Wear properties of waste silk fibre reinforced PLA bio composites using taguchi technique

Ram Subbiah¹*, B. Krishna Kumar², T Sathish³, M. Ravichandran⁴, V. Mohanavel⁵, T. Raja⁶

¹Department of Mechanical Engineering, Gokaraju Rangaraju Institute of Engineering and Technology, Hyderabad, Telangana 500090
²Department of Mechanical Engineering, Chennai Institute of Technology, Chennai – 600069, Tamil Nadu, India.
³Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai – 602 105, Tamil Nadu, India.
⁴Department of Mechanical Engineering, K.Ramakrishnan College of Engineering, Trichy-621112, Tamilnadu, India.
⁵Centre for Materials Engineering and Regenerative Medicine, Bharath Institute of Higher Education and Research, Chennai - 600073, Tamilnadu, India.
⁶Department of Mechanical Engineering, Vel Tech Rangarajan Dr.Sagunthala R&D Institute of Science and Technology, Chennai - 600062, Tamilnadu, India.

*Corresponding author mail ID: ram4msrm@gmail.com

Abstract: In the last two decades, composites that are biodegradable and environmentally friendly are becoming more popular. In this paper, Biodegradable polyactic acid (PLA) biocomposites reinforced with waste silk fiber were fabricated using the hot molding technique. PLA bio-composites containing silk fibers had better wear properties, according to the findings. For superior properties, the fiber content of 30% by weight is ideal. A silk-based biodegradable composite with enhanced mechanical and wear properties can be designed due to this research. Taguchi’s L25 orthogonal array was used to study sliding speed (S), wear load (L), fiber loading (F), and abrasive distance (D). The ANOVA results found that the abrading distance was the most significant parameter, with load, sliding velocity, and fiber loading in order of importance.

Keywords: Hand layup, PLA, Taguchi Method, Wear, Optimization.

1. Introduction
In the highly developed culture of the human beings, all mainly depend on the usage of the composite materials for many aspects of our lives. A Composite material is a combination of two or more materials that differ in shape, chemical composition, physical and chemical properties, but these materials are insoluble with each other [1 – 5]. To have a substitute of the conventional materials, the composite materials are being developed, which have better mechanical properties such as the high fracture toughness and specific strength, good resistance to cold, moisture, heat and also it is very easy for fabrication [6-9].

Polymeric composites have been used in industry as an alternative to metallic materials due to their lighter weight. For their excellent strength-to-weight ratio, corrosion resistance, ease of fabrication, design flexibility, and wear resistance, they are increasingly used in mechanical and tribological applications. Polymer composites are most commonly found in the tribological application of gears, cams, and other automobile components [10]. Steel has been replaced with polymer composites because of their lighter weight. Due to their excellent strength-to-weight ratio, corrosion resistance, ease of fabrication, design flexibility, and wear resistance, they are becoming
increasingly popular in mechanical and tribological applications. Gears, cams, and other tribological components are commonly made from polymer composites [11-15].

To create composite structures, silk and cotton waste fibres were mixed with high-density polyethene polymer. As reported by [16], silk and cotton waste was mixed with recycled PA6 polymer to create a composite structure. Silk and cotton wastes were measured at 1 mm, 2.5 mm, and 5 mm, respectively, in length. It was determined that 97/3 of the reclaimed PA6/silk and cotton wastes should be mixed. Composites made from PA6 polymer and waste silk fibres showed an increase in their elasticity modulus. Poly Lactic Acid thermoplastic resin can be reinforced with waste silk fibres to create a novel biocomposite with excellent mechanical characteristics (PLA). As a type of polyester, PLA exhibits good thermal properties and a high degree of processability[17]. It also decomposes into carbon dioxide and water. Due to the growing demand for eco-friendly products, it holds promise for a variety of applications [18-27]. As a result, tensile, flexural, compression, flexural, and dry-slide tests were performed on PLA biocomposites reinforced with waste silk fibres of different contents. Sliding speed (S), wear load (L), fibre loading (F), and sliding distance (S) have all been examined using this method (D).

2. Materials and Methods
Silk waste and cocoons were pierced with special machines provided by the producers of silk yarn to produce waste silk yarns. The cloth was made from twisted yarns. Plain weave is created by interlacing warp and weft threads. Fabric with 56 warps and 15 weft strings per centimetre was utilized to reinforce the woven cloth. There were 19.62 grams per square centimetre (g/cm2) of surface density. Materials used in the matrix included 35 micron-thick PLA sheets. In terms of thickness, it weighed 1.78 grams per cubic centimeter and had a melting point of between 132 and 143 degrees Celsius.

