MECHANICAL CHARACTERIZATION OF ARTOCARPUS ELASTICUS SKIN BASED BIOCOMPOSITE WITH TIO_2 VARIATION FOR AUTOMOTIVE APPLICATIONS

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Summary: This study investigates biocomposites reinforced with *Artocarpus elasticus* (Lantung) bark fibers and titanium dioxide (TiO_2) nanoparticles to develop sustainable automotive materials. Natural fiber composites typically suffer from lower mechanical stiffness compared to synthetic counterparts. This study solves this by optimizing TiO_2 filler concentrations to enhance tensile and flexural properties without compromising the eco-friendly nature of the material. Mechanical testing revealed that a 1% TiO_2 concentration yielded the highest tensile strength of 26.56 MPa. Conversely, increasing the filler to 5% maximized flexural strength at 45.52 MPa and modulus at 5.54 GPa, significantly outperforming the unfilled samples. The superior tensile performance at 1% TiO_2 is explained by optimal particle dispersion, which improves fiber-matrix adhesion and load transfer. At higher concentrations (3–5%), particle agglomeration creates stress points that reduce tensile strength but simultaneously forms a rigid particulate network that resists bending deformation, thus enhancing stiffness. A distinctive feature of this study is the identification of a performance trade-off: low filler content favors tensile applications, while high filler content favors flexural stiffness. This allows for precise material engineering based on specific component requirements, a capability often lacking in generic biocomposite studies. The resulting biocomposites are highly suitable for semi-structural automotive interior components such as dashboard panels (requiring high stiffness) and door trims (requiring tensile integrity), offering a viable, lightweight, and biodegradable alternative to conventional ABS plastics.

Keywords: biocomposite, *Artocarpus elasticus*, Titanium dioxide, tensile strength, flexural strength, automotive material, natural fiber, polymer matrix, nanocomposite, hand lay-up.

1. Introduction

The increasing amount of plastic waste and synthetic materials derived from petroleum has become a major concern in the automotive industry due to environmental pollution issues. This situation has driven the search for more environmentally friendly alternative materials, with the life cycle assessment (LCA) approach being utilized to evaluate the overall product impact [1]. The urgency for developing environmentally sustainable materials in the automotive sector is further underscored by a series of recent reviews confirming the increasing adoption and potential of natural fiber-based biocomposites for automotive components, owing to their low density, renewability, and environmental compatibility, despite ongoing challenges regarding mechanical performance and consistency [2, 3]. One of the most rapidly developing materials is the natural fiber-based biocomposite, which offers biodegradability, lightweight characteristics, renewability, and a low carbon footprint [4, 5]. This type of biocomposite has strong potential for structural and semi-structural applications in the automotive sector [6], and current advancements even point toward nanobiocomposites, wherein natural fibers and nanoscale fillers like TiO_2 are combined to improve not just strength, but functionality such as thermal stability, biodegradability, and flame retardancy for automotive, aerospace, and construction products [7].

Synthetic materials such as ABS plastics and glass fiber composites are still commonly used in automotive body kits. However, they are environmentally unfriendly and difficult to degrade. Thus, utilizing natural fibers as an alternative also supports the circular economy and reduces carbon emissions [8, 9]. One promising source of natural fibers is lantung bark (Artocarpus elasticus), an agro-industrial byproduct abundantly available in Indonesia. It contains hemicellulose (22.28%), cellulose (21.34%), lignin (16.15%), and ash (23.32%), providing good compatibility within polymer matrices [10].

While natural fiber composites are attractive eco-friendly replacements, their lower mechanical performance particularly toughness, stiffness, and resistance to moisture remain a crucial challenge when compared to widely used glass and carbon fiber composites in automotive applications. Studies have shown that hybridization with synthetic fibers or resin modification may improve performance, but full sustainability requires biocomposite systems with properties rivaling those of synthetics while maintaining biodegradability and cost efficiency [7]. Numerous studies over the past five years affirm that, although advances have been made, biocomposites based on natural fibers generally still exhibit inferior tensile strength, modulus, and impact resistance compared to glass and carbon fiber-reinforced composites thereby representing a fundamental research gap in their application for high-end automotive parts [11, 12].

