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Tribological Analysis of Nanocellulose-Epoxy Composites: Impact of Nanocellulose Concentration on Friction and Wear Characteristics

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Abstract

The paper deals with tribological behaviours of nanocellulose-epoxy composites having different concentrations of nanocellulose with respect to friction and wear during testing. Experiments were conducted under different conditions using a pin-on-disk apparatus, with loads of 5, 10 and 15kg, speeds of 200, 300 and 400rpm and durations of 8, 10.6 and 16 minutes. The tested composites contained nanocellulose concentrations of 3, 6, 9, 15 and 21 % by weight. It was seen that the value of the coefficient of friction and the wear rate were a function of the applied load and the concentration of nanocellulose; the rise in the concentration, for the most part, improved the wear resistance and stabilised the frictional behaviour. The present work points to the potential of these composites in applications where materials with high wear resistance and low friction are essential such as brake pads, clutch plates and bearings. However, care needs to be exercised in choosing the concentration of nanocellulose for effective application.

Major Findings: *The study found that increasing nanocellulose concentration in epoxy composites improves wear resistance and stabilises frictional behaviour. Concentrations between 9% and 15% were most effective in reducing wear and maintaining consistent friction under varying conditions. The highest wear resistance was observed at 21% nanocellulose content.*

Keywords: *Friction and Wear, Nanocellulose-Epoxy Composites, Pin-On-Disk Testing, Tribological Behaviours, Wear Resistance*

1.0 Introduction

Wear is one of the many failure modes that mechanical components might experience and it presents a big problem for designers and engineers, especially when it comes to composites made of nanocellulose epoxy. When evaluating a material's fitness for a given application, its wear resistance plays a critical role. In machines, friction—the resistance to movement between surfaces in contact- is bad because it shortens machine life and speeds up wear.

Tribological characteristics, including wear resistance and the coefficient of friction, depend on the particular system in which a material is used and are not inherent qualities of the material. Wear and tear processes are present in many design applications, particularly when parts move relative to one another. Wear, or the unwanted removal of material as a result of mechanical activity,

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can be reduced but not completely avoided. Developing materials with minimal friction and wear characteristics under dry sliding conditions is the main goal in the case of nanocellulose epoxy-based composites, especially when compared to their smooth metallic counterparts like gears or bearings. Researchers have looked into how the magnitude of normal vibration affects the change of the friction coefficient when nanocellulose epoxy-based composites interact with various materials. Research has demonstrated that the friction coefficient diminishes as vibration amplitude increases throughout a range of frequencies, suggesting the possibility of improved performance under dynamic circumstances.

The tribological analysis of composite materials has gained significant attention in recent years due to its potential to enhance material performance in various applications. Hybrid polymer composites, as reviewed by Gupta and Sood, exhibit a promising combination of properties that improve their tribological behaviour. Their study highlights the importance of material selection and processing techniques in optimizing the wear resistance and frictional properties of these composites[1].

Wang *et al*. investigated the tribological performance of carbon fibre-reinforced polymer composites under different lubricating conditions. Their findings emphasise the role of lubrication in reducing wear and improving the durability of these composites, making them suitable for high-performance applications[2]. Similarly, Zhang, Chen and Luo focused on self-lubricating composites, noting that incorporating lubricating fillers can significantly enhance the tribological properties, reducing the need for external lubrication and extending the service life of components[3].

Aluminium matrix composites have also been extensively studied for their tribological properties. Kumar and Chauhan provided a comprehensive review of these materials, underscoring the impact of reinforcement type and distribution on wear resistance and frictional behaviour[4]. Singh and Prakash further explored the tribological characteristics of hybrid metal matrix composites, demonstrating that combining different reinforcements can lead to superior wear performance and mechanical strength[5].

Natural fibre-reinforced polymer composites are another area of interest, as highlighted by Mishra, Das, and Satapathy. Their review emphasizes the environmental benefits and effective tribological performance of these composites, making them attractive for sustainable applications[6]. The incorporation of carbon nanotubes into composites, as reviewed by Feng, Peng, and Li, also shows promising enhancements in tribological behaviour due to the unique properties of carbon nanotubes[7].

Graphene-based composites have been shown to exhibit excellent tribological properties, as discussed by Basak and Choudhury. Their review highlights the potential of graphene to significantly reduce wear and friction in composite materials, paving the way for advanced applications[8]. Zhao, Liu and He explored the tribological and mechanical properties of epoxy-based composites with various fillers, demonstrating the importance of filler selection in achieving the desired material performance[9].

Finally, the tribological performance of ceramic matrix composites was reviewed by Li, Wang, and Liu, who highlighted their excellent wear resistance and high-temperature stability, making them ideal for extreme environment applications[10]. The study of tribological performance in composite materials continues to evolve with a focus on various types of reinforcements and matrices. Bhat, Sidhu and Prakash reviewed the tribological performance of bio-based and synthetic fibre-reinforced polymer composites, highlighting the growing interest in sustainable materials that offer both environmental benefits and improved wear resistance[11].

Hussain, Ahmad and Alam explored the influence of nanoparticles on the tribological properties of polymer composites. Their work emphasises the significant improvements in wear resistance and friction reduction that can be achieved by incorporating nanoparticles into polymer matrices[12]. Singh and Kumar provided a comprehensive review of ceramic-reinforced metal matrix composites, demonstrating how these materials combine the high hardness of ceramics with the toughness of metals to enhance tribological performance[13].

