

RESEARCH ARTICLE

Tensile Behavior of Injection-Molded PLA Composites Reinforced with Turkey Feather Fibers at Different Loadings

Momin Alihuseyinov¹  • Ugur Soykan²  • Turker Akkoyunlu³  • Gurcan Yildirim¹ 

¹Bolu Abant İzzet Baysal University, Faculty of Engineering, Department of Mechanical Engineering, Bolu/Türkiye

²Bolu Abant İzzet Baysal University, Yeniçağa Yaşar Çelik Vocational School, Bolu/Türkiye

³Kırıkkale University, Faculty of Engineering and Natural Sciences, Department of Mechanical Engineering, Kırıkkale/Türkiye

ARTICLE INFO

Article History

Received: 18.06.2026

Accepted: 25.06.2026

First Published: 28.06.2026

Keywords

Fiber-matrix adhesion

Mechanical performance

Natural fiber reinforcement

PLA composites



ABSTRACT

This study investigates the development and mechanical performance of environmentally friendly polylactic acid (PLA)-based biocomposites reinforced with turkey feather fibers (TFFs) at different weight fractions (1, 3, 5, 7, and 10 wt.%). The primary aim is to evaluate the potential of poultry waste-derived keratin fibers as sustainable reinforcements for lightweight engineering materials. TFFs were extracted, purified, and incorporated into the PLA matrix via melt mixing followed by injection molding. The mechanical behavior of the resulting composites was assessed through tensile testing, focusing on maximum load, elongation at break, and maximum displacement. The results obtained revealed that the incorporation of TFFs significantly influenced the mechanical properties of PLA matrix. While pure PLA exhibited the highest tensile strength and deformation capability, the addition of fibers generally reduced mechanical performance. Among all the samples, the 3 wt.%-reinforced TFF composite displayed the best balance of mechanical properties, exhibiting the highest tensile load and relatively improved ductility compared to other fiber loadings. However, further increases in fiber content led to a progressive deterioration in tensile properties due to fiber agglomeration, insufficient fiber-matrix adhesion, and increased microstructural defects such as void formation and interfacial debonding. In conclusion, the experimental findings indicate that turkey feather fibers can be effectively utilized as low-cost, renewable reinforcement agents for PLA-based composites, contributing to waste valorization and sustainable material development. The study identifies an optimal fiber loading of approximately 3 wt.% for achieving a balance between mechanical performance and structural integrity, providing useful information for the design of green composite materials for lightweight engineering applications.

Please cite this paper as follows:

Alihuseyinov, M., Soykan, U., Akkoyunlu, T., & Yildirim, G. (2026). Tensile behavior of injection-molded PLA composites reinforced with turkey feather fibers at different loadings. *Journal of Advanced Applied Sciences*, 5(1), 45-54. <https://doi.org/10.61326/jaasci.v5i1.505>

1. Introduction

In recent years, the development of lightweight and sustainable engineering materials has become a major research priority in mechanical engineering due to increasing demands for energy efficiency, resource conservation, and environmental responsibility. Composite materials play a critical role in numerous engineering sectors, including

automotive, aerospace, construction, packaging, and consumer products, where the reduction of structural weight while maintaining adequate mechanical performance is highly desirable. Lightweight materials contribute directly to reduced fuel consumption, lower greenhouse gas emissions, and improved overall system efficiency throughout the product life cycle. Consequently, the replacement of conventional

✉ Correspondence

E-mail address: turkerakkoyunlu@kku.edu.tr

petroleum-based materials with renewable and biodegradable alternatives has emerged as a key strategy for achieving sustainable manufacturing and circular economy objectives (Ghorbal et al., 2019).

Among biodegradable polymers, PLA has attracted considerable attention because of its renewable origin, biodegradability, biocompatibility, and relatively favorable processing characteristics (Trivedi et al., 2023). Nevertheless, its inherent brittleness, limited impact resistance, and moderate thermal stability restrict its broader engineering applications (Akdogan & Soykan, 2025; Mrajji et al., 2022; Shankar & Netravali, 2025). Reinforcement with natural fibers has therefore become one of the most effective approaches to improve the mechanical performance of PLA-based materials while maintaining their environmental advantages (Murariu & Dubois, 2016). In addition to conventional lignocellulosic fibers, animal-derived fibers have recently gained attention because they provide an opportunity to transform agricultural and food-industry wastes into value-added engineering materials (Mann et al., 2023; Soykan, 2022).

Poultry feathers represent one of the most abundant animal-derived wastes worldwide, with annual generation exceeding two million tonnes (Reddy et al., 2021). Disposal of these residues poses environmental and economic challenges, whereas their utilization as reinforcement materials offers an attractive route for waste valorization and resource recovery (Dutta et al., 2024; Shankar & Netravali, 2025). Owing to their keratin-rich structure and low density, feather fibers possess a unique combination of lightweight characteristics, flexibility, and mechanical stability that can be advantageous for the fabrication of bio-based composites (Akdogan & Soykan, 2024; Mrajji et al., 2022). Furthermore, the incorporation of feather fibers into PLA matrices has been reported to improve mechanical performance, reduce environmental impacts, and lower the density of the resulting composites, making them attractive candidates for sustainable lightweight engineering applications (Aranberri et al., 2017; Baba 6 Özmen, 2017).

Despite the growing interest in feather-reinforced PLA composites, the majority of previous studies have focused on chicken feather fibers, while the potential of turkey feather fibers remains largely unexplored (Khan et al., 2022). Turkey feather barbs are characterized by longer fiber lengths and relatively high strength compared with conventional contour feathers, suggesting their suitability as reinforcement materials for biodegradable polymer matrices. Moreover, their distinctive double-sided comb-like morphology and the presence of polar functional groups may promote improved interfacial interactions with PLA, potentially leading to enhanced load transfer and mechanical performance.

Therefore, the present study aims to develop a novel series of PLA-based biocomposites reinforced with different contents of turkey feather fibers and to evaluate their mechanical

behavior through tensile testing. By establishing the relationship between turkey feather fiber content and the resulting mechanical properties, this work seeks to contribute to the development of sustainable, lightweight, and high-performance composite materials. From a sustainability perspective, the study promotes the valorization of poultry-processing waste and supports circular economy principles. From a mechanical engineering perspective, it provides insights into the design of environmentally friendly structural materials with potential applications in lightweight components and sustainable product development.