![Figure 1. Schematic of matrix and fibre arrangement](image-url)
Hand-layered silk fabric/PLA biocomposites. Initial pieces of waste silk fiber (WSF) were chopped into 250 mm × 120 mm squares, followed by 120 mm squares of PLA film. The PLA film follows suit with the fabric's warp or weft. 15 to 25 plies were laid out, aligned, and then stacked. It was then placed in a steel mold that I had built myself. There was a performance with a 180-millimeter diameter utilized. It was heated to a temperature of up to 162°C in pressurized chambers and then pressed. They applied pressure of 4.1 MPa for 25 to 35 minutes.

![Schematic of conventional hand layup method](image)

**Figure 2.** Schematic of conventional hand layup method

| Designation of composites | PLA Film | Waste Silk Fibre |
|---------------------------|----------|------------------|
| PLA/SF0                   | 100      | 0                |
| PLA/SF10                  | 90       | 10               |
| PLA/SF20                  | 80       | 20               |
| PLA/SF30                  | 70       | 30               |
| PLA/SF40                  | 60       | 40               |

It was taken from the mold and left to cool to room temperature. After removing it from the mold, the biocomposite laminate panel could be cut into test specimens. Each sample had a wt% fiber content of 0, 10, 20, 30, and 40%. Table 1 compares the weight percentage contributions of the matrix and reinforcement in pure and hybrid composite specimens. The thickness of the silk fiber/PLA biocomposite specimens varied from 2.30mm to 3.70mm due to the varying fiber compositions. Figure 1 depicts a PLA film with silk fiber mate. Figure 2 illustrates a diagram of the traditional hand layup procedure.

### 2.1 Wear Test

For abrasive wear tests, the ASTM G99 standard was followed. Many researchers have described the detailed wear test procedure, which will not be reported here. The surface area of the wear specimens is 10 mm, while the roughness of the silicon carbide abrasive in 350 grits. Figure 3 shown the pin-on-disc setup.
2.2. Experimental Design for Optimum Wear Condition

Control factors on execution yield are studied using the Design of Experiments (DOE) method. Fifty levels of four parameters were examined as part of the L25 orthogonal cluster plan: sliding speed (S), wear load (L), fibre loading (F), and sliding distance (D). Worse is better as a strategy for reducing wear rate. Within an acceptable level of accuracy, statistics of variance and signal-to-noise ratios predict the optimal combination of wear parameters.

### Table 2. Control Factors for Specific Wear Rate

| Factors            | 1  | 2  | 3  | 4  | 5  |
|--------------------|----|----|----|----|----|
| Sliding Speed (m/s)| 0.5| 1  | 1.5| 2.0| 2.5|
| Wear Load (N)      | 10 | 15 | 20 | 25 | 30 |
| Fibre Weight (%)   | 0  | 10 | 20 | 30 | 40 |
| Sliding Distance (m)|150|300|450|600|750|

3. Results and Discussions

3.1. Effect of Fibre Loading on Specific Wear Rate

Analyses were conducted using conventional optimization software designed for experiment design. An analysis of the composite test specimen's abrasive wear behaviour using the Taguchi technique was performed. 35.68 decibels is found to be the average signal-to-noise ratio for a specific wear rate. For the lowest specific wear rate, the following factors were combined: 2 m/s sliding speed, 30 wt % fibre content, 10 N wear load, and 750m sliding distance Figure 3 provides a visual overview of the factors that influence the specific wear rate. To determine the best quality with the least variance, the maximum signal-to-noise ratio must be achieved. The signal-to-noise ratio changes in relation to the control factor transition levels. Response graphs indicate that higher signal-to-noise ratios result in the best wear rate. This means that a factor combination of sliding speed of 2 m/s, fibre content of 35%, wear load of 10% and sliding distance of 750 m results in the lowest specific wear value possible.
3.2. Confirmation Experiment
When a mix of control variables and their levels are predetermined, experiments are valid. In an L25 orthogonal array, no wear test validated the ideal blend of control factors for a least specific wear rate of 2m/s sliding speed, 30 percent fibre content, 10 N wear load, and 750 m sliding distance. To achieve a specific wear rate of 0.0291 mm³/Nm, it was necessary to perform both a forecast and a confirmation test at optimal settings.