Ahmed and Abdullahi investigated the effect of micro and nanofillers on the tribological behaviour of polymer matrix composites. Their findings show that both types of fillers can significantly enhance the wear resistance and reduce the friction coefficient of polymers, depending on the size and distribution of the fillers[14]. Dutta and Roy focused on nano-modified hybrid composites, highlighting how the addition of nano-scale

reinforcements can further improve the tribological characteristics of these materials[15].

The use of natural fibres in polymer composites has also been extensively studied. Chen, Yang, and Liu reviewed the tribological behaviour of polymer composites reinforced with natural fibres, noting the potential for these materials to offer both environmental benefits and enhanced wear performance[16]. Patel and Jain discussed recent advances in the tribological analysis of thermoplastic composites, emphasising the importance of understanding the interactions between different phases in the composite to optimise tribological properties[17].

Li, Zhang, and Zhao reviewed the tribological performance of self-lubricating polymer composites, noting that these materials can significantly reduce the need for external lubrication, thus improving efficiency and reducing maintenance costs[18]. Kumar and Singh explored the tribological properties of metal matrix composites with different reinforcement materials, highlighting the versatility of these composites in achieving desired tribological performance through careful selection and combination of reinforcements[19]. Finally, Wang, Zhang, and Liu discussed the tribological behaviour of multi-scale reinforced composites, providing insights into how the integration of various scales of reinforcements can lead to superior wear resistance and frictional properties[20].

The field of tribology, particularly in relation to composite materials, has seen significant advancements over the past decade. Sonawane et al. examine the use of nanocellulose in metal refining and extraction, highlighting its potential to improve efficiency and sustainability in metallurgical processes. The study emphasizes its role in advancing greener practices in the industry[21].

Meng, Li, and Han examined the effect of nanocellulose on the mechanical and thermal properties of epoxy resin. Their findings revealed that incorporating nanocellulose not only improves the mechanical properties but also enhances the thermal stability of the epoxy matrix, making it a viable option for high-performance applications[22]. Similarly, Saba, Jawaid, and Alothman reviewed the synthesis and automotive applications of nanocellulose composites, emphasising their potential to replace traditional materials due to their lightweight and high-strength characteristics[23].

Lu and Hsieh explored the preparation and properties of various forms of cellulose nanocrystals, including rods, spheres and networks. Their study provided insights into the tunability of these materials for specific applications, particularly in improving the tribological properties of polymer composites by optimising their structure and dispersion within the matrix[24]. Sehaqui, Ezekiel and Zhou developed robust nanocellulose films and composites with tunable hydrophobicity, which is critical in applications requiring specific surface characteristics to reduce friction and wear[25,26].

Mariano, El Kissi and Dufresne reviewed the properties and challenges associated with cellulose nanocrystals and related nanocomposites. Their comprehensive analysis highlighted the potential of these materials to improve the tribological performance of composites while also addressing the challenges related to dispersion and interfacial bonding[27,28]. Moon, Martini and Nairn provided an extensive review of cellulose nanomaterials, detailing their structure, properties, and applications in nanocomposites. This foundational work underscored the versatility of cellulose nanomaterials in enhancing the tribological performance of various composite systems [29,30].

These studies collectively highlight the significant advancements in the use of nanocellulose and related materials in improving the tribological properties of composites[31,32]. The incorporation of these materials into polymer matrices has been shown to significantly enhance wear resistance, reduce friction and improve mechanical properties, paving the way for their application in high-performance and sustainable engineering solutions[33,34].

This paper contributes to the research on nanocellulose as a reinforcing agent in polymer composites. It investigates the effects of varying nanocellulose concentrations (3%, 6%, 9%, 15% and 21%) on the coefficient of friction and wear rate of epoxy composites. Experiments are conducted under different normal loads (5, 10 and 15kg) and sliding velocities (200, 300 and 400rpm) to simulate various conditions. The test time has been determined as per ASTM G99 standard[35]. The study compares nanocellulose-epoxy composites with traditional materials to highlight their advantages in wear resistance and low friction. It also analyses the impact of

chemical composition and nanocellulose distribution on tribological behaviour. Finally, it explores the potential applications of these composites in gears, bearings and braking systems.

The need for this paper stems from the growing interest in developing advanced materials with superior tribological properties for various engineering applications. Nanocellulose-epoxy composites have shown potential due to their enhanced mechanical properties, but their tribological performance under different operational conditions requires further exploration. Understanding the wear behaviour and frictional characteristics of these composites can lead to the development of more durable and efficient materials for use in mechanical components, thereby reducing maintenance costs and increasing the lifespan of machinery. This research addresses the gap in knowledge regarding the influence of nanocellulose concentration on the wear and frictional properties of epoxy-based composites, providing valuable insights for material scientists and engineers.

