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Enhanced tribological performance of PLA/CNC composites: A comparison with phenolic resin and nylon

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Abstract: PLA has been developed to replace plastic because it is degradable. For more advanced applications, more research is needed on PLA. This study investigates the tribological properties of phenolic resin, nylon, and PLA/CNC composites under varying sliding distances and loads. Both phenolic resin and nylon demonstrate exceptional wear resistance and stable friction coefficients. PLA/CNC composites exhibit improved wear resistance, showing a 17% reduction in friction coefficient at a 3 wt.% CNC content. While the wear volume of PLA/CNC composites increases with sliding distance, the addition of CNC enhances PLA's self-lubricating properties and overall wear resistance. The correlation between dissipated energy and wear volume confirms that higher CNC content significantly improves the durability of PLA. These findings suggest that CNC has considerable potential as an additive to enhance the tribological performance of PLA composites, making it a valuable material for various applications requiring superior wear resistance.

Keywords: Wear resistance; Tribological properties; Life below water; Reduce plastic pollution

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1. Introduction

According to a 2017 report by Ocean Conference, approximately 8 million metric tons of plastic waste enter the world's oceans each year—equivalent to one truckload of plastic waste dumped every minute (United Nations, 2017). Over half of this waste originates from five major Asian countries: China, Indonesia, the Philippines, Thailand, and Vietnam, which have experienced rapid economic growth in the past two decades and are among the highest consumers of plastic products globally. In recent years, biodegradable polymers have gained significant attention in research and industrial applications worldwide, with polylactic acid (PLA) being the most notable (Shi et al., 2024b). Compared to conventional plastics, biodegradable plastics can decompose by 90% within three to six months in composting environments, breaking down into water and carbon dioxide, thus significantly reducing plastic pollution and environmental impact (Islam et al., 2024). However, the lower mechanical properties and heat resistance make the manufacturing process more challenging, and their higher cost than traditional plastics limits broader adoption.

To enhance their properties, nanocellulose, derived from natural plants, has been

extensively researched as a reinforcement material for biodegradable polymers. Cellulose is the most abundant renewable resource, with global annual production reaching 830 million metric tons through photosynthesis (Churam et al., 2024). This research is driven by the depletion of fossil fuels, rising costs, increasing environmental awareness, and the growth of green energy industries. The applications of PLA have also evolved. In the early 1980s, the first generation of PLA was developed for biomedical uses, such as surgical sutures and tissue engineering scaffolds (Agrawal & Ray, 2001). With growing environmental consciousness, the second generation of PLA, introduced in the early 2000s, was designed to replace conventional plastics in short-term products like disposable packaging. The third generation now focuses on substituting engineering plastics for more advanced applications.

Polylactic acid (PLA) is a biodegradable polymer material derived from natural plant resources through chemical reactions. It belongs to the category of thermoplastic plastics and is typically produced from crops such as corn, potatoes, sugarcane, and sugar beets. These crops are first processed to extract starch, which is then converted into lactic acid through microbial fermentation or chemical fermentation. The extracted lactic acid undergoes either direct polymerization or ring-opening polymerization to produce aliphatic polyester (Domenek & Ducruet, 2016). Cellulose is the most important organic compound found in plants, algae, tunicates, and bacteria. The fundamental unit of cellulose is formed by two glucose molecules linked by β 1-4 glycosidic bonds (β-(1→4)-glycosidic bonds), and these units repeat to form a linear cellulose molecular chain.

Each cellulose unit contains six hydroxyl groups and three oxygen atoms, making it capable of forming six hydrogen bond donors and acting as nine hydrogen bond acceptors. These groups participate in forming various intramolecular and intermolecular hydrogen bonds. This complex hydrogen bonding system and van der Waals interactions organize cellulose chains into a semi-crystalline polymer. These chains further intertwine to form microfibrils at the micron scale. Each microfibril, through biosynthesis, combines with hemicellulose to form cellulose, which is found in the plant cell wall and is the primary component responsible for providing plants with high strength and toughness. Cellulose is the primary component responsible for the high strength of plants, with its axial Young's modulus averaging between 132 and 150 Gpa (Iwamoto et al., 2009; Mariano et al., 2014).

2. Material and methods

The PLA used in this experiment, Nature Works 2003D from Cargill-Dow LLC, is a compounding-grade material suited for injection molding, thermoforming, and blow molding applications in pure form and composites. Its key feature is a high molecular weight, making it ideal for traditional extrusion processes.