3.3. Analysis of Variance and the Effect of Factors
In order to calculate the impact on quality characteristics, all control factors were divided by their respective percentage contributions. The optimal combination of operational parameters was predicted using 95 percent confidence level analysis of variance. This was done using an analysis of variance based on the experimental data (D). According to table 3, the wear-tested samples were subjected to variance analysis. Significant influences on biocomposite wear rates included sliding distance (P = 38.4521%), fibre loading (18.9634%), wear load (17.4523%), and sliding speed (P = 14.6532%), according to a new study.
Table 3. Variance Analysis Table for Specific Wear Rate of Waste Silk Fibre/PLA Composites

| Factors             | DF | Adj SS  | Adj MS  | F-Value | Contribution P (%) |
|---------------------|----|---------|---------|---------|--------------------|
| Sliding Speed (m/s) | 4  | 0.0145  | 0.00421 | 1.12    | 14.6532            |
| Wear Load (N)       | 4  | 0.0182  | 0.00263 | 1.41    | 17.4523            |
| Fibre Weight (%)    | 4  | 0.0196  | 0.00294 | 0.98    | 18.9634            |
| Sliding Distance (m)| 4  | 0.0561  | 0.00123 | 2.67    | 38.4521            |
| Error               | 12 | 0.0312  | 0.00432 |         | 10.4790            |
| Total               | 28 | 0.01396 |         |         |                    |

4. Conclusions
As a result of their 3D fabric structure, waste silk fibre-reinforced biocomposites outperform pure PLA composites in wear properties. For a minimum wear rate, a 2 m/s sliding speed, 30 wt.% fibre content, a 10 N wear load, and a 750 m sliding distance were found to be the ideal combination of wear parameters. A variance analysis revealed that sliding distance, fibre loading, wear load, and sliding speed were the most important variables. The mechanical and wear properties of PLA biocomposites, which can be used in household, transportation, and medical engineering applications, were improved by using waste silk fibre from sewing machines.

References
[1] R. Kalidoss, S. Umapathy 2019 An overview on the exponential growth of non-invasive diagnosis of diabetes mellitus from exhaled breath by nanostructured metal oxide Chemiresistive gas sensors and μ-preconcentrator Biomedical Microdevices 22 2.
[2] R. Kalidoss et al., 2021 Socio-economic demands and challenges for non-invasive disease diagnosis through a portable breathalyzer by the incorporation of 2D nanosheets and SMO nanocomposites RSC Advances 11 21216-21234.
[3] R. Kalidoss, S. Umapathy, R. Kothalam, U. Sakthivel 2020 Adsorption kinetics feature extraction from breathprint obtained by graphene based sensors for diabetes diagnosis Journal of Breath Research 15 016005.
[4] R. Kalidoss et al., 2019 Comparative Study on the Preparation and Gas Sensing Properties of Reduced Graphene Oxide/SnO₂ Binary Nanocomposite for Detection of Acetone in Exhaled Breath Analytical Chemistry 91 5116-5124.
[5] R. Kalidoss, S. Umapathy, Y. Sivalingam 2018 An investigation of GO-SnO₂-TiO₂ ternary nanocomposite for the detection of acetone in diabetes mellitus patient’s breath Applied Surface Science 449 677-684.
[6] W Ruirui, Y Zheng and L Qiushu 2017 Microstructure and mechanical properties of 7075 Al alloy based composites with Al₂O₃ nanoparticles International Journal of Cast Metal Research 30 337-40
[7] O’donnell, M. A. Dweib, and R. P. Wool, “Natural fiber composites with plant oil-based resin,” Compos. Sci. Technol., vol. 64, no. 9, pp. 1135–1145, 2004.
[8] D. Rouison, M. Sain, and M. Couturier, “Resin transfer molding of natural fiber reinforced composites: cure simulation,” Compos. Sci. Technol., vol. 64, no. 5, pp. 629–644, 2004.
[9] D. U. Shah, D. Porter, and F. Vollrath, “Opportunities for silk textiles in reinforced biocomposites: Studying through-thickness compaction behaviour,” Compos. Part A Appl. Sci. Manuf., vol. 62, pp. 1–10, 2014.
[10] J. Li and Z. N. Liang, “Sliding wear performance of TiO2/short carbon fiber/polyamide 66 hybrid composites,” Polym. Plast. Technol. Eng., vol. 49, no. 8, pp. 848–852, 2010.