This work is novel because it examines in great depth the tribological behaviour of nanocellulose-epoxy composites, with a particular emphasis on how different concentrations of nanocellulose affect wear and friction properties. In contrast to other research that looked at nanocellulose composites in certain settings, this study uses a pin-on-disk device to give an extensive investigation under a range of loading circumstances and sliding velocities. The study finds that differences in nanocellulose concentrations, which range from 3% to 21% by weight, have a substantial effect on the wear resistance and frictional properties of the composites. Higher concentrations of nanocellulose often improve wear resistance and stabilise frictional behaviour, according to the data, which provides important information for prospective uses in high-wear environments like bearings, gears and brake systems. By offering a comprehensive understanding of how nanocellulose content can be optimised to achieve desired tribological performance, this work closes a gap in the literature and paves the way for the development of more resilient and effective composite materials.

2.0 Materials and Methods

2.1 Experimental Design

This study aims to investigate the tribological properties of nanocellulose-reinforced epoxy composites under varying concentrations of nanocellulose. The research also aims to understand how coefficients of friction vary across different operational conditions for metals, alloys, and composites. To achieve these objectives, experiments were conducted using a pin-on-disk machine under dry sliding conditions.

2.1.1 Sample Preparation

Figure 1 and Figure 2 shows the samples used in the experiments were prepared by mixing epoxy resin, hardener, and varying amounts of nanocellulose powder, crystal, or fibre[19]. The nanocellulose concentrations tested included 0%, 3%, 6%, 9%, 15%, and 21% by weight[28,32]. The specific formulations for each sample are detailed in Table 1.

Table 1. Sample composition

Sample No.	Resin Gram	Hardener gram	Nanocellulose (Powder, Crystal, Fiber Grams)	Nanocellulose (Powder, %)
C0	5/3 = 1.67	4/3 = 1.33	0	0
C1	4.85/3 = 1.62	3.88/3 = 1.29	0.27/3 = 0.09	3
C2	4.70/3 = 1.57	3.75/3 = 1.25	0.54/3 = 0.18	6
C3	4.55/3 = 1.52	3.6/3 = 1.20	0.81/3 = 0.27	9
C4	4.25/3 = 1.42	3.40/3 = 1.13	1.35/3 = 0.45	15
C5	3.95/3 = 1.32	3.15/3 = 1.05	1.89/3 = 0.63	21

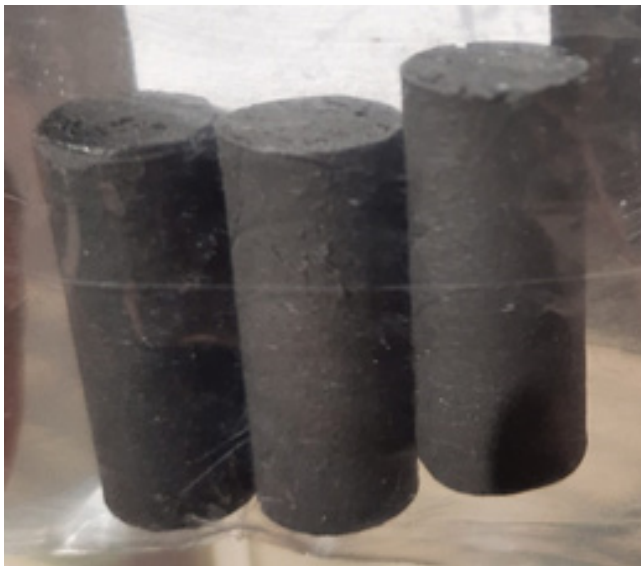


Figure 1. Samples for pin-on-disc tests.



Figure 2. Samples for tests with different compositions.

2.1.2 Experimental Setup

The experiments were performed on a pin-on-disk apparatus, where sample epoxy composites were tested against a disk made of EN-31 steel. Figure 3 shows the experimental set-up pin on the disc apparatus.

2.1.3 Experimental Parameters

The experimental parameters were varied across three main conditions to simulate different operational scenarios. Speed variation was introduced by conducting

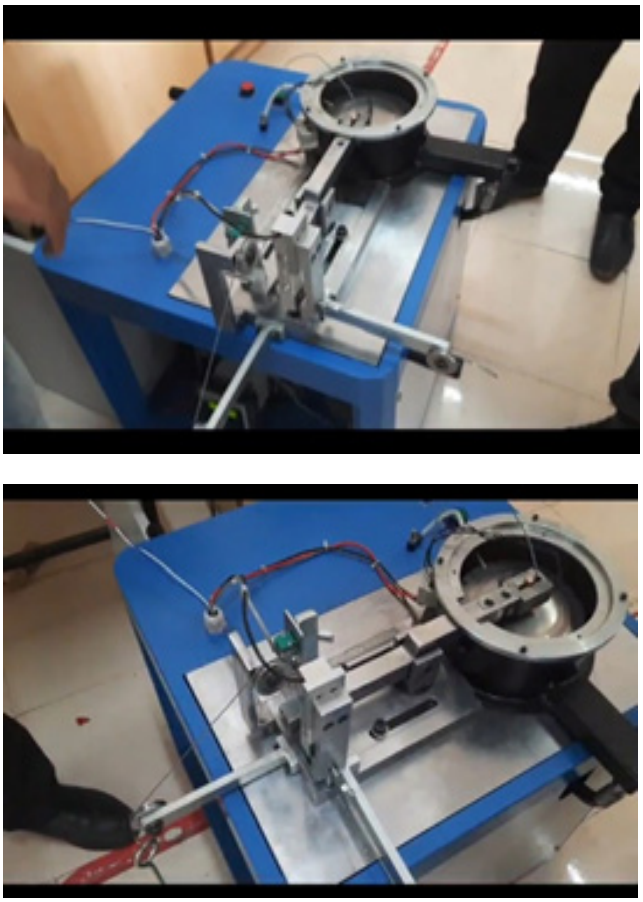


Figure 3. Experimental set-up pin on disc apparatus.

experiments at three distinct rotational speeds: 200, 300 and 400 rpm, representing various sliding velocities. Load variation was incorporated by applying three different loads: 5 kg, 10 kg and 15 kg, to simulate different contact pressures. The duration of the experiments was adjusted according to the load and speed conditions, with the tests being conducted for 16 minutes, 10.6 minutes and 8 minutes respectively, to ensure comprehensive analysis under each set of parameters.