A recent study further highlights the great potential of Artocarpus elasticus (Lantung bark) fibers as reinforcement in biocomposites by demonstrating that alkali treatment, specifically with optimized NaOH concentrations, not only removes surface impurities like lignin and hemicellulose but also significantly enhances fiber-matrix adhesion and overall mechanical performance compared to untreated fibers. The study found that composites fabricated with Lantung fibers treated using a 2% NaOH solution achieved the highest tensile and flexural properties, outperforming higher NaOH concentrations due to the preservation of fiber integrity and improved load transfer efficiency. These findings underscore how fiber surface modification strategies can maximize the structural capabilities of natural-fiber biocomposites for automotive applications, supporting the development of stronger, more sustainable alternatives to conventional plastics and glass fiber composites [13].

However, natural fiber biocomposites generally exhibit lower mechanical properties, such as tensile strength and stiffness, compared to synthetic composites. The incorporation of inorganic fillers such as titanium dioxide (TiO_2) nanoparticles has shown potential to improve stiffness, thermal stability, and durability without compromising biocompatibility [14, 15]. Excessive TiO_2 concentration may cause particle agglomeration and reducing strength. Therefore, optimization of filler content is crucial [16–18]. The hand lay-up method, which is widely used in the automotive panel industry, exhibits satisfactory dispersion of both fibers and nanoparticles if the process is carefully managed [19].

The widely used hand lay-up technique can produce products with efficient distribution of particles and uniform fiber orientation, meeting the complex requirements of automotive body kits [20]. Nevertheless, in-depth research related to optimizing TiO_2 content and understanding the contribution of microstructural aspects to the mechanical performance of lantung bark biocomposites remains limited in the literature.

However, while there is ample evidence of general benefits from TiO_2 and natural fiber combinations, there is limited specific research exploring the optimized content and microstructure-property relationships for lantung bark-based nanobiocomposites, especially in automotive body kit applications. There is also a lack of comprehensive studies comparing various TiO_2 loading levels on tensile and flexural performance, as well as a nuanced exploration of processing techniques and fiber treatments tailored to Indonesian agro-waste fibers.

Consequently, comprehensive exploration and optimization of natural fiber–TiO_2 nanobiocomposite systems remain an urgent area of study, as emphasized in several recent reviews, particularly concerning their microstructural, mechanical, and long-term durability characteristics in the context of automotive lightweighting and sustainability targets. This study aims to fill that gap by developing and characterizing Artocarpus elasticus skin-based biocomposites reinforced with TiO_2 particles at varying concentrations, evaluating the effects on tensile and flexural properties through experimental testing, and rigorously assessing their feasibility for sustainable automotive applications.

2. Materials and methods

2. 1. Materials

Dried Artocarpus elasticus skin fibers were sourced locally from traditional craftsmen. The fibers were manually beaten to uniform thickness, cut to size, and used directly without further chemical treatment. Oven-dried at 103°C for 24 hours to reduce the moisture content. Polyester resin (Yukalac 157) was used as the matrix, catalyzed with 4% MEPOXE by weight of the resin. Titanium dioxide (TiO_2) micro powders with ≥ 99% purity were employed as reinforcement filler at concentrations of 1%, 3%, and 5% by resin weight. Detailed particle size and morphology data were not available.

2. 2. Fabrication procedure

The composite fabrication employed the hand lay-up method. TiO_2 powder was mechanically stirred into the polyester resin at 300 rpm for 30 minutes to ensure homogeneous dispersion before the addition of catalyst. Fiber mats were layered three times, each impregnated with the resin-TiO_2 mixture, and subjected to compression at 3 MPa for 30 minutes. Specimens were cured at ambient temperature for 7 days (approximately 30 ± 2°C).