[11] K. FRIEDRICH, “Wear of reinforced polymers by different abrasive counterparts,” in Composite Materials Series, vol. 1, Elsevier, 1986, pp. 233–287.

[12] D. U. Shah, “Developing plant fibre composites for structural applications by optimising composite parameters: a critical review,” J. Mater. Sci., vol. 48, no. 18, pp. 6083–6107, 2013.

[13] M. I. Misnon, M. M. Islam, J. A. Epaarachchi, and K. Lau, “Potentiality of utilising natural textile materials for engineering composites applications,” Mater. Des., vol. 59, pp. 359–368, 2014.

[14] D. Koçak, M. Taşdemir, I. Usta, N. Merdan, and M. Akalin, “Mechanical, thermal, and microstructure analysis of silk-and cotton-waste-fiber-reinforced high-density polyethylene composites,” Polym. Plast. Technol. Eng., vol. 47, no. 5, pp. 502–507, 2008.

[15] S. M. Lee, D. Cho, W. H. Park, S. G. Lee, S. O. Han, and L. T. Drzal, “Novel silk/poly(butylene succinate) biocomposites: the effect of short fibre content on their mechanical and thermal properties,” Compos. Sci. Technol., vol. 65, no. 3–4, pp. 647–657, 2005.

[16] D. K. Setua and B. Dutta, “Short silk fiber-reinforced polychloroprene rubber composites,” J. Appl. Polym. Sci., vol. 29, no. 10, pp. 3097–3114, 1984.

[17] M. Taşdemir, D. Koçak, İ. Usta, M. Akalin, and N. Merdan, “Properties of polypropylene composite produced with silk and cotton fiber waste as reinforcement,” Int. J. Polym. Mater., vol. 56, no. 12, pp. 1155–1165, 2007.

[18] V. Mohanavel, K. S. Ashraff Ali, S. Prasath T. Sathish, M. Ravichandran, Journal of Materials Research and Technology, 9 (2020) 14662-14672.

[19] V. Mohanavel, K. Rajan, M. Ravichandran, Journal of Materials Research, 31 (2016) 3824-3831.

[20] V. Mohanavel, M. Ravichandran, Materials Research Express, 6 (2019) 106557.

[21] Arul, K, Senthil Kumar, VS 2020, ‘Magnetorheological Based Minimum Quantity Lubrication (MR-MQL) With Additive n-CuO’, Materials and Manufacturing Processes, vol. 35, no. 4, pp. 404-414.

[22] Vinayagam Mohanavel, Thandavamoorthy Raja, Anshul Yadav, Manickam Ravichandran, Jerzy Winczek. Evaluation of Mechanical and Thermal Properties of Jute and Ramie Reinforced Epoxy-based Hybrid Composites, Journal of Natural Fibers, DOI: 10.1080/15440478.2021.1958432

[23] Arul, K, Senthil Kumar, VS 2020, ‘Effect of Magneto Rheological Minimum Quantity Lubrication on Machinability, Wettability and Tribological Behavior in Turning of Monel K500 Alloy’, International Journal of Machining Science and Technology, vol. 24, no. 5, pp. 810-836.

[24] Ram Subbiah, Md. Rahel, A Sravika, R Ambika, A Srujana, E Navya, 2019, Investigation on Microstructure and Mechanical Properties of P91 Alloy Steel Treated With Normalizing Process - A Review, Materials Today: Proceedings, 18, 7, 2265-2269.

[25] A. Rohit Sai Krishna, B. Vamshi Krishna, T. Sashank, D. Harshith, Ram Subbiah, 2020, Influence and Assessment of Mechanical Properties on Treated P91 Steel with Normalizing Processes, Materials Today: Proceedings. 27, 2, 1555-1558.

[26] M. Taşdemir, D. Koçak, I. Usta, M. Akalin, and N. Merdan, “Properties of recycled polycarbonate/waste silk and cotton fiber polymer composites,” Int. J. Polym. Mater., vol. 57, no. 8, pp. 797–805, 2008.

[27] M. Taşdemir, D. Koçak, N. Merdan, U. İsmail, and M. AKALIN, “Recycled polyamide-6/waste silk & cotton fibre polymer composites: Effect of fibre length,” Marmara Fen Bilim. Derg., vol. 25, no. 4, pp. 157–166, 2013.