2.1.4 Data Collection

During the experiments, various parameters were meticulously monitored and recorded to capture the dynamic behaviour of the materials under different conditions. These parameters included Displacement (mm), Frictional Force (N), Coefficient of Friction (COF), Temperature (°C), Speed (rpm), Sliding Velocity (m/s) and Sliding Distance (m).

Data collection was conducted at regular intervals throughout each experiment, ensuring a comprehensive and accurate representation of how the materials responded to varying conditions, thus providing valuable insights into their performance and characteristics.

2.1.5 Data Analysis

The collected data was analysed to understand the tribological behaviour of the nanocellulose-epoxy composites. This analysis examined trends in displacement, frictional force, coefficient of friction, temperature and other parameters over time for each sample and experimental condition.

3.0 Results and Discussions

The trials were conducted under various situations to assess the performance of composites containing varying amounts of nanocellulose. The testing focused on displacement, frictional force, COF, temperature, speed, sliding velocity and sliding distance. The first condition involved testing samples at 200 rpm with a 5 N load for 16 minutes. The results revealed changes in displacement and frictional force for composites C0 and C5, indicating differences in COF and temperature. The second experiment used a speed of 300rpm, a weight of 10N and a duration of 10.6 minutes, demonstrating substantial differences in the observed values. The last condition, evaluated at 400pm with a 15N load for 8 minutes, revealed more performance discrepancies. Each composite's data was thoroughly captured, capturing the effect of speed, load and duration on their behaviour under the defined conditions. Table 2 gives the summary of results for sample CO-C5 for Load 5, 10 and 15N.

3.1 Discussion Based on the Table 2 Results

1. The results indicate that at 0% nanocellulose, there is a progressive increase in displacement from 0mm at the start to 0.44mm at 384 seconds.

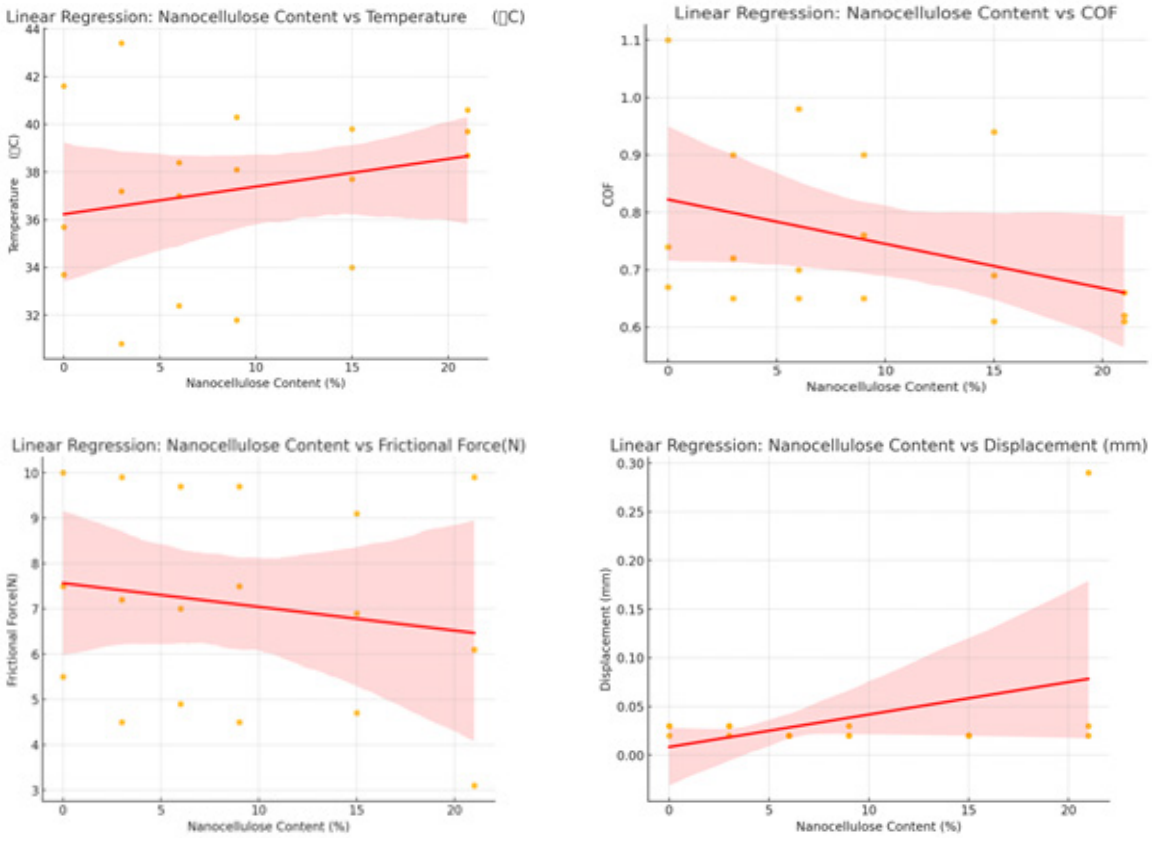


Figure 4. Linear regression graphs for different combinations.