2. 3. Mechanical testing

Tensile testing was conducted on specimens measuring 162 × 18 × 3 mm according to ASTM D339, and flexural testing on specimens 105 × 15 × 3 mm per ASTM D7264 standards. Tests were performed using Shimadzu AGS-X Series 10 kN universal testing machine at crosshead speeds of 10 mm/min (tensile) and 10 mm/min (flexural). For each TiO_2 concentration, three independent composite panels were fabricated, and tested from each panel (total n = 3 per condition). Specimens were visually inspected prior to testing and those showing defects like voids or cracks were excluded to ensure quality control. Average tensile strength, tensile modulus, flexural strength, and flexural modulus were reported with standard deviations. All experimental workflow is summarized in **Fig. 1**.

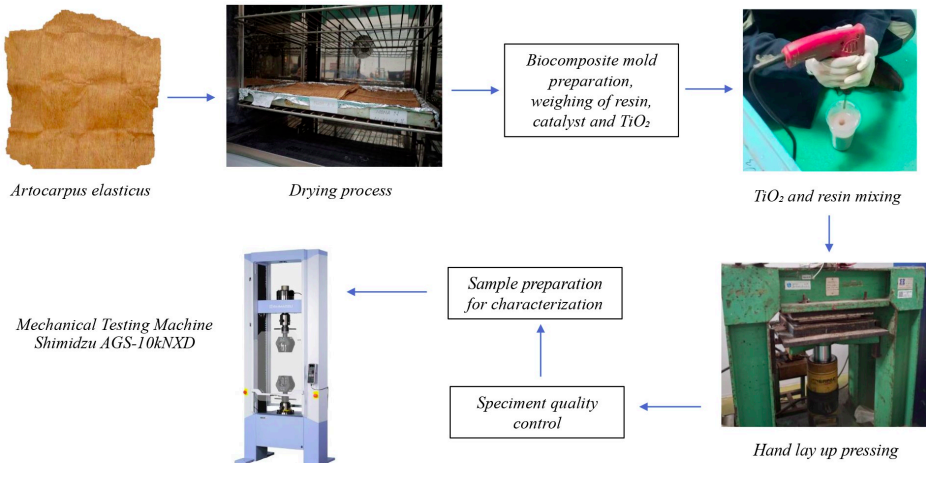


Fig. 1. Schematic flow of the preparation and characterization process of *Artocarpus elasticus* skin-based biocomposite reinforced with TiO_2

3. Results and discussion

3. 1. Tensile properties

Tensile testing was performed to determine the maximum tensile strength and tensile modulus of elasticity of the lantung skin biocomposite. Analysis of the tensile modulus of elasticity was conducted within the force range of 1–6 MPa. **Fig. 2** shows the tensile test specimens for each TiO_2 concentration.

The highest tensile strength at 1% TiO_2 is attributed to uniform filler dispersion and optimal matrix-fiber bonding, allowing even distribution of applied stress and preventing localized failure. In this scenario, TiO_2 particles bridge the polymer and fiber phases, enhancing load transfer and delaying crack initiation. When TiO_2 content rises to 3% with 12.80 ± 5.63 MPa for tensile strength and 1.03 ± 0.09 GPa for tensile modulus, particles aggregate (agglomerate), forming weak points or stress concentration zones that act as crack initiation sites. The resin's ability to 'wet' and encapsulate each particle is exceeded, which undermines overall matrix coherence and leads to a drop in tensile strength. At 5% with 17.88 ± 6.44 MPa for tensile strength and 0.90 ± 0.20 GPa for tensile modulus, some TiO_2 continues to function as crack stoppers, so a partial strength recovery occurs, but agglomeration still limits overall performance compared with the optimal 1% content with 26.56 ± 10.32 MPa for tensile strength and 1.09 ± 0.09 GPa for tensile modulus. This phenomenon is widely observed in natural fiber–polymer composites with inorganic additions, where exceeding a threshold filler load reverses reinforcement benefits due to mixing and interfacial effects [21]. **Table 1** presented the tensile test results for Artocarpus elasticuss skin-based biocomposite with TiO_2 reinforcement.

The tensile strength peaked at 26.56 MPa with 1% TiO_2 content, exceeding values reported for ABS plastics (~18.9 MPa) and some natural fiber composites [21–24] as seen in **Fig. 3**. Increasing TiO_2 to 3% caused a significant decline to 12.8 MPa, attributed to particle agglomeration disrupting fiber-matrix

bonding and introducing stress concentration points. At 5%, a slight tensile strength recovery to 17.88 MPa occurred, likely due to filler acting as crack propagation barriers but remaining inferior to the optimal 1% loading.