2. Materials and Methods

Commercial polylactic acid materials with a density of 1.24 g/cm³ and a relative viscosity of 3.1 were supplied by NatureWorks LLC under the trade name Ingeo Biopolymer 6100D. Besides, turkey feathers were used as the primary source of reinforcement fibers. A non-ionic surfactant, Setawet ANY-R2205 was employed as a detergent during the cleaning process when ethanol was used for the disinfection and purification of the fibers. All other chemicals and solvents used in this study were of analytical grade and utilized as received without further purification. As for the preparation of turkey feather fibers (TFFs), the procedure described in our previous studies was followed (Abdur Rahman et al., 2023; Rajendran et al., 2025). Briefly, raw turkey feathers were washed with distilled water and subsequently cleaned using Setawet ANY-R2205 detergent at 40 °C for 1 h to remove contaminants while preserving the fiber microstructure. The cleaned feathers were then disinfected by immersion in ethanol for a duration of 24 h, a process repeated 3 times, and subsequently dried in a vacuum oven at 30 °C for a duration of 24 h. After drying, the barb sections were mechanically separated from the quills according to the method reported by Baron and Schmidt (Barone & Schmidt, 2005), cut into smaller pieces, and sieved through a 400 µm mesh to obtain fibers with a more uniform size distribution. Finally, the TFF-Reinforced PLA composites were prepared by the following procedure. Prior to processing, PLA pellets and TFF compounds were dried under vacuum at 40 °C for the time of 1 h. The composites containing 1, 3, 5, 7, and 10 wt.% TFFs were prepared by melt mixing in a Brabender W50 EHT+ Plastograph EC Plus mixer at 175 °C for 20 min, while neat PLA served as the reference. The samples prepared are accordingly labeled as 1 wt.% PLA-1, 3 wt.% PLA-3, 5 wt.% PLA-5, 7 wt.% PLA-7, and 10 wt.% PLA-10. A reference sample is prepared under identical conditions without turkey feather fibers and was named as pure. The resulting blends were granulated using a Retsch SM-100 knife mill and subsequently injection molded using a Thermo Scientific Haake MiniJet II machine. Molding was performed at a mold temperature of 105 °C and an injector temperature of 175 °C under injection and holding pressures of 650 and 400 bar, respectively. For each

composition, at least five dog-bone specimens (75x12.5x2 mm³) were produced.

3. Results and Discussion

3.1. Variation of Maximum Load Values

The tensile behavior of the PLA/turkey feather fiber composites was evaluated by analyzing the maximum load (F_{max}) sustained by each specimen during tensile testing. The maximum load represents the highest force that a material can withstand before the onset of catastrophic failure and provides an important indication of the reinforcing efficiency of the incorporated fibers. The obtained results are provided in Table 1. The obtained results were also presented graphically in Figure 1 to enhance the impact of turkey feather fibers on the maximum load parameters. It is seen from the table that the neat PLA (pure reference sample) specimens exhibited the highest tensile performance among all tested materials, with a maximum load of 0.8267 kN, which is higher than those of all fiber-reinforced composites. The result obtained indicated that the unreinforced PLA matrix possesses superior tensile load-bearing capability under the present processing conditions.

Table 1 Change of the maximum load (F_{max}) parameters of turkey feather-reinforced fibers at different weight fractions.

Samples	F_{max} (kN)
Pure	0.8267
%1 PLA-1	0.5304
%3 PLA-3	0.5863
%5 PLA-5	0.548
%7 PLA-7	0.4903
%10 PLA-10	0.4884

The incorporation of turkey feather fibers generally resulted in a reduction in the maximum tensile load. The 1 wt.% TFF composite exhibited F_{max} value of 0.5304 kN, representing a noticeable decrease compared with neat PLA. Increasing the fiber content to 3 wt.% improved the tensile response, with maximum load of 0.5863 kN. This composition exhibited the highest tensile performance among all reinforced specimens, revealing that a moderate amount of turkey feather fibers can contribute positively to load transfer while maintaining sufficient continuity of the PLA matrix. Further increases in fiber content resulted in a gradual deterioration of tensile performance. The 5 wt.% composite exhibited F_{max} value of 0.5480 kN, while the 7 wt.% composite showed a value of 0.4903 kN. The lowest maximum load was obtained for the 10 wt.% composite, which fractured under a load of 0.4498 kN, as provided in Table 1. These results recorded indicted that increasing the turkey feather fiber content beyond the optimum level progressively reduces the tensile load-bearing capacity of the composites.

The relatively superior performance of the 3 wt.% TFF composite displays that this reinforcement level provides the most effective balance between fiber reinforcement and matrix integrity. At low fiber concentrations, the feather fibers are more likely to be uniformly dispersed throughout the PLA matrix, allowing more efficient stress transfer across the fiber-matrix interface. Under these conditions, the fibers can partially impede crack propagation and contribute to load sharing without severely disrupting the continuity of the polymer phase. Consequently, the composite exhibits improved mechanical performance compared with the other reinforced formulations. However, as can be seen from the numerical data obtained, the tensile performance of the composite with a 3% weight ratio remained lower than that of pure PLA, as seen in Figure 1. The relatively limited improvement in tensile performance indicates that the reinforcing potential of the untreated turkey feather fibers was not fully exploited. This behavior is most likely attributable to the weak interfacial adhesion between the hydrophilic keratin-based feather fibers and the relatively hydrophobic PLA matrix. Such inadequate interfacial bonding hinders efficient stress transfer from the matrix to the reinforcing fibers, accordingly limiting their ability to function as effective load-bearing constituents during tensile deformation.

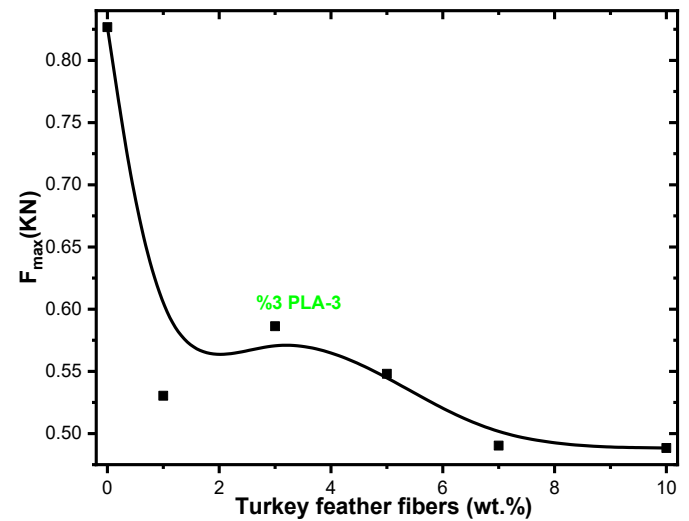


Figure 1. Variation of F_{max} values depending on turkey feather fiber-reinforced composites. Lines represent the general trend to guide the eye.

The gradual decrease in F_{max} observed at fiber contents above 3% can be explained by various microstructural mechanisms. As fiber concentration increases, achieving homogeneous distribution within the polymer matrix becomes increasingly difficult. Fibers tend to clump together, resulting in localized regions of high fiber density surrounded by matrix-deficient areas. These clumped regions act as stress concentration points where cracks can more easily form under applied tensile loads. In addition, higher fiber loadings increase the likelihood of void formation during composite fabrication.

The presence of voids reduces the effective cross-sectional area available to carry tensile loads and promotes premature fracture by facilitating crack nucleation. Furthermore, insufficient wetting of the feather fibers by the molten PLA matrix can produce interfacial defects and micro-gaps around the fibers, further reducing stress transfer efficiency.

Another important factor contributing to the reduction in tensile strength is the increased frequency of fiber pull-out and interfacial debonding during loading. Instead of transferring the applied stress efficiently, weakly bonded fibers may separate from the surrounding matrix, consuming only a limited amount of fracture energy before complete failure occurs. This phenomenon becomes more pronounced at higher fiber contents due to the larger total interfacial area and the increased probability of fiber–fiber interactions.

The observed tensile behavior is consistent with numerous studies on natural fiber-reinforced PLA composites (Dhaou & Mnif, 2026; Hinchcliffe, 2015; Yiga et al., 2023), where moderate fiber contents often provide slight improvements in mechanical performance, whereas excessive fiber loading leads to reduced tensile strength because of poor dispersion, inadequate fiber-matrix adhesion, and increased structural defects (Kilinc, 2025; Morabiya & Joshi, 2026; Singhal et al., 2016). Similar trends have been reported for composites reinforced with cellulose (Ljungberg et al., 2006; Rahman et al., 2026; Siqueira et al., 2011), flax (Kesentini et al., 2022; Radkar et al., 2019; Yan et al., 2025), hemp (Hernández-Díaz et al., 2020; Masirek et al., 2007), bamboo (Bautista et al., 2025; Sayed et al., 2022), and poultry feather fibers (Soykan et al., 2022), where an optimum reinforcement content typically exists before mechanical properties begin to deteriorate.

All in all, the F_{max} parameters deduced from tensile strength results obtained showed that the incorporation of turkey feather fibers influences the mechanical performance of PLA in a concentration-dependent manner. While the addition of 3 wt.% TFF provides the most favorable tensile response among the reinforced composites, higher fiber loadings gradually reduce the maximum load-carrying capacity due to weaker interfacial bonding, fiber agglomeration, increased porosity, and premature crack initiation. The findings obtained indicate that further improvements in the F_{max} parameters may be achieved through fiber surface modification, chemical treatments, or the use of compatibilizing agents to enhance the interfacial adhesion between turkey feather fibers and the PLA matrix, accordingly enabling more efficient stress transfer and improved reinforcement efficiency.

3.2. Change of Elongation at Break

Secondly, the tensile strength findings enable us to determine the change of elongation of PLA matrix. Table 2 including the elongation at break results clearly displays that the incorporation of turkey feather fibers significantly

influenced the ductility of the PLA composites. To illustrate the dramatic change of the elongation at break, we used Figure 2. The pure PLA specimen exhibited elongation value of 2.58%, indicating the characteristic deformation behavior of unreinforced PLA. Although PLA is generally regarded as a relatively brittle thermoplastic compared with conventional engineering polymers, the pure specimen retained a measurable capacity for plastic deformation prior to fracture. The addition of turkey feather fibers resulted in a substantial reduction in elongation at break, indicating that fiber reinforcement restricted the deformation capability of the polymer matrix. In more detail, the 1 wt.% TFF composite exhibited an elongation of approximately 0.80%, corresponding to a considerable decrease compared with pure PLA material. This reduction indicates that even a small amount of feather fiber limits polymer chain mobility and promotes earlier crack initiation during tensile loading. However, it is interesting that, the 3 wt.% TFF composites exhibited an elongation value of 1.75%, representing the highest ductility among all reinforced specimens, as shown in Table 2. The recorded value approach those of the pure PLA sample, indicating that a moderate fiber content provides a relatively balanced microstructure in which the fibers are sufficiently dispersed to reinforce the matrix without excessively restricting its deformation. This observation is consistent with the maximum load results, where the 3 wt.%-reinforced composite also exhibited the best tensile performance among the reinforced materials, as given in Figure 2.

Table 2 Differentiation of the elongation at break of prepared samples.

Samples	Elongation at Break (%)
Pure	2.58
%1 PLA-1	0.80
%3 PLA-3	1.75
%5 PLA-5	-
%7 PLA-7	0.86
%10 PLA-10	0.65

As the fiber loading increased beyond 3 wt.%, the elongation at break decreased continuously. The 7 wt.% composites exhibited an elongation value of 0.86%, while the 10 wt.% composite showed the lowest value of 0.65%. This is attributed to the fact that increasing the fiber content transforms the composite from a relatively ductile material into one exhibiting increasingly brittle fracture behavior. Although no elongation value is recorded for the 5 wt.%-reinforced specimen (Table 2), the corresponding reduction in maximum load and displacement indicates that the prepared composite structure would likely follow the same decreasing trend.