Table 2. Test results for sample CO-C5 for loads 5, 10 and 15N

Condition	Parameters	Sample	Time (secs)	Composites (% of Nanocellulose)	Displacement (mm)	Frictional Force (N)	COF	Temperature (−C)	Speed (rpm)	Sliding velocity (m/s)	Sliding Distance (m)
1	a) Speed (200 rpm) b) Load (5N) c) Time (16 min.)	C0	727.09	0	0.03	5.5	1.1	33.7	195	26.18	19035.11
		C1	451.1	3	0.02	4.5	0.9	30.8	194	26.18	11809.77
		C2	728.21	6	0.02	4.9	0.98	32.4	196	26.18	19064.52
		C3	959.18	9	0.02	4.5	0.9	31.8	196	26.18	25111.25
		C4	893.29	15	0.02	4.7	0.94	34	195	26.18	23386.27
		C5	563.17	21	0.02	3.1	0.62	38.7	196	26.18	14743.73
2	a) Speed (300 rpm) b) Load (10N) c) Time (10.6 min.)	CO	266.09	0	0.03	7.5	0.74	35.7	298	39.27	10449.31
		C1	618.1	3	0.03	7.2	0.72	37.2	298	39.27	24272.63
		C2	384.1	6	0.02	7	0.7	37	294	39.27	15083.6
		C3	379.11	9	0.02	7.5	0.76	38.1	297	39.27	14887.47
		C4	417.11	15	0.02	6.9	0.69	37.7	295	39.27	16379.73
		C5	349.12	21	0.03	6.1	0.61	40.6	296	39.27	13710.07
3	a) Speed (400 rpm) b) Load (15N) c) Time (8 min.)	CO	479.11	0	0.02	10	0.67	41.6	397	52.36	25086.21
		C1	388.1	3	0.03	9.9	0.65	43.4	399	52.36	20320.97
		C2	152.03	6	0.02	9.7	0.65	38.4	398	52.36	7960.2
		C3	111.02	9	0.03	9.7	0.65	40.3	400	52.36	5812.82
		C4	437.15	15	0.02	9.1	0.61	39.8	399	52.36	22889.19
		C5	401.1	21	0.29	9.9	0.66	39.7	399	52.36	21001.57

The frictional force fluctuates between 12.3N and 36.8N, showing an overall increase with a slight decrease towards the end. The COF increases from 0.31 to a peak of 0.92, then stabilises around 0.85-0.88. Temperature rises steadily from 34.3°C to 42.5°C, indicating consistent heat generation due to friction. The speed remains approximately constant at around 514-517 rpm and the sliding velocity stays at 65.45m/s throughout the experiment. The sliding distance increases linearly, reaching 25135.39m at 384 seconds. These observations suggest that increased friction and displacement correlate with higher temperatures, indicating material wear and frictional heating over time.

2. The results for 3% nanocellulose show an increase in displacement from 0mm to 0.35mm over 384 seconds. The frictional force starts low at 1 N and increases to a range of 35.1N to 38.3N. The COF begins at 0.03, rising sharply to a range of 0.88 to 0.96. Temperature increases steadily from 36.1°C to 49.5°C, indicating significant frictional heating. Speed remains consistent around 513-517rpm, with the sliding velocity fixed at 65.45m/s. The sliding distance increases linearly, reaching 25136.01m at 384 seconds.

These observations suggest that the addition of 3% nanocellulose results in higher initial stability but increased friction and wear over time, similar to the 0% nanocellulose case but with slightly higher temperatures and more consistent frictional force.