A schematic diagram of this research is presented in Figure 1. Proper drying procedures are essential for optimal processing to prevent hydrolysis in the molten state. This semi-crystalline grade offers good nucleation and growth rates, with a molecular weight of approximately 2×10^4 g/mol, a 1.25 g/ml density, a melting point of 150-180°C, and a glass transition temperature of 55-60°C. The cellulose and

CNC/PLA composite processing methods can be referred to in the literature (Shi et al., 2024a, 2024b; Shi & Liu, 2021). The sample manufacturing process was carried out using an injection mould.

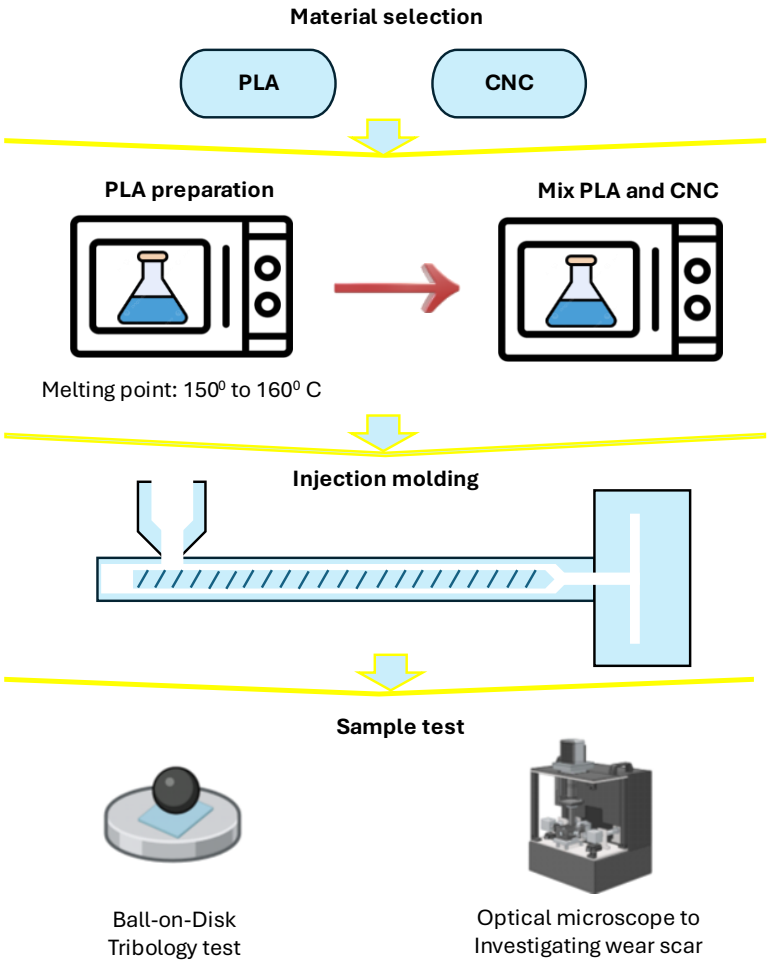

Figure 1. Schematic diagram of the research process

A ball-on-disk tribology tester (POD-FM800-25NT, FREEFORM P.M. CO., Taiwan) was used to evaluate tribological properties, as described in our previous study (Good, 1992). Test specimens, 20 mm in diameter and 3 mm thick, were cut using a CO_2 laser cutter. The tests were conducted with a rotation diameter of 10 mm, sliding speed of 0.2 m/s, load of 1.5N, rotational speed of 239 rpm, and chromium steel wear ball. The surface morphology and wear marks were observed using optical microscopy.

3. Results and discussion

Wear is a primary concern for plastic gears operating without lubrication, as heat generation under low loads often leads to wear and failure. Therefore, engineering materials should offer high wear resistance and good self-lubricating properties. Fiber-reinforced plastic gears exhibit improved wear resistance, enhanced thermal performance, and increased transmission efficiency. Additionally, fiber reinforcement reduces damping and lowers operational noise (Singh et al., 2018). The results in Figure 2 show that the friction coefficients of all materials across different sliding distances fall within the AGMA-recommended range of 0.1 to 0.4. Phenolic resin

exhibits a friction coefficient 8.5% higher than the recommended standard, while nylon maintains an average of 0.24 with minimal variation across distances. The friction coefficient of PVA decreases with the addition of CNC, indicating a self-lubricating effect. When 3 wt.% CNC is added, and the friction coefficient drops by 17%. However, with 5 wt.% CNC, the coefficient increases slightly, though overall, CNC enhances the lubrication of PLA.