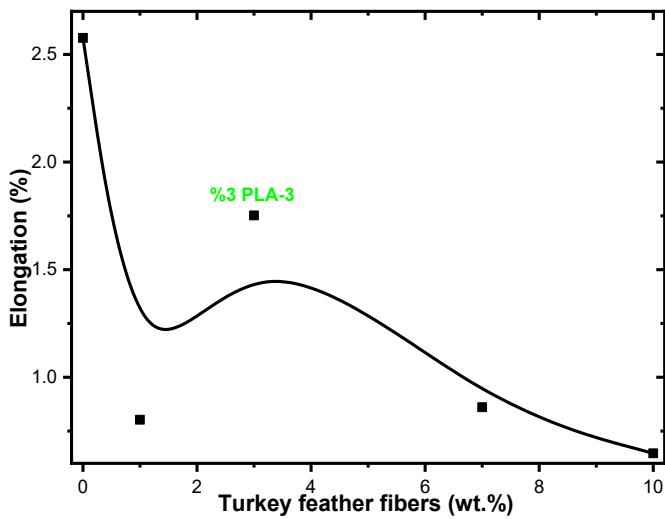


Figure 2. Variation of elongation at break with turkey feather fiber reinforcement of PLA matrix. Lines represent the general trend to guide the eye.

The reduction in elongation at break can be explained by several interacting mechanisms associated with the presence of natural fibers in the polymer matrix. Turkey feather fibers possess a significantly higher stiffness than PLA (Nur Ainin et al., 2022; Srinara et al., 2020; Talimi, 2011; Zhang et al., 2019) and therefore act as physical constraints that restrict the mobility of polymer chains during tensile deformation (Nur Ainin et al., 2022). As the fiber concentration increases, the continuous polymer phase becomes interrupted by a greater number of reinforcing fibers, reducing the matrix's ability to undergo plastic deformation before fracture (Chen & Turng, 2024; Khakalo et al., 2017; Sandeep et al., 2026; Zheng, 2000).

In addition to restricting polymer chain movement, higher fiber loadings increase the likelihood of fiber agglomeration, non-uniform fiber dispersion, and void formation within the composite structure. The microstructural defects reported may form localized stress concentration sites where cracks can initiate more easily under applied tensile loads. Once initiated, the cracks occurred propagate rapidly through the matrix, resulting in premature failure and lower elongation values. The quality of the fiber-matrix interface also plays a crucial role in determining the ductility of composites. Since untreated turkey feather fibers exhibit limited chemical compatibility with the hydrophobic PLA matrix, interfacial adhesion is relatively poor. The similar discussion is also performed for F_{max} values. Consequently, tensile loading typically leads to interfacial separation and fiber rupture instead of effective stress transfer from the matrix to the fibers. These interfacial failures reduce the composite's ability to absorb deformation energy and accelerate crack propagation, ultimately leading to reduced elongation at break.

To sum up, the elongation results deduced from the tensile strength experiments indicate that turkey feather fiber reinforcement decreases the ductility of PLA composites, with

the extent of reduction becoming more pronounced as the fiber content increases. Among the reinforced specimens, the 3 wt.%-reinforced TFF composite exhibited the most favorable balance between tensile strength and ductility, revealing that this fiber loading provides the most effective compromise between reinforcement and deformation capability. In contrast, composites containing 7 wt.% and 10 wt.%-reinforced TFF compounds displayed significantly reduced elongation at break, confirming that the presence of excess fiber incorporation promotes brittle fracture due to restricted polymer chain mobility, increased stress concentrations, and insufficient fiber-matrix interfacial bonding. These findings are in good agreement with previous studies on natural fiber-reinforced PLA composites (Sandeep et al., 2026; Soykan et al., 2022; Zheng, 2000), where increasing fiber content generally leads to reduced ductility unless fiber surface modification or compatibilization techniques are employed to improve interfacial adhesion and stress transfer efficiency.

3.3. Effect of Turkey Feather Fiber Reinforcement on Maximum Displacement of PLA Matrix

We also determined the effect of turkey feather fiber on the maximum displacement of PLA matrix with the tensile strength experiments. We depicted the experimental findings in Table 3 and used Figure 3 to clearly illustrate the dramatic changes. One can see from the table that the maximum displacement at fracture exhibited a clear decreasing trend with increasing turkey feather fiber content in the PLA matrix, indicating a progressive reduction in the deformation capacity of the composites. The pure PLA matrix showed the highest displacement value of 2.305 mm, indicating the inherent ductility of the unreinforced polymer and its ability to sustain relatively large deformations before failure. Following the incorporation of turkey feather fibers, the displacement values decreased noticeably (Figure 3).

Table 3 Differentiation of the maximum displacement of prepared samples.

Samples	Maximum displacement
Pure	2.305
%1 PLA-1	1.025
%3 PLA-3	1.085
%5 PLA-5	1.05
%7 PLA-7	0.895
%10 PLA-10	0.959

The 1 wt.% TFF composite exhibited a maximum displacement of approximately 1.025 mm, representing a considerable reduction compared with the pure PLA specimen prepared. The 3 wt.% composite showed a displacement value of 1.085 mm, revealing that although the fibers limited the deformation capacity of the matrix, the reduction was relatively moderate at this reinforcement level. Similarly, the 5 wt.%

composite displayed a fracture displacement of 1.05 mm (Table 3), indicating that the addition of more fibers did not provide any improvement in deformation behavior. Increasing the fiber loading led to decreasing in the maximum displacement. In this context, as the fiber loading increased to 10 wt.%, the maximum displacement further decreased to 0.959 mm, while the 7 wt.% composites exhibited the lowest displacement value of 0.895 mm. The reported results clearly indicated that increasing the turkey feather fiber content progressively reduces the ability of the PLA matrix to undergo deformation prior to fracture.

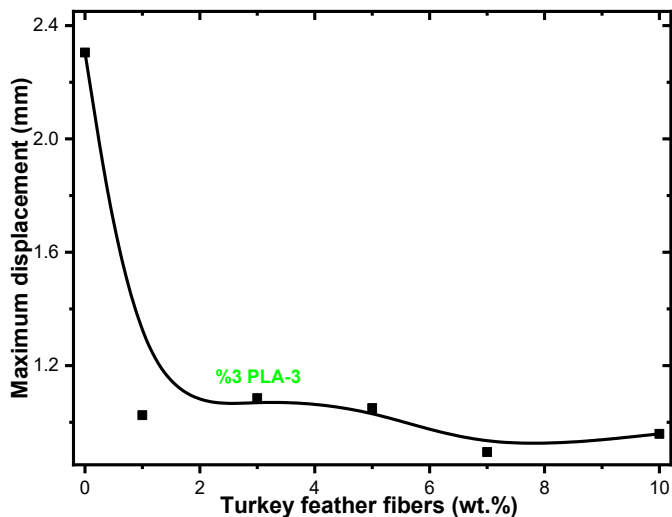


Figure 3. Influence of turkey feather fiber reinforcements on maximum displacement of PLA matrix. Lines represent the general trend to guide the eye.

The reduction in maximum displacement can be attributed to several microstructural factors associated with fiber reinforcement (Majdzadeh et al., 2006; Muhammad et al., 2018; Rapoport et al., 2002; Rashid et al., 2023; Run-ke et al., 2018; Trinh-Duc et al., 2021). Turkey feather fibers are considerably stiffer than the PLA matrix and therefore restrict the mobility of polymer chains during tensile loading. As the fiber concentration increases, the polymer matrix becomes increasingly constrained, limiting its ability to deform plastically. Furthermore, higher fiber loadings often lead to non-uniform fiber dispersion, fiber agglomeration, and the formation of voids or micro-defects within the composite (Chen & Turng, 2024; Muhammad et al., 2018; Rashid et al., 2023; Trinh-Duc et al., 2021; Zheng, 2000). These structural imperfections serve as stress concentration sites that promote premature crack initiation and accelerate crack propagation under tensile loading. Another important factor influencing the displacement behavior is the fiber-matrix interfacial adhesion, having already been discussed above. Since untreated natural fibers generally exhibit limited compatibility with hydrophobic PLA, the efficiency of stress transfer across the interface is restricted. Under tensile loading, weak interfacial bonding facilitates fiber pull-out and interfacial debonding instead of

allowing the matrix to undergo significant deformation. Consequently, fracture occurs at lower displacement values, particularly at higher fiber contents where the total interfacial area increases substantially.

The observed decrease in displacement is also closely associated with the reduction in elongation at break obtained from the tensile tests. Both parameters consistently indicate that increasing turkey feather fiber content changes the mechanical response of the composite from relatively ductile to increasingly brittle. While low fiber concentrations (particularly 3 wt.%) still allow limited deformation before failure, higher reinforcement levels significantly reduce the composite's toughness and energy absorption capability.

Correspondingly, the maximum displacement results indicate that although turkey feather fibers can reinforce PLA, excessive fiber loading compromises the composite's deformation capability. The 3 wt.% TFF composite provides the most balanced mechanical response among the reinforced samples, whereas composites containing 7 wt.% and 10 wt.% TFF exhibit the greatest loss in ductility due to restricted polymer chain mobility, increased stress concentrations, and weaker fiber-matrix interactions. The recorded findings are consistent with previous studies on natural fiber-reinforced PLA composites (Bautista et al., 2025; Majdzadeh et al., 2006; Muhammad et al., 2018), where increasing fiber content generally leads to reduced fracture displacement and increased brittleness unless appropriate fiber surface treatments or compatibilizers are employed to improve interfacial adhesion.

3.4. Effect of Fiber Content on Maximum Displacement and Tensile Behavior

All the results recorded clearly present that turkey feather fiber content has a significant influence on the tensile response of PLA-based composites, particularly in terms of maximum displacement and deformation behavior. A systematic reduction in deformation capacity is observed as the fiber loading increases, indicating a transition from a more ductile polymer-dominated response toward a more brittle composite structure.

At low fiber contents (1–3 wt.%), the composites exhibit a balanced mechanical response, where moderate reinforcement is achieved without severely compromising ductility. In particular, the 3 wt.%-reinforced TFF composite stands out as the most favorable composition, showing the highest maximum load and comparatively higher elongation among all reinforced samples. This shows that at low loadings, turkey feather fibers are more effectively embedded within the PLA matrix, enabling relatively efficient stress transfer while still allowing limited polymer chain mobility. However, when the fiber content is increased beyond 3 wt.%, a clear deterioration in tensile performance is observed. Both maximum load and maximum displacement decrease progressively, indicating reduced load-

carrying capacity and diminished deformation capability. This degradation is primarily attributed to the increasing likelihood of fiber agglomeration, non-uniform dispersion, and insufficient interfacial bonding between the hydrophobic PLA matrix and hydrophilic feather fibers. On the other hand, at higher fiber concentrations, the probability of fiber-fiber contact increases, leading to incomplete encapsulation of fibers by the polymer matrix. This results in inefficient stress transfer across the interface and promotes localized stress concentration zones. Consequently, microcrack initiation occurs at lower strain levels, and crack propagation becomes more rapid, ultimately leading to premature failure. The mechanisms discussed collectively explain the observed reduction in ductility and maximum displacement at higher fiber loadings.

All in all, the findings observed reveal that while turkey feather fibers can act as effective natural reinforcements for PLA at low concentrations, excessive fiber incorporation adversely affects the structural integrity of the composite. Therefore, an optimal fiber content of 3 wt.% is identified, where a favorable balance between reinforcement efficiency and mechanical integrity is achieved.

3.5. Change of Mechanical Behavior Belonging to Turkey Feather Fiber-Reinforced PLA

The tensile test results obtained clearly show that the incorporation of turkey feather fibers significantly influences the mechanical behavior of PLA composites. The addition of TFF altered not only the tensile strength but also the deformation characteristics of the material, resulting in a gradual transition from relatively ductile behavior toward increasingly brittle fracture with increasing fiber content. This trend is evident from the simultaneous reductions in maximum load F_{max} , elongation at break, and maximum displacement observed as the fiber loading increased. The pure PLA specimens exhibited the highest tensile strength related parameters, such as F_{max} , elongation, and fracture displacement, confirming the superior mechanical integrity and deformation capability of the unreinforced polymer. Although PLA is generally considered a brittle thermoplastic, its continuous polymer matrix allows a relatively uniform distribution of applied stresses and enables limited plastic deformation before fracture. In contrast, the introduction of turkey feather fibers disrupted the continuity of the matrix and introduced additional interfaces that influenced crack initiation and propagation.

Among all reinforced composites, the 3 wt.% TFF formulation consistently exhibited the most favorable mechanical performance. This composition produced the highest maximum load, the greatest elongation at break, and one of the highest displacement values among the reinforced specimens, indicating that this fiber concentration provides the most effective balance between reinforcement and matrix continuity. At this relatively low fiber loading, the feather fibers appear to be sufficiently dispersed within the PLA matrix,

allowing more efficient stress transfer while minimizing the formation of structural defects such as fiber agglomerates and voids. Consequently, the composite retains a reasonable degree of ductility while benefiting from the reinforcing effect of the fibers.

However, increasing the fiber content beyond 3 wt.% resulted in a progressive deterioration of tensile properties. Composites containing 5 wt.%, 7 wt.%, and particularly 10 wt.%-reinforced TFF exhibited lower maximum loads, reduced elongation at break, and smaller fracture displacements, indicating diminished tensile performance and reduced toughness. The findings obtained reveal that excessive fiber incorporation exceeds the reinforcing capability of the matrix and instead promotes defect formation within the composite. Several mechanisms may explain this behavior. Higher fiber contents increase the probability of fiber agglomeration, producing localized regions where stress is concentrated during tensile loading. In addition, insufficient wetting of closely packed fibers by the molten PLA matrix can generate voids, microcracks, and interfacial defects, all of which serve as preferential sites for crack initiation. Furthermore, the inherent incompatibility between the hydrophilic keratin structure of turkey feather fibers and the relatively hydrophobic PLA matrix limits the effectiveness of stress transfer across the interface. Under tensile loading, weak interfacial adhesion facilitates fiber pull-out and interfacial debonding, reducing the reinforcing contribution of the fibers and accelerating catastrophic failure.

The combined reductions in tensile strength, F_{max} , elongation, and displacement indicate that increasing fiber loading restricts polymer chain mobility and limits the ability of the matrix to undergo plastic deformation. Consequently, fracture occurs at lower strains and lower displacement values, showing a transition toward increasingly brittle mechanical behavior. This phenomenon is commonly observed in natural fiber-reinforced thermoplastic composites when the fiber content exceeds the optimum reinforcement level.

Accordingly, the experimental findings indicate that turkey feather fibers can function as an environmentally friendly reinforcement for PLA; however, their reinforcing efficiency is highly dependent on achieving an appropriate fiber concentration and adequate fiber-matrix interfacial bonding. The present results suggest that approximately 3 wt.% reinforcement represents the optimum reinforcement level for the composites produced in this study.

4. Conclusion

The tensile properties of PLA composites reinforced with turkey feather fibers were systematically investigated as a function of fiber loading. The results indicated that the mechanical performance of the composites is strongly influenced by the amount of fiber incorporated into the polymer

matrix. It is found that the pure PLA sample exhibited the highest tensile strength, F_{max} , elongation at break, and maximum displacement, revealing the superior mechanical integrity and deformation capability of the unreinforced polymer. The addition of turkey feather fibers generally reduced these tensile properties; however, the extent of deterioration depended on the fiber concentration. Among all reinforced specimens, the 3 wt.%-reinforced TFF composite exhibited the best mechanical performance, achieving the highest maximum load together with relatively high elongation and displacement values. This indicates that moderate fiber loading provides the most effective balance between reinforcement efficiency and preservation of matrix continuity.

In contrast, increasing the fiber content beyond 3 wt.% resulted in continuous reductions in tensile strength, ductility, and fracture displacement. These reductions are primarily attributed to fiber agglomeration, inadequate fiber dispersion, void formation, restricted polymer chain mobility, and weak interfacial adhesion between the turkey feather fibers and the PLA main matrix. These microstructural factors promote stress concentration, premature crack initiation, and brittle fracture, thereby limiting the reinforcing efficiency of higher fiber loadings.

Although untreated turkey feather fibers did not improve the tensile properties beyond those of neat PLA, the results demonstrate that they can be successfully incorporated into PLA to produce lightweight and sustainable biocomposites. The identification of 3 wt.%-reinforced material as the optimum fiber content provides valuable guidance for future material development.

Further improvements in mechanical performance are expected through fiber surface modification, alkaline or silane treatments, plasma treatment, or the incorporation of compatibilizers capable of enhancing the interfacial bonding between turkey feather fibers and the PLA matrix. Such approaches can improve strain transfer efficiency, reduce fiber clumping, and allow for higher fiber loads without compromising tensile performance. Therefore, the findings of this study provide an important basis for the development of environmentally friendly PLA-based biocomposites reinforced with poultry feather waste, contributing to both sustainable materials engineering and the valorization of agricultural by-products.

Conflict of Interest

The authors declare that they have no conflict of interest.

Disclosure of Generative AI Use

No generative artificial intelligence tools were used in the preparation of this article.

References

- Abdur Rahman, M., Haque, S., Athikesavan, M. M., & Kamaludeen, M. B. (2023). A review of environmental friendly green composites: production methods, current progresses, and challenges. *Environmental Science and Pollution Research*, 30(7), 16905-16929. <https://doi.org/10.1007/s11356-022-24879-5>
- Akdogan, E., & Soykan, U. (2025). Sustainable rigid polyurethane foam composites based on used palm oil and turkey feather fiber: structural, morphological, thermal, insulation and mechanical properties. *Clean Technologies and Environmental Policy*, 27(9), 3969-3984. <https://doi.org/10.1007/s10098-024-03080-x>
- Aranberri, I., Montes, S., Azcune, I., Rekondo, A., & Grande, H. J. (2017). Fully biodegradable biocomposites with high chicken feather content. *Polymers*, 9(11), 593. <https://doi.org/10.3390/polym9110593>
- Baba, B. O., & Özmen, U. (2017). Preparation and mechanical characterization of chicken feather/PLA composites. *Polymer Composites*, 38(5), 837-845. <https://doi.org/10.1002/pc.23644>
- Barone, J. R., & Schmidt, W. F. (2005). Polyethylene reinforced with keratin fibers obtained from chicken feathers. *Composites Science and Technology*, 65(2), 173-181. <https://doi.org/10.1016/j.compscitech.2004.06.011>
- Bautista, B. E., De Gracia, E. H., Cacanando, C. J. D., & Leño, J. L. (2025). *Comparison of the tensile behavior of coated vs uncoated bamboo (Bambusa blumeana JA & JH Schultes) textile reinforced mortar (TRM)*. The 5th International Symposium on Concrete and Structures for the Next Generation (CSN2025)At: The Verdure, Henry Sy Sr. Hall, De La Salle University. Manila.
- Chen, E., & Turng, L. S. (2024). A double-expanded polytetrafluoroethylene fabrication method for increased mechanical compliance in tubular vascular graft applications. *Polymer Engineering & Science*, 64(4), 1756-1769. <https://doi.org/10.1002/pen.26652>
- Dhaou, I., & Mnif, R. (2026). Flexural, dynamic mechanical, and rheological properties of date palm fiber-reinforced PLA composites. *Fibers and Polymers*, 27, 3447-3463. <https://doi.org/10.1007/s12221-026-01430-8>
- Dutta, H., Bora, D., Chetia, P., Bharadwaj, C., Purbey, R., Bohra, R. C., Dutta, K., Varada Rajulu, A., Sadiku, E. R., Periyar Selvam, S., Gurusamy, P., Rawal, R. K., & Jayaramudu, J. (2024). Biopolymer composites with waste chicken feather fillers: A review. *Renewable and Sustainable Energy Reviews*, 197, 114394. <https://doi.org/10.1016/j.rser.2024.114394>
- Ghorbal, A., Sdiri, A., & Elleuch, B. (2019). Green approaches for materials, wastes, and effluents treatment. *Environmental Science and Pollution Research*, 26(32), 32675-32677. <https://doi.org/10.1007/s11356-019-06848-7>

- Hernández-Díaz, D., Villar-Ribera, R., Julián, F., Tarrés, Q., Espinach, F. X., & Delgado-Aguilar, M. (2020). Topography of the interfacial shear strength and the mean intrinsic tensile strength of hemp fibers as a reinforcement of polypropylene. *Materials*, 13(4), 1012. <https://doi.org/10.3390/ma13041012>
- Hinchcliffe, S. A. (2015). *Feasibility study of prestressed natural fiber-reinforced polylactic acid (PLA) composite materials* (Master's thesis, Colorado at Boulder University).
- Kesentini, Z., El Mahi, A., Rebiere, J. L., El Guerjouma, R., Beyaoui, M., & Haddar, M. (2022). Static and fatigue tensile behavior and damage mechanisms analysis in aged flax fiber/PLA composite. *International Journal of Applied Mechanics*, 14(08), 2250080. <https://doi.org/10.1142/S1758825122500806>
- Khakalo, A., Vishtal, A., Retulainen, E., Filpponen, I., & Rojas, O. J. (2017). Mechanically-induced dimensional extensibility of fibers towards tough fiber networks. *Cellulose*, 24(1), 191-205. <https://doi.org/10.1007/s10570-016-1102-z>
- Khan, A. A., Parikh, H., & Qureshi, M. R. N. (2022). A review on chicken feather fiber (CFF) and its application in composites. *Journal of Natural Fibers*, 19(16), 12565-12585. <https://doi.org/10.1080/15440478.2022.2073495>
- Kilinc, A. C. (2025). Additive manufacturing and characterization of continuous nettle fiber-reinforced PLA composites. *Polymers*, 17(17), 2388. <https://doi.org/10.3390/polym17172388>
- Ljungberg, N., Cavailé, J. Y., & Heux, L. (2006). Nanocomposites of isotactic polypropylene reinforced with rod-like cellulose whiskers. *Polymer*, 47(18), 6285-6292. <https://doi.org/10.1016/j.polymer.2006.07.013>
- Majdzadeh, F., Soleimani, S. M., & Banthia, N. (2006). Shear strength of reinforced concrete beams with a fiber concrete matrix. *Canadian Journal of Civil Engineering*, 33(6), 726-734. <https://doi.org/10.1139/105-118>
- Mann, G. S., Azum, N., Khan, A., Rub, M. A., Hassan, M. I., Fatima, K., & Asiri, A. M. (2023). Green composites based on animal fiber and their applications for a sustainable future. *Polymers*, 15(3), 601. <https://doi.org/10.3390/polym15030601>
- Masirek, R., Kulinski, Z., Chionna, D., Piorowska, E., & Pracella, M. (2007). Composites of poly (L-lactide) with hemp fibers: Morphology and thermal and mechanical properties. *Journal of Applied Polymer Science*, 105(1), 255-268. <https://doi.org/10.1002/app.26090>
- Morabiya, D., & Joshi, H. (2026). Natural fiber-reinforced PLA composites for fused deposition modeling: A critical assessment and experimental feasibility of jute fiber reinforcement. *ITEGAM-JETIA*, 12(59), 611-624. <https://doi.org/10.5935/jetia.v12i59.3533>
- Mrajji, O., El Wazna, M., El Bouari, A., & Cherkaoui, O. (2022). The properties of feather fiber-reinforced polymer composites: A review. *Journal of Natural Fibers*, 19(13), 4868-4885. <https://doi.org/10.1080/15440478.2020.1870633>
- Muhammad, A., Rashidi, A. R., & Buddin, M. M. H. S. (2018). Effect of coconut fiber reinforcement on mechanical properties of corn starch bioplastics. *International Journal of Engineering and Technology*, 7(4.18), 267-270.
- Murariu, M., & Dubois, P. (2016). PLA composites: From production to properties. *Advanced Drug Delivery Reviews*, 107, 17-46. <https://doi.org/10.1016/j.addr.2016.04.003>
- Nur Ainin, F., Azaman, M. D., Abdul Majid, M. S., & Ridzuan, M. J. M. (2022). Low-velocity impact behavior of sandwich composite structure with 3D printed hexagonal honeycomb core: varying core materials. *Functional Composites and Structures*, 4(3), 035007. <https://doi.org/10.1088/2631-6331/ac8d7a>
- Radkar, S. S., Amiri, A., & Ulven, C. A. (2019). Tensile behavior and diffusion of moisture through flax fibers by desorption method. *Sustainability*, 11(13), 3558. <https://doi.org/10.3390/su11133558>
- Rahman, M. A., Rahman, M. Z., Nag, R. K., Debnath, S., Al Rafi, H., Suad, M. R., Al Bashar, A., & Dev, B. (2026). Biocomposites reinforced with cellulose-rich snake plant and *Sesbania aculeata* lignocellulosic fibers: Fabrication, property optimization and structure-performance relationships. *Materials Today Communications*, 52, 115110. <https://doi.org/10.1016/j.mtcomm.2026.115110>
- Rajendran, S., Al-Samydai, A., Palani, G., Trilaksana, H., Sathish, T., Giri, J., Saravanan, R., Isaac Joshua Ramesh Lalvani, J., & Nasri, F. (2025). Replacement of petroleum based products with plant-based materials, green and sustainable energy—a review. *Engineering Reports*, 7(4), e70108. <https://doi.org/10.1002/eng.2.70108>
- Rapoport, J., Aldea, C. M., Shah, S. P., Ankenman, B., & Karr, A. (2002). Permeability of cracked steel fiber-reinforced concrete. *Journal of Materials in Civil Engineering*, 14(4), 355-358. [https://doi.org/10.1061/\(ASCE\)0899-1561\(2002\)14:4\(355\)](https://doi.org/10.1061/(ASCE)0899-1561(2002)14:4(355))
- Rashid, A. A., Ikram, H., & Koc, M. (2023). Effect of carbon fiber reinforcement on dimensional variations of 3D printed polyamide-6 composites: A simulation study. *Turkish Journal of Chemistry*, 47(1), 33-39. <https://doi.org/10.55730/1300-0527.3513>
- Reddy, C. C., Khilji, I. A., Gupta, A., Bhuyar, P., Mahmood, S., AL-Japairai, K. A. S., & Chua, G. K. (2021). Valorization of keratin waste biomass and its potential applications. *Journal of Water Process Engineering*, 40, 101707. <https://doi.org/10.1016/j.jwpe.2020.101707>