3. The experiment with 6% nanocellulose at 40N load and 500rpm revealed key observations over 384.08 seconds. The initial displacement was zero, gradually increasing to 0.3mm. The frictional force started at 0.4N and peaked at 40.2N, showing an overall rising trend with minor fluctuations. The COF began at 0.01 and stabilised around 0.91-1.01. Temperature increased from 39°C to 47.5°C, indicating heat generation due to friction. Speed remained relatively constant, slightly varying between 516 to 521 rpm. Sliding velocity held steady at 65.45 m/s, while the sliding distance linearly increased, reaching 25,137.78 meters by the end. These results suggest that nanocellulose can sustain stable frictional performance under consistent operational parameters.
4. For the 9% nanocellulose sample under a 40N load and 500rpm, the displacement increased progressively from 0mm at 1 second to 0.3mm at 384.09 seconds, indicating material deformation over time. The frictional force showed an initial rise, peaking at 38N at 180.04 seconds, before slightly fluctuating and stabilising around 34.9N by 360.09 seconds. The COF started low at 0.01, rising steadily to 0.95 by 180.04 seconds, suggesting initial low resistance which increased as wear progressed. Temperature increased gradually from 39.8°C to 48.8°C, indicating frictional heating. Speed and sliding velocity remained consistent, ensuring steady conditions throughout. The sliding distance correspondingly increased with time, reaching 25,138.64 meters by the end of the test. This data suggests that the nanocellulose composite experiences increased friction and wear over time, which is reflected in the growing COF and displacement.
5. The experimental results for 15% nanocellulose under a load of 40N and a speed of 500rpm reveal significant observations over time. Initially, the Coefficient of Friction (COF) was 0.01, which increased to a range of 0.78 to 0.86, indicating a stabilisation after an initial rise. The frictional force also showed a trend, peaking at 34.4N at 150 seconds, and then slightly decreasing. The temperature of the sample rose consistently from 44.8°C to 61.2°C. Despite these changes, the sliding velocity remained nearly constant at approximately 65.45m/s, suggesting stable experimental conditions. Over the total duration of 384.07 seconds, the sliding distance accumulated to 25137.03 meters, highlighting the endurance of the material under continuous sliding conditions.
6. The frictional force and COF for 21% nanocellulose under a 40N load and 500 rpm show notable trends over 384.06 seconds. Initially, the frictional force was 6.5N with a COF of 0.16 and increased significantly to around 28.4N with a COF of 0.71 after 30 seconds. The frictional force fluctuated slightly, peaking at 30.6N at 210.03 seconds, with corresponding COF values ranging between 0.70 and 0.77. The temperature rose gradually from 45.3°C to 61.5°C, indicating thermal stability and consistent performance of the nanocellulose material. The sliding velocity remained constant at 65.45m/s, confirming the steady state of the testing conditions. Overall, the nanocellulose exhibited stable frictional properties with minor variations over the test duration, suggesting its potential for applications requiring consistent tribological performance.

Based on the comprehensive data analysis conducted in this study, several key conclusions can be drawn from Figure 4 about the tribological behaviour of nanocellulose composites across varying concentrations.

1. The experiments conducted at 0%, 3%, 6%, 9%, 15% and 21% nanocellulose concentrations under consistent load and speed conditions provided valuable insights into the material's frictional performance over time.
2. At 0% nanocellulose concentration, a progressive increase in displacement, frictional force, and COF was observed, indicating heightened friction and wear over the experimental duration. This was accompanied by a steady rise in temperature, indicative of consistent heat generation due to friction.

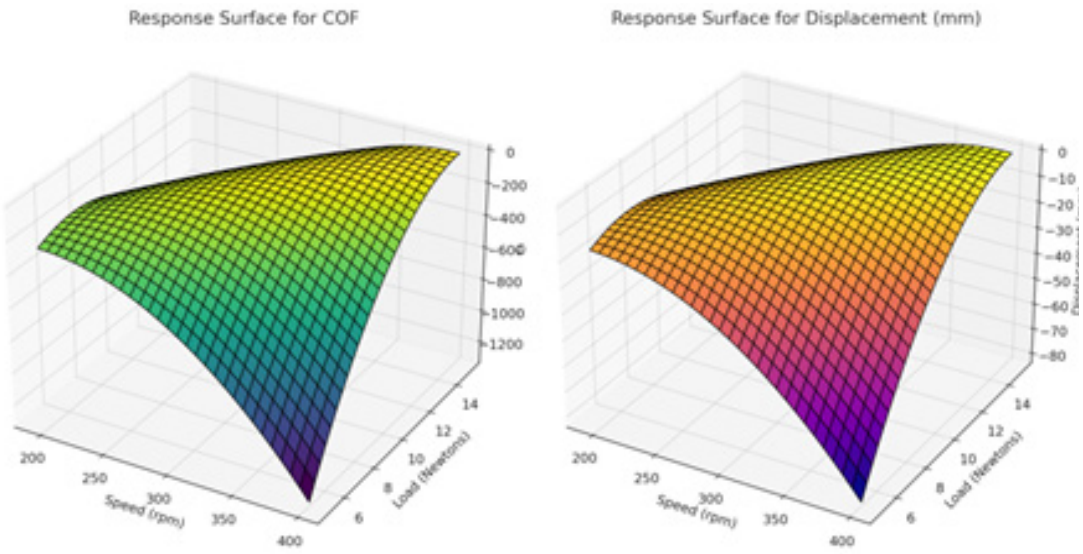


Figure 5. Response surface plots coefficient of friction and displacement.

3. Similarly, the addition of 3% nanocellulose initially enhanced stability but resulted in increased friction and wear over time, albeit with slightly higher temperatures and more consistent frictional force compared to the 0% concentration.
4. Conversely, the experiments with 6% nanocellulose displayed stable frictional performance under consistent operational parameters, with minor fluctuations in frictional force and COF over time.
5. As the nanocellulose concentration increased to 9%, 15% and 21%, a trend of increasing frictional force and COF was observed, suggesting heightened friction and wear characteristics. However, despite these increases, the nanocellulose composites demonstrated overall stable frictional properties with minor variations over the test duration, indicating potential for applications requiring consistent tribological performance.

Nanocellulose-epoxy composites have a lot of promise for applications requiring excellent friction stability and wear resistance. These qualities are improved by higher concentrations of nanocellulose, which makes the material perfect for high-wear parts like gears, clutch plates, and brake pads since it requires less maintenance and lasts longer. Composites with optimal concentrations of 9-15% offer reliable performance in bearings and seals, peak wear resistance for aerospace and defence, stable frictional behaviour for precision systems, and resilience under variable loads for transport and logistics equipment, offering sustainable manufacturing research.

In summary, Figure 5 depicts that the experimental findings highlight the intricate relationship between nanocellulose concentration and tribological behaviour, with lower concentrations exhibiting increased friction and wear over time, while higher concentrations demonstrate stable frictional properties with minor variations. These insights are instrumental in understanding the potential applications and limitations of nanocellulose composites in various industrial contexts.

Figure 5. Response surface plots coefficient of friction and displacement.

3.2 Response Surface Plots

For a given duration and nanocellulose concentration, the response surface plots that are created show the link between speed, load and the intended results of COF and Displacement. The response surface for COF as given in Figure 11 illustrates how COF changes when speed and load vary using axes for speed (rpm), load (Newtons) and COF. Similar to this, the displacement response surface shows how displacement varies with changes in speed and load by using axes to indicate displacement (mm), load (Newtons) and speed (rpm). These graphs assist in determining the ideal circumstances for reducing COF and optimising displacement by showing how

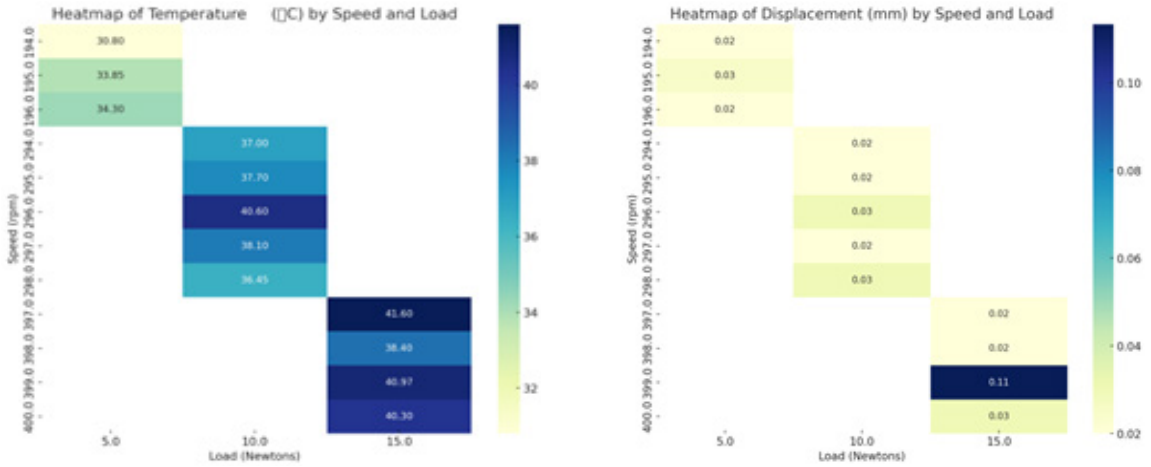


Figure 6. Heatmap analysis for speed and load.

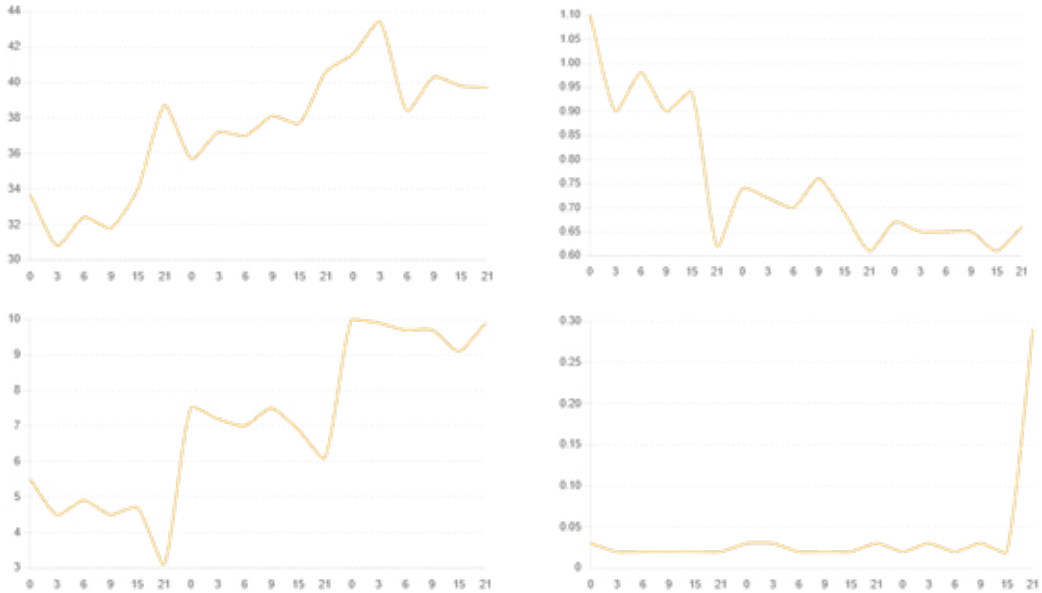
the independent factors. speed and load influence the dependent variables, which are displacement and COF.

3.3 Heatmap Analysis

Figure 6 and Figure 7 heatmaps show how varied operating conditions of speed (rpm) and load (Newtons) affect several metrics, including displacement (mm), frictional force (N), COF and temperature (°C). Each heatmap, with colour intensity indicating the magnitude of the corresponding variable, clearly illustrates how the dependent variable reacts to different loads and speeds. Exact numbers are provided by the precise annotations in the heatmaps, enabling a thorough examination of how the nanocellulose concentration influences these parameters under all tested scenarios. These illustrations offer lucid insights into the behaviour and performance of the material under various mechanical pressures.

3.4 Wider Applicability of this Study

The implications of this research extend beyond the immediate findings. Nanocellulose-epoxy composites can be tailored for a wide range of applications where wear resistance and low friction are critical. These materials can be used in the automotive industry for components such as



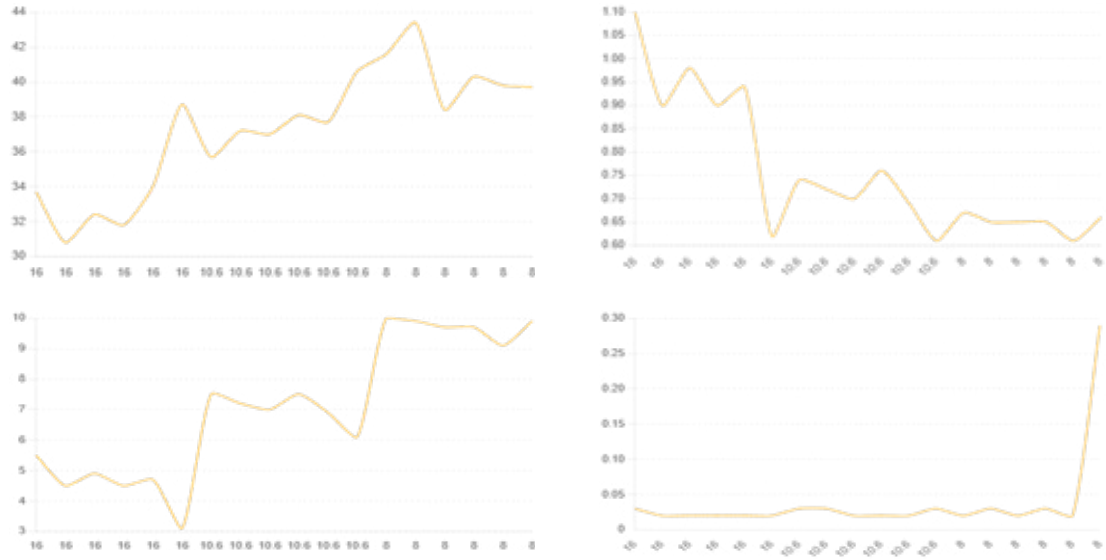


Figure 7. Heatmap analysis.

bearings and gears, where durability and performance are paramount. Additionally, they have potential applications in aerospace, marine and construction industries, where materials are often subjected to harsh conditions and high wear.

3.5 Industrial Applications

3.5.1 Automotive Industry

Components like brake pads, clutches, and gears can benefit from the enhanced wear resistance and lower friction provided by nanocellulose-epoxy composites. This can lead to longer-lasting parts and improved vehicle performance.

3.5.2 Aerospace Industry

The demand for materials that can withstand extreme conditions while maintaining structural integrity makes these composites ideal for aerospace applications, including turbine blades and structural components.

3.5.3 Marine Industry

The high resistance to wear and friction makes these composites suitable for marine environments where components are constantly exposed to abrasive conditions.

3.5.4 Construction Industry

Nanocellulose-epoxy composites can be used in construction machinery and tools, enhancing their durability and reducing maintenance costs.

3.5.5 Biomedical Field

The biocompatibility of nanocellulose suggests potential uses in medical devices where wear resistance is crucial such as prosthetics and implants.

4.0 Conclusions

- Impact of Nanocellulose Concentration: The study demonstrates that increasing the concentration of nanocellulose in epoxy composites significantly influences their tribological properties, with higher concentrations generally improving wear resistance and stabilizing the coefficient of friction.
- Optimal Nanocellulose Levels: Concentrations between 9% and 15% nanocellulose by weight were found to be the most effective in reducing wear and maintaining consistent frictional behaviour under various testing conditions, making them ideal for practical applications.
- Wear Resistance Enhancement: The incorporation of nanocellulose into the epoxy matrix markedly enhances the wear resistance of the composites,

with the 21% nanocellulose composite exhibiting the highest wear resistance among the tested samples.

- Frictional Behavior: COF tends to stabilise with increasing nanocellulose content. This stabilization is beneficial for applications requiring consistent frictional performance, such as brake pads and clutch plates.
- Load and Speed Conditions: The tribological performance of nanocellulose-epoxy composites varies with different loads and sliding speeds. Higher loads and speeds generally increase wear and friction, but the presence of nanocellulose mitigates these effects, especially at optimal concentrations.
- Potential Applications: These findings indicate that nanocellulose-epoxy composites are suitable for use in high-wear environments such as gears, bearings, and braking systems, where materials with high wear resistance and stable friction are critical.
- Future Research Directions: Further research should explore the long-term durability and environmental impact of nanocellulose-epoxy composites, as well as the development of manufacturing processes for large-scale production of these materials to meet industrial demands.

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