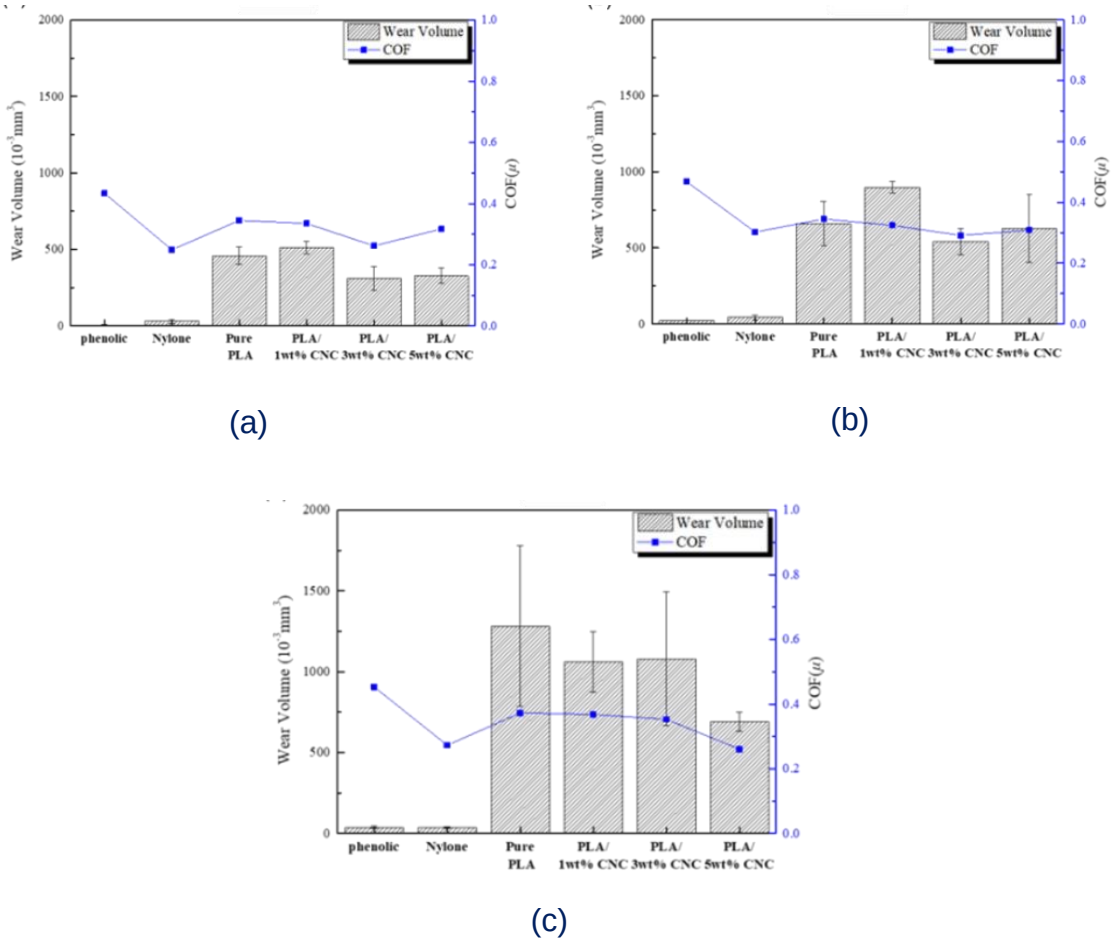

Figure 2. Changes in wear volume (μm³) and friction coefficient (μ) for phenolic resin, nylon, and PLA/CNC series at (a) 100, (b) 200, and (c) 300 meters

Figure 3 also reveals that phenolic resin and nylon exhibit minimal wear volume increases. In contrast, the wear volume of PLA and PLA/CNC composites increases with sliding distance. Figure 4 shows that under a 1.5 N load and wear distances of 100, 200, and 300 meters, the wear rate of PLA/CNC composites decreases as CNC content increases, suggesting that PLA/CNC composites are more wear-resistant than pure PLA. This enhancement is likely due to the cellulose reinforcing the PLA matrix, preventing material loss during wear (Bajpai et al., 2013). Phenolic resin and nylon exhibit superior wear resistance compared to the PLA series. Wear in sliding contact is attributed to energy dissipation due to friction.

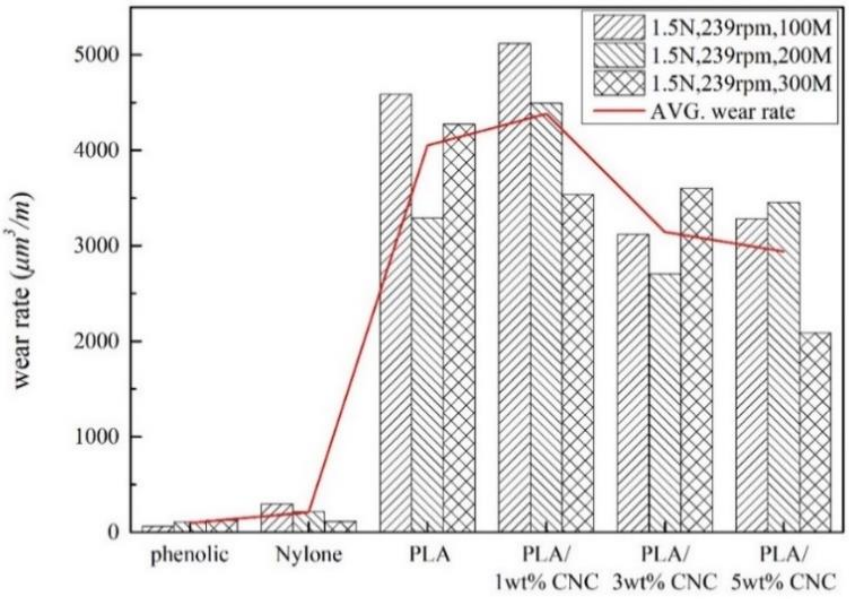

Figure 3. Phenolic resin, nylon, and PLA/CNC series wear rates

Figure 4 establishes the relationship between dissipated energy and wear volume for phenolic resin (Phenolic C), nylon (MC 901), pure PLA, and the PLA/CNC series. The wear volume of these polymers increases linearly with dissipated energy, with the slope indicating wear resistance. The nearly flat slopes of phenolic resin and nylon in Figure 4 indicate high wear resistance. In contrast, the hill of PLA/CNC composites decreases with higher CNC content, confirming improved wear resistance.

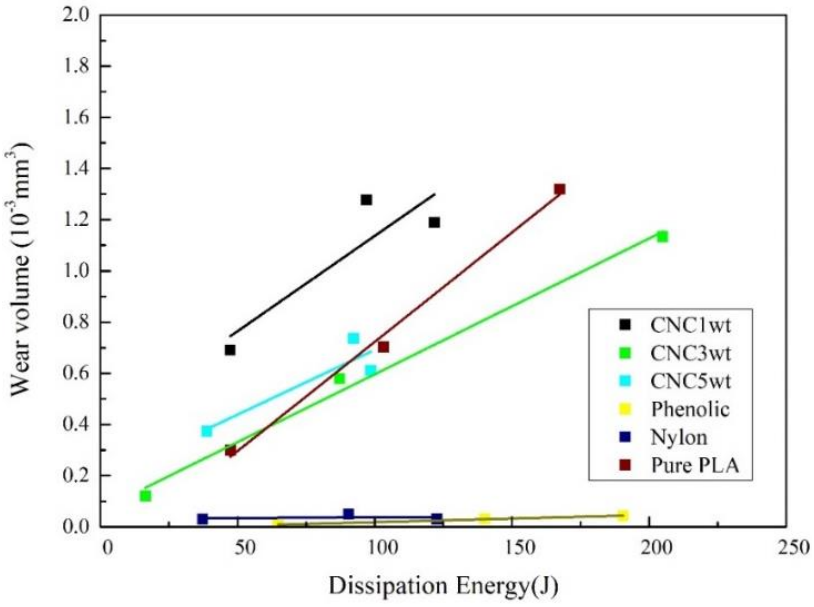

Figure 4. Dissipated energy corresponding to material wear

Further, Figure 5 shows that nylon exhibits deeper wear marks than phenolic resin as the sliding distance increases. In Figure 6, the wear marks of the PLA/CNC series become less pronounced as CNC content rises, further supporting the conclusion that CNC enhances the wear resistance of PLA composites.

