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Effect of Banana Stem Ash Reinforcement on Dry Sliding Wear Behavior of Polymer

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ABSTRACT

Nowadays, Natural Fiber Reinforced Polymers (NFRPCs) are often used due to their superior physical properties and higher biodegradability than other materials. The purpose of this study is to analyze the mechanical and tribological performances of NFRPCs, which include hardness, surface roughness, and surface morphology. The specific placement and nature of the reinforcement materials on the specimens are also analyzed for their role in the degree of surface roughness. Solutions for hardness determination (HV) were applied with the help of the Vickers hardness tester. As a result, it was found that the NFRPCs with polypropylene (PP) and Musa stem ash reinforcement demonstrated the highest HV value. On top of that, the surface morphology was examined using an optical microscope, and it was found that the PP/Musa ash composite exhibited the smoothest surface. The results obtained can potentially direct future research and industrial applications in the fields of materials science and engineering, along with adding to the expanding knowledge of NFRPCs.

Keywords: Natural fibre-reinforced polymer Composites, Polymer-matrix composite, Banana, Musa, Sliding wear, Polypropylene

1. INTRODUCTION

In recent years, the quest for sustainable and environmentally friendly materials has led to a surge in research focusing on natural fibre-reinforced polymer composites (NFRPCs) as promising alternatives to conventional materials in various engineering applications. NFRPCs offer a compelling combination of desirable mechanical properties, such as a high strength-to-weight ratio and excellent biodegradability, and lightweight, making them attractive candidates for use in automotive, construction, aerospace, and consumer goods industries (Alarifi, 2023; Keya et al., 2019; Ku et al., 2011; Li et al., 2020). Despite their many benefits, NFRPCs are frequently confronted with issues regarding their mechanical performance and tribological characteristics, especially regarding wear and friction in extreme operating situations (Aldousiri et al., 2013; Parikh and Gohil, 2015). This has led to a lot of interest in investigating new reinforcement materials and processing methods to improve the mechanical strength and wear resistance of NFRPCs, opening the door to a more promising future in materials science and engineering.

A lot of research has been done on natural fibers as a possible substitute for synthetic fibers, especially in tribological applications. The study examined the applicability of polyester resin for reinforcing unidirectional cotton fibres, explaining the better wear rates with an increase in the percentage of reinforcement and enhanced material properties (Eleiche and Amin, 1986). Fibre tips make it possible to increase the diameter and practically encapsulate the resin to avert considerable destruction. Based on these findings, introducing natural fibres as reinforcement increases the physical properties of composite materials.

Thermoplastic polymers possess the unique characteristic of being able to be reheated and transformed into a molten state indefinitely. Moreover, polymers exhibit self-lubricating properties, eliminating the need for additional lubricants. Polymer composites in sliding conditions exhibit low energy transfer due to increased frictional temperature, leading to elevated wear rates when the material approaches its melting temperature under loading conditions (Pattanaik et al., 2016). Table 1 provides a comparison of polymers with varying specific wear rates.

Table 1: Comparison of polymers that have different specific wear rates

Polymer Matrix	Specific wear rate, mm^3/Nm	Maximum sliding speed, m/s	Sliding distance, km	Load, N	Ref.
Polylactic Acid	$4x10^{-5}$	3	3	30	(Bajpai et al., 2013)
Epoxy	$14x10^{-5}$	2.8	3.36	30	(Omrani et al., 2016)
Polyester	$5.6 x10^{-5}$	2.22	-	10	(Hashmi et al., 2007)
Polypropylene	$3.3x10^{-7}$	3	-	30	(Yallew et al., 2014)
Polyamide (PAs2)	$4x10^{-7}$	0.3	6	200	(Samyn et al., 2007)

Enhancing the mechanical and tribological performance of NFRPCs through Musa stem ash reinforcement has been studied in several papers. The use of Musa acuminata stem fibre (MASF) as a reinforcement for polyester composites has been investigated, showing improved mechanical properties (Darmo and Sutanto, 2023; Sujita and Sari, 2022). Additionally, the properties of treated and untreated Musa acuminate peduncle fibre (MAPF)-reinforced epoxy composites have been studied, with alkali-treated MAPF-reinforced composites showing enhanced tensile, flexural, and impact properties (Wu et al., 2023).

Furthermore, the tribological behaviour of sisal fibre-reinforced polypropylene composites has been examined, with experiments conducted to determine the friction and wear loss behaviour. The highest volumetric wear loss was observed at the highest values of applied load (Praveen Nagarajan Durai, 2022). The highlighted studies pointed out that Musa stem fibres have the potential to be reinforcements of polymer composites, which enhance their mechanical and tribological properties. A review has also been provided detailing the utilization of natural sisal fibre-reinforced composites in engineering systems and their wear properties (Parikh, 2023). It explains how various material parameters such as fibre length, weight fraction, surface treatment, and orientation affect these composites' friction and wear characteristics.