In **Fig. 4**, the tensile modulus showed minimal variation (~0.9–1.1 GPa) across all concentrations, suggesting TiO_2 predominantly influences strength rather than stiffness at tested loadings.



a *b* *c*

Fig. 2. Tensile test samples of lantung skin biocomposite with varying TiO_2 concentrations: *a* – 1%; *b* – 3%; *c* – 5%

Table 1

Artocarpus elasticuss skin-based biocomposite with TiO_2 reinforcement variation tensile results

Samples	Replications	Tensile strength (MPa)	Average	Tensile modulus (GPa)	Average
TiO_2 1%	1	34.02	26.56 ± 10.32	1.009	1.09 ± 0.09
	2	30.88		1.187	
	3	14.78		1.06	
TiO_2 3%	1	7.84	12.80 ± 5.63	0.931	1.03 ± 0.09
	2	11.66		1.108	
	3	18.91		1.059	
TiO_2 5%	1	17.98	17.88 ± 6.44	0.981	0.90 ± 0.20
	2	24.27		1.047	
	3	11.39		0.677	

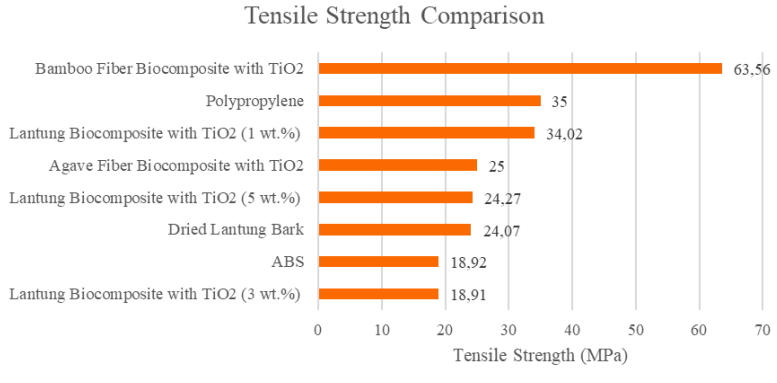


Fig. 3. Comparison chart of TiO_2 reinforced lantung skin biocomposite tensile strength with reference materials [21–24]

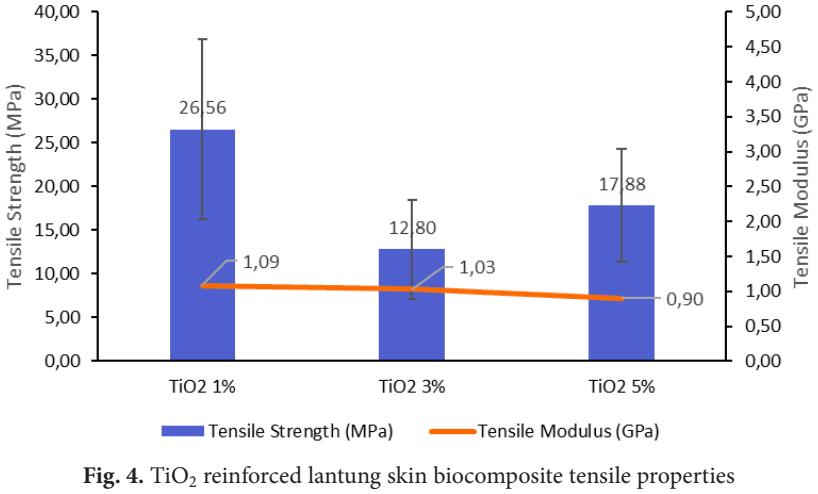


Fig. 4. TiO_2 reinforced lantung skin biocomposite tensile properties

3. 2. Flexural properties

The bending modulus was analyzed in the force range of 0–1.4 N, **Fig. 5** shows the bending test samples of specimens for each TiO_2 concentration.

Flexural strength increased continuously with TiO_2 concentration, achieving a maximum of 45.52 ± 20.20 MPa at 5%, indicating enhanced composite stiffness from particle reinforcement. The corresponding flexural modulus also peaked at 5.54 ± 3.08 GPa for 5% TiO_2, more than 4 times higher than the 1% filler level (0.95 ± 0.81 GPa). These improvements reflect better load transfer efficiency and resistance to bending deformation. **Table 2** presented the bending test results for artocarpus elasticuss skin-based biocomposite with TiO_2 reinforcement.

The continuous increase of flexural strength up to 5% TiO_2 is related to the rigid, particulate nature of titanium dioxide, which enhances the composite's resistance to bending deformation. Particles effectively restrict matrix mobility, thereby raising stiffness. Micro-fillers bridge gaps and distribute applied force more efficiently in bending situations, counteracting the decline in tensile strength due to agglomeration. Even as agglomerates emerge, the structure benefits from a stiffer backbone, making the material more resistant to flexure. The trend signifies different fracture mechanics under tensile and flexural loading. Bending is less sensitive to matrix crack concentration than tension, so more particulate reinforcement results in improved bending even if tensile behavior declines. As illustrated in **Fig. 6**, both bending strength and bending modulus of the Artocarpus elasticus biocomposites increase with higher TiO_2 content, reaching their peaks at 5% TiO_2, where the bending strength is 56.40 MPa and the modulus jumps significantly to 5.54 GPa, demonstrating the reinforcing effect of TiO_2 on the composite's flexural performance.

Comparisons with polypropylene and ABS materials in **Fig. 7** reveal that the biocomposites bending performance competes with or surpasses these widely used synthetics [24, 25].



a *b* *c*

Fig. 5. Bending test samples of lantung skin biocomposite with varying TiO_2 concentrations: *a* – 1%; *b* – 3%; *c* – 5%

Table 2

Artocarpus elasticuss skin-based biocomposite with TiO_2 reinforcement variation bending results

Samples	Replications	Bending strength (MPa)	Average	Bending modulus (GPa)	Average
TiO_2 1%	1	51.62	36.41 ± 13.76	1.85	0.95 ± 0.81
	2	24.82		0.74	
	3	32.80		0.27	
TiO_2 3%	1	32.33	42.29 ± 15.34	0.32	0.84 ± 0.66
	2	34.57		0.62	
	3	59.96		1.58	
TiO_2 5%	1	63.70	45.52 ± 20.20	8.84	5.54 ± 3.08
	2	49.10		5.03	
	3	23.78		2.75	

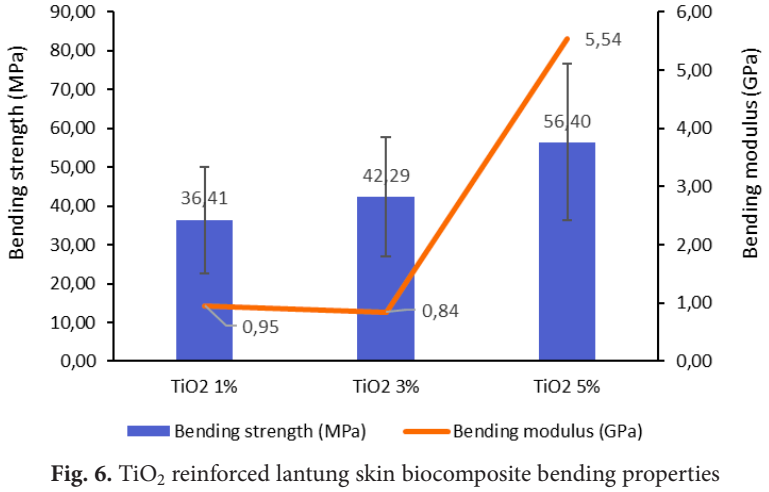


Fig. 6. TiO_2 reinforced lantung skin biocomposite bending properties

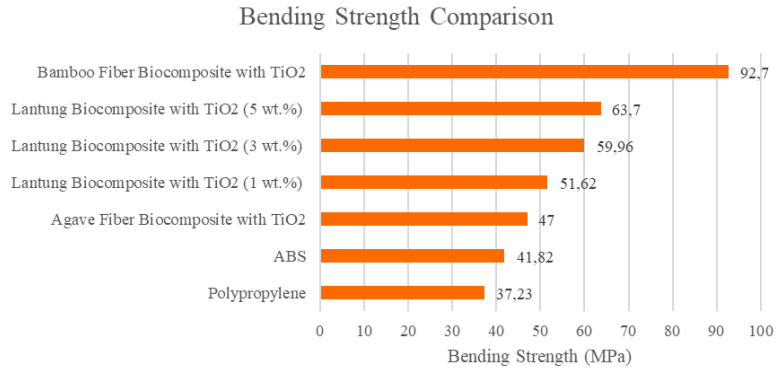


Fig. 7. Comparison chart of TiO_2 reinforced lantung skin biocomposite bending strength with reference materials [21, 22, 25, 26]

3. 3. Mechanistic insights

The mechanical testing results clearly demonstrate the significant impact of TiO_2 addition on the tensile and flexural properties of Artocarpus elasticus-based biocomposites. The optimal performance was observed at a TiO_2 concentration of 1%, yielding the highest average tensile strength (26.56 MPa) and a competitive tensile modulus (1.09 GPa). This result surpasses both the reference ABS plastic and natural fiber biocomposites such as agave with higher TiO_2 content. The marked improvement at 1% TiO_2 can be attributed to the effective dispersion of filler particles, which promotes strong matrix-fiber adhesion, ensuring efficient load transfer during mechanical loading. This is supported by findings that uniform TiO_2 distribution reduces stress concentration, thereby increasing tensile strength in natural fiber composites [27]. Furthermore, research has concurred that nanoparticle dispersion critically influences matrix-fiber interfaces, resulting in improved tensile and flexural properties [17].

At higher concentrations (3% and 5% TiO_2), a pronounced decrease in tensile strength was recorded. This decline is consistent with the phenomenon of particle agglomeration – a widely reported challenge when incorporating high levels of inorganic filler into polymeric matrices. Particle agglomeration creates stress concentration points that initiate microcracks, compromising composite integrity. Despite a moderate recovery in tensile strength at 5% TiO_2, the value (17.88 MPa) did not reach that of the 1% concentration, highlighting the delicate balance needed to optimize filler content to maximize mechanical reinforcement while minimizing defects [17, 22]. Supporting this, it has been highlighted in previous research that excessive filler loading leads to poor dispersion and agglomeration, which generate flaws and voids at the filler-matrix interface, weakening stress transfer and causing tensile strength reduction [28].

Flexural test results exhibited a distinct trend while all TiO_2-containing composites outperformed ABS and polypropylene in bending strength, the highest value (45.52 MPa, modulus 5.54 GPa) was achieved at 5% TiO_2. This suggests that, despite some particle agglomeration, the presence of rigid TiO_2 domains can still hinder crack propagation under flexural load and increase the composite's stiffness. Nonetheless, this mechanical reinforcement comes at the expense of ductility, with the elevated standard deviation in flexural data indicative of sample heterogeneity likely caused by imperfect particle dispersion at high filler content. Such observations are consistent with previous findings, which reported increased brittleness and mechanical variability due to agglomeration [28].

Comparison to both untreated lantung-based composites and other natural fiber composites reveals the competitive performance of the 1% TiO_2 system in tensile strength and the 5% TiO_2 system in flexural rigidity. For example, the highest reported strength of agave biocomposite with 10% TiO_2 was on par with the best-performing lantung systems on this research. Still, optimal properties were only achievable when filler content was controlled to avoid agglomeration, reinforcing the critical importance of filler dispersion and interfacial engineering in composite optimization.

It should be noted that the absence of direct morphological (3D/SEM) analysis in this study limits the capacity to visually correlate microstructural features such as particle agglomeration, voids, or fiber/matrix bonding quality with mechanical results. As evidenced in the referring article, 3D microscope imaging or SEM provides crucial insights into these correlations, validating the performance trends observed in mechanical testing. Future work should incorporate such microstructural analysis to strengthen mechanistic explanations and guide process improvements.

Moreover, while the current mechanical property values suggest that lantung/TiO_2 biocomposites are feasible alternate candidates for body kit and interior automotive applications, additional studies are recommended to assess durability under various environmental and operational conditions (e.g., humidity, UV, fatigue, and thermal aging). Practical scaling, life-cycle environmental analyses, and functional tests should also be explored to confirm industrial viability.

3. 4. Suitability for automotive applications

While this study confirms the lightweight and ecofriendly nature of lantung bark-based biocomposites reinforced with TiO_2 fillers, asserting their direct applicability in automotive body kits necessitates a multidimensional evaluation. The mechanical properties achieved indicate potential for semi-structural interior components rather than primary load bearing exterior panels due to tensile limitations at higher filler loads. Moreover, their biodegradability and low carbon footprint align well with increasing automotive industry mandates for sustainable materials. However, practical deployment demands that these composites meet rigorous safety, durability, and thermal stability standards. Here, the influence of particle agglomeration on the reproducibility of mechanical properties suggests that process control and filler optimization are critical for industrial scalability.

Furthermore, the compatibility with existing automotive manufacturing techniques (e.g., hand lay-up) is advantageous but limited by production throughput and material homogeneity challenges. In sum, the optimized TiO_2-biocomposite system presents a promising material for lightweight, sustainable automotive applications provided that future work addresses durability, environmental degradation, and comprehensive simulation of in-service conditions.

4. Conclusion

Artocarpus elasticus skin-based biocomposites reinforced with titanium dioxide demonstrate promising mechanical properties for sustainable automotive materials such as dashboard or door trim. The optimal TiO_2 concentration of 1% delivers maximum tensile strength, while 5% improves flexural strength significantly. Particle agglomeration at higher TiO_2 levels compromises tensile properties but enhances bending stiffness. These results validate the material's competitiveness with conventional polymers like ABS and polypropylene while offering environmental benefits.

In conclusion, based on the research findings and supported by recent literature, the optimal TiO_2 concentration for maximizing tensile strength without compromising structural integrity is approximately 1%. At this level, the dispersion of particles is effectively maintained, promoting stronger matrix-fiber interfacial bonding and efficient load transfer, thus serving as the main contribution of this study toward developing sustainable automotive biocomposites. Still, property maximization depends critically on balancing filler content to achieve uniform dispersion, strong interfacial adhesion, and minimized structural defects. These findings underscore the broader significance of filler-matrix interactions in biocomposite engineering and provide a valuable platform for subsequent technological development and ecofriendly material innovation in the automotive sector.

Future research should focus on advanced microstructural characterization (SEM/3D imaging), impact and thermal testing to validate longterm application in automotive environments. Scaling up fabrication and lifecycle analysis is recommended for commercial viability. Additionally, numerical simulation (e.g., ANSYS) can aid in optimizing composite design for complex automotive geometries, ensuring reliability and durability under real service conditions. All datasets are available upon request, and the authors declare no conflict of interest.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the study, obtaining and using its results, as well as any non-financial personal relationships.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

Model and number of AI: ChatGPT-4o (OpenAI). Where exactly it was used: In the "Introduction" and "Discussion" sections of the manuscript. What exactly was done using AI tools: The AI tool was used solely for paraphrasing and grammar correction to improve the clarity, flow, and readability of the English text. Specifically, draft paragraphs were input into the tool with the prompt "improve grammar and academic tone". How the authors checked the results: The authors manually reviewed every sentence generated by the AI to ensuring that the scientific meaning, data interpretation, and technical terminology remained accurate and unchanged from the original draft. How the result provided by the AI tool influenced the conclusions: The AI tool did not generate any data, analyze results, or formulate conclusions. Its influence was strictly limited to linguistic improvements; thus, it had no impact on the scientific findings or conclusions of the study.

Authors' contributions

Sulaksana Permana: Conceptualization, Methodology, Writing – original draft, supervision; **Ryan Anggoro Patty**: Investigation, Data curation; **Tri Mulyanto:** Validation, Formal analysis; **Firda Aulya Syamani**: Resources, Writing – review & editing.

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