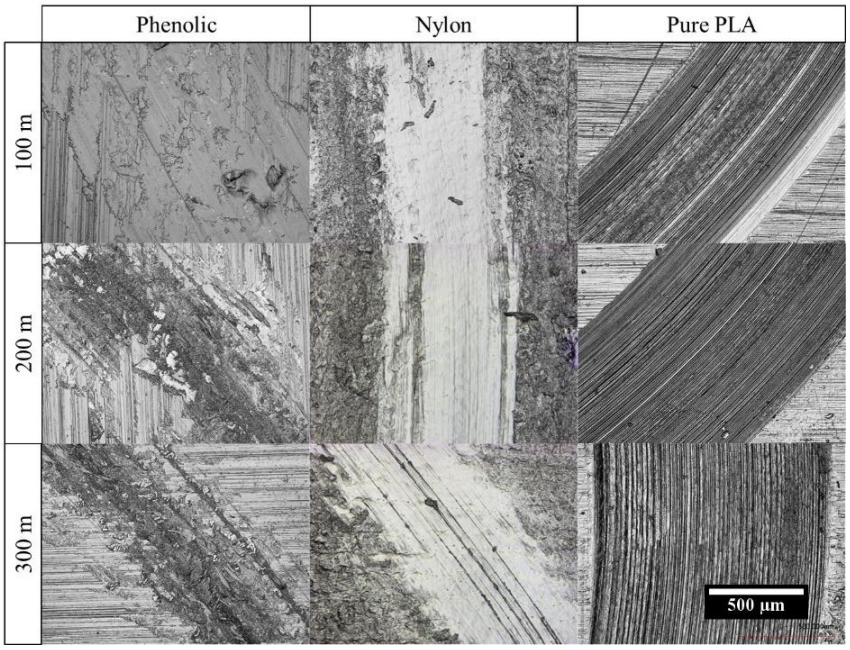

Figure 5. Wear marks of phenolic resin, nylon, and PLA/CNC series at 100, 200, and 300 meters, respectively

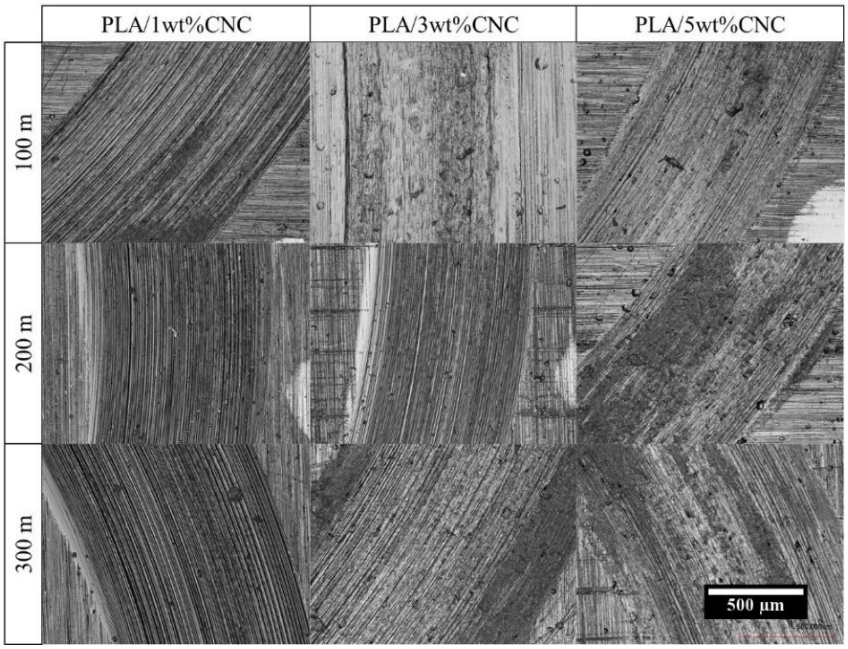

Figure 6. Wear marks of phenolic resin, nylon, and PLA/CNC series at 100, 200, and 300 meters, respectively

4. Conclusion

The study reveals that fiber reinforcement and CNC additives improve the tribological performance of PLA-based composites. Phenolic resin and nylon demonstrate superior wear resistance, with a minimal increase in wear volume and stable friction coefficients. PLA/CNC composites exhibit a significant decrease in friction coefficient

and wear rate as CNC content increases, showing enhanced wear resistance compared to pure PLA. The self-lubricating properties of CNC contribute to the improved performance of PLA, especially at 3 wt.% CNC. However, higher CNC content slightly increases the friction coefficient, though the overall tribological properties of PLA/CNC composites remain superior.

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Declarations

Author contribution

Chia-Feng Hsieh: Formal analysis, investigation, visualization, data curation. Shih-Chen Shi: Conceptualization, supervision, methodology, funding acquisition, writing - original draft. Dieter Rahmadiawan: Validation, writing - review & editing.

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Competing interest

There are no conflicts of interest in this research.

Ethical Clearance

There are no human or animal subjects in this manuscript and informed consent is not applicable.

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