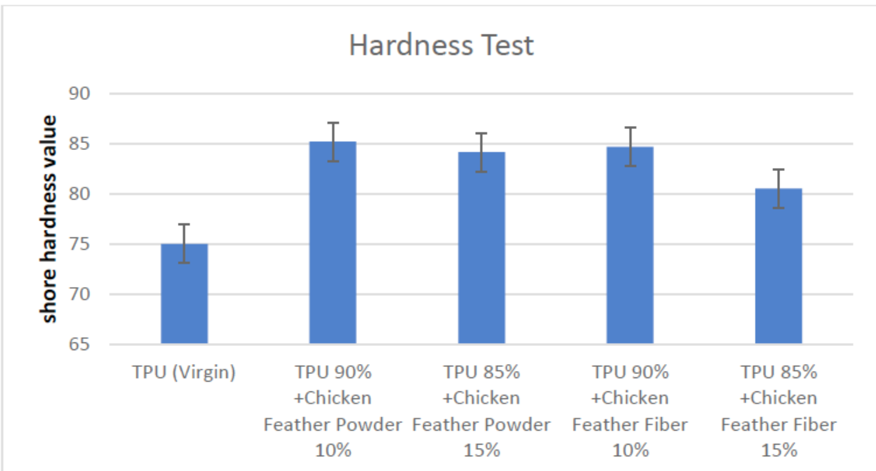

Figure 12: Comparison of the hardness test of TPU + Chicken feather samples with varying filler content.

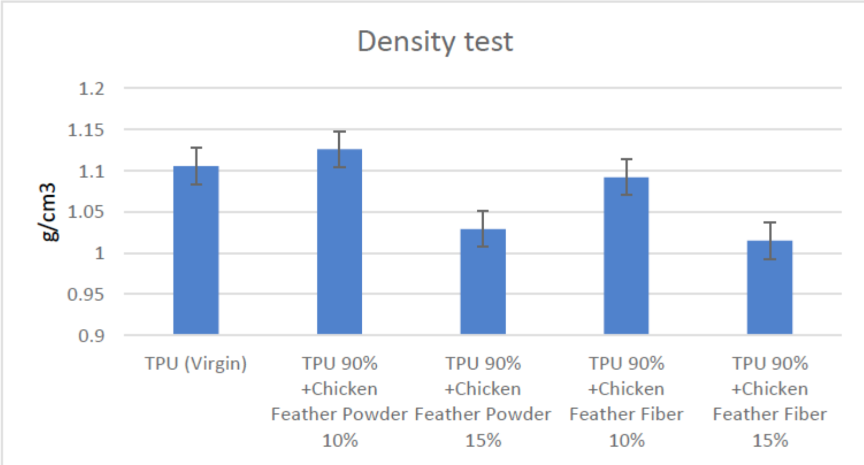

Figure 13: Comparison of the density test of TPU + Chicken feather samples with varying filler content.

bio-composites. Among all formulations, the composite containing 15 wt% feather fiber exhibited the highest tensile strength and modulus, which can be attributed to the elongated structure and high aspect ratio of the fibers. These morphological characteristics enhance stress transfer across the filler–matrix interface, thereby contributing to superior load-bearing capacity. In contrast, the feather powder-reinforced composites showed improved compressive strength, a result likely stemming from the more homogeneous dispersion and compact packing of the finer particles within the TPU matrix.

The enhancement in mechanical properties observed in composites with silane-treated fillers is closely associated with improved interfacial adhesion. The (3-aminopropyltriethoxysilane) coupling agent employed in this study undergoes hydrolysis in the presence of ethanol and water, producing reactive silanol groups (–Si–OH). These groups subsequently form covalent Si–O–Keratin bonds with hydroxyl (–OH) functionalities present on the keratin surface. Concurrently, the terminal amine ($-NH_2$) moiety of APTES is capable of forming hydrogen bonds with carbonyl (–C=O) groups in the TPU matrix. This dual interfacial bonding mechanism covalent bonding on the filler side and hydrogen bonding on the matrix side significantly improves stress transfer efficiency and contributes to the mechanical reinforcement of the composite system.

The molecular-level interactions facilitated by APTES are schematically represented in Figure **1**, which illustrates the bonding mechanisms between silane-functionalized feather keratin and the TPU matrix. Covalent Si–O–Keratin bonds are indicated by red lines, while hydrogen bonds ($-NH_2 \cdots C=O$) are depicted using blue dashed lines. This bonding architecture underscores the transition of chicken feather waste from a passive bio-filler to an active reinforcement phase capable of imparting both mechanical and structural enhancements to the composite.

Moreover, a modest increase in Shore A hardness and a concurrent reduction in material density were observed across all composite samples. These findings suggest the dual benefit of enhanced surface rigidity and reduced weight properties highly desirable in applications where mechanical performance must be balanced with material lightness, such as in the automotive, aerospace, and consumer goods sectors.

5. CONCLUSION

This study demonstrates the technical viability and effectiveness of utilizing chicken feather waste as a sustainable reinforcement material in thermoplastic polyurethane (TPU) composites. Through systematic processing of the feathers into two distinct morphologies fibrous and powdered and the application of (3 aminopropyltriethoxysilane) surface modification, the resulting composites displayed morphology-dependent enhancements in mechanical performance. Specifically, fiber-reinforced composites exhibited superior tensile strength and modulus due to the high aspect ratio and improved stress transfer capacity of the fibers. In contrast, powder-based composites achieved greater compressive strength, likely attributable to their uniform dispersion and dense packing within the polymer matrix.

The success of silane surface functionalization in promoting interfacial compatibility underscores the critical role of interfacial engineering in natural fiber-reinforced polymer composites. The dual bonding mechanism covalent bonding between silanol-modified feather surfaces and keratin, and hydrogen bonding with the TPU matrix significantly enhanced interfacial adhesion and mechanical integrity. These findings highlight the potential of low-cost chemical treatments to transform agrowaste fillers into functionally integrated composite constituents.

Additionally, the composites demonstrated modest increases in hardness and reductions in density, suggesting a favorable balance between rigidity and lightweight properties. Such characteristics are particularly advantageous in sectors demanding high strength-to-weight ratios, including automotive, aerospace, packaging, and consumer goods manufacturing.

Overall, this research establishes a compelling case for the valorization of poultry industry byproducts as functional, eco-efficient reinforcements in high-performance polymer composites. Future studies may focus on optimizing processing parameters, exploring alternative coupling agents, and assessing long-term durability and environmental performance to further advance the application potential of feather-based biocomposites.

6. FUTURE SCOPE

Future research should aim to optimize fiber treatment and dispersion techniques, investigate the long-term environmental durability of the composites, and explore the scalability of production processes. Expanding the range of potential applications and refining composite processing methods will be essential for transitioning these bio-composites from laboratory-scale prototypes to commercially viable products.

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Under the mentorship of Prof. Jens Schuster, this research represents a significant step forward in the field of sustainable polymer composites and contributes to the ongoing effort to transform low-value waste into high-performance engineering materials.

CONFLICT OF INTEREST STATEMENT

The author declares that there is no conflict of interest. This research was funded by Hochschule Kaiserslautern, which had no role in the design, execution, interpretation, or publication of this study.

REFERENCES

[1] Ali, M. F., Hossain, M. S., Moin, T. S., Ahmed, S., & Chowdhury, A. M. S., "Utilization of waste chicken feathers for the preparation of eco-friendly and sustainable composite", Cleaner Engineering and Technology, 2021.

[2] Soykan, U., "Development of turkey feather fiber-filled thermoplastic polyurethane composites: Thermal, mechanical, water-uptake, and morphological characterizations". Journal of Composites and Compounds, 2022. https://doi.org/10.1177/00219983211056137

[3] Cañavate, J., Aymerich, J., Garrido, N., Colom, X., Macanás, J., Molins, G., Álvarez, M. D., & Carrillo, F., "Properties and optimal manufacturing conditions of chicken feathers/poly (lactic acid) biocomposites", Journal of Composite Materials, 2015. https://doi.org/10.1177/0021998315595534

[4] Tseng, F. C. J., "Biofibre Production from Chicken Feather", Master's Thesis, The University of Waikato, 2011.

[5] Bansal, G., Singh, V. K., Verma, A., Negi, P., & Rastogi, S., "Properties and Application of Chicken Feather Fiber (CFF) in Composites", International Journal of Research in Mechanical Engineering, 2017.

[6] Pourjavaheri, F., "Avian-Keratin Refinement and Application in Biomaterials", 2017.

[7] Jagadeeshgouda, K. B., Reddy, P. R., & Ishwaraprasad, K., "Experimental Study of Behaviour of Poultry Feather Fiber - A Reinforcing Material for Composites", International Journal of Research in Engineering and Technology, 2014.

[8] Rawi, S. K. M., "Study on the Effects of Reinforcing Chicken Feather Fiber (CFF) on Mechanical Properties of Polypropylene (PP)", 2009.

[9] Pourjavaheri, F., Shanks, R. A., Czajka, M., & Gupta, A., "Purification methods for chicken feather keratin", International Conference on Advance Polymeric Materials, 2013. https://doi.org/10.4028/www.scientific.net/AMR.941-944.1184

[10] Lubrizol. What is TPU? Engineered Polymers. Retrieved September 21, 2023, from https://www.lubrizol.com/Engineered-Polymers/About/What-is-TPU

[11] Mutlu, A., Tayfun, U., & Doğan, M., "Performance evaluation of melamine derivatives as flame retardant additives in chicken feather containing thermoplastic polyurethane bio-composites", Journal of Thermoplastic Composite Materials, 2023. https://doi.org/10.1177/08927057221133090

[12] Mutlu, A., & Doğan, M., "Fire retardant properties of chicken feather/TPU composites containing phosphorus fillers", Journal of Thermoplastic Composite Materials, 2023.

[13] Soykan, U., "Development of turkey feather fiber-filled thermoplastic polyurethane composites", Polymer Composites, 2022. https://doi.org/10.1177/00219983211056137

https://doi.org/10.31875/2410-4701.2025.12.03