- Run-ke, H., Shu-guang, L., Li-hui, D., Jun-qing, Y., & Fei, H. (2018). Tunnel lining reinforced with carbon fiber: Effect simulation and construction technique. *Journal of Changjiang River Scientific Research Institute*, 35(11), 69-75. <https://doi.org/10.11988%2Fckyyb.20170536>
- Sandeep, M. P., Rudresh, B. M., Kumar, M. P., Kumar, M. P., Lingesh, B. V., Naik, N. C. K., & Emma, A. F. (2026). Exploring the effect of higher loading of short carbon fibers on mechanical and physico-mechanical characterization of polyamide66 and polytetrafluoroethylene blend composites. *Scientific Reports*. <https://doi.org/10.1038/s41598-026-53792-x>
- Sayed, U., Dauletbek, A., Xin, X., Lorenzo, R., & Li, H. (2022). A review on the mechanical behaviour of bamboo reinforced concrete beams. *Journal of Renewable Materials*, 10(12), 3629-3657. <https://doi.org/10.32604/jrm.2022.022624>
- Shankar, A. N., & Netravali, A. N. (2025). Mechanical properties of chicken feather modified soy protein-based resins and jute fabric-reinforced green composites. *Polymer Composites*, 46(6), 5517-5531. <https://doi.org/10.1002/pc.29308>
- Singhal, A. V., Debnath, K., Singh, I., & Daniel, B. S. S. (2016). Critical parameters affecting mechanical behavior of natural fiber reinforced plastics. *Journal of Natural Fibers*, 13(6), 640-650. <https://doi.org/10.1080/15440478.2015.1102788>
- Siqueira, G., Tapin-Lingua, S., Bras, J., da Silva Perez, D., & Dufresne, A. (2011). Mechanical properties of natural rubber nanocomposites reinforced with cellulosic nanoparticles obtained from combined mechanical shearing, and enzymatic and acid hydrolysis of sisal fibers. *Cellulose*, 18(1), 57-65. <https://doi.org/10.1007/s10570-010-9463-1>
- Soykan, U. (2022). Development of turkey feather fiber-filled thermoplastic polyurethane composites: Thermal, mechanical, water-uptake, and morphological characterizations. *Journal of Composite Materials*, 56(2), 339-355. <https://doi.org/10.1177/00219983211056137>
- Soykan, U., Khaleel, M., Cetin, S., Yahsi, U., & Tav, C. (2022). Investigation of the relation between free volume and physico-mechanical performance in rigid polyurethane foam containing Turkey feather fibers: Part 2. *Journal of Cellular Plastics*, 58(6), 893-915. <https://doi.org/10.1177/0021955X221144541>
- Srinara, T., Lowrattanaounjit, N., & Chaochanchaikul, K. (2020). Improvement of mechanical properties of polylactic acid/oil palm fiber composites by alkali treatment. *Applied Mechanics and Materials*, 901, 73-78. <https://doi.org/10.4028/www.scientific.net/AMM.901.73>
- Talimi, M. (2011). *Characterization of natural fibre reinforced biodegradable composites* (Doctoral dissertation, Ontario Institute of Technology University).
- Trinh-Duc, D., Piotrowski, A., Ajdukiewicz, C., Woyciechowski, P., & Gajewski, M. (2021). Estimation of post-cracking dissipation capabilities of fiber reinforced concretes in three point bending test monitored with application of digital image correlation system. *Materials*, 14(17), 5088. <https://doi.org/10.3390/ma14175088>
- Trivedi, A. K., Gupta, M. K., & Singh, H. (2023). PLA based biocomposites for sustainable products: A review. *Advanced Industrial and Engineering Polymer Research*, 6(4), 382-395. <https://doi.org/10.1016/j.aiepr.2023.02.002>
- Yan, Z. W., Bai, Y. L., & Zhou, Q. C. (2025). Dynamic tensile properties of flax fiber reinforced polymer composites. *Journal of Reinforced Plastics and Composites*, 44(15-16), 926-938. <https://doi.org/10.1177/07316844241233156>
- Yiga, V. A., Lubwama, M., Pagel, S., Olupot, P. W., Benz, J., & Bonten, C. (2023). Optimization of tensile strength of PLA/clay/rice husk composites using Box-Behnken design. *Biomass Conversion and Biorefinery*, 13(13), 11727-11753. <https://doi.org/10.1007/s13399-021-01971-3>
- Zhang, X., Chen, L., Mulholland, T., & Osswald, T. A. (2019). Effects of raster angle on the mechanical properties of PLA and Al/PLA composite part produced by fused deposition modeling. *Polymers for Advanced Technologies*, 30(8), 2122-2135. <https://doi.org/10.1002/pat.4645>
- Zheng, S. (2000). *The effect of interphase and interfacial cracks on the elastic and elastoplastic behavior of fiber-reinforced composites* (Doctoral dissertation, Rutgers The State University).