Previous studies have been conducted on the mechanical properties of banana fibre-reinforced epoxy composites, which could have environmental benefits and be a substitute for conventional composites in this field (Sapuan et al., 2006). The work concentrates on testing the composites' tensile, flexural, and impact features and provides additional information about the parameters such as strength, stiffness, and toughness.

The study investigates how the mechanical characteristics of the composites can be influenced by fibre orientation and fibre volume fractions and provides information on the best design and manufacturing parameters. The results of the study help to clarify the possible uses of banana fiber composites in the construction, automotive, and aerospace sectors, where there is a need for eco-friendly and lightweight materials. In another study, adding sisal fibre in banana/epoxy composites up to 50% by weight improves the mechanical properties and decreases the moisture absorption property (Venkateshwaran et al., 2011).

In this study, the NFRPC specimens comprise a combination of polypropylene (PP) as the matrix material and Musa stem ash/fibre as the reinforcement. The term NFRPCs in this study refers to a composite in which PP is composed of Musa stem ash or fibre. The essential purpose of this research work, which is of significant importance to our academic community, is to qualitatively assess the mechanical and tribological properties of NFRPCs, emphasizing hardness, surface roughness, and the nature of the surface.

The study aims to analyze the role of the type, shape, configuration, and geometry of the reinforcement materials embedded in the specimens on the interface roughness. The findings of this study, with the invaluable contribution of our academic peers and colleagues, will help manufacture environmentally friendly materials that can withstand stress and are helpful in various industries.

2. METHODS

2.1. Materials

For this research, the raw materials selected include polypropylene (PP) pellets as the matrix material and Musa fibre in the form of banana stem ash/fibre as the reinforcement. Polypropylene has a melting point of 160°C, and its density at room temperature is measured to be 0.905g/cm^3.

2.2. Preparation of Test Specimens

In the initial step, PP pellets weighing 35.89g were melted in an oven at 200°C for 1 hour. Banana stem fibres were obtained by burning the banana stem in a furnace at 100°C for 30 minutes. These fibres were further subjected to a second burning process at 600°C for 1 hour, producing banana stem ashes. To construct the specimens, layers of PP sheets weighing 3.76g each (3 wt%) were used to sandwich the banana stem fibres. These specimens were then heated in an oven at 200°C for 1 hour, taking advantage of the thermoplastic nature of PP. An additional specimen was prepared by sandwiching 5g of banana stem ash between three pieces of 35.89g PP sheets (4.4 wt%). Lastly, a specimen was created by mixing 5g of banana stem ash with 107.67g of PP pellets (4.4 wt%). After 1 hour of heating at 200°C, the mixture was stirred and left to heat for another hour at the same temperature.

2.3. Hardness Test

The hardness of the PP material was measured using the Vickers Hardness Test, which measures the permanent deformation of an object. The specimens were machined and polished on a grinding machine with 1000 cw sandpaper for these measurements until a smooth surface was obtained. Then, a force of 10kN was applied to find the hardness.

2.4. Surface Roughness Test

A Perthometer S2 profilometer was used to examine the surface finish of PP specimens. It was also observed that this test requires extra grinding and polishing in order to obtain a flat surface for appropriate measurement. A constant spindle speed of 1250 rpm was set for all specimens to determine the average roughness (R_a), root mean square roughness (R_q), and maximum roughness height within a specific sample length (R_{max}).

2.5. Surface Morphology Test

The surface morphology of the specimens was examined using an optical microscope. This allowed for the identification of surface topography and a comparison of surface roughness. The specimens were focused so that the data obtained had a magnification of 20x. They also employed a 'Focus' mode to ensure the images were captured clearer by stacking images of the same subject.

3. RESULTS AND DISCUSSION

3.1. Hardness Test

Each specimen's hardness value in the study has its corresponding value in Table 2. Each test was performed twice to ensure the reliability of results; several experiments must be performed to reduce the possible measurement errors and variations encountered. Additionally, hardness values help assess the various characteristics of the specimen and the resistance to the external forces applied.

For the first sample of the PP/Musa stem ash (layered), the hardness was recorded at 542.3 in the first sample, and during the second sample, the value was recorded at 575.7. It is possible to evaluate the comparative hardness and the deformation ability for more specimens using the toughness values of different specimens. At the first test, the PP/Musa stem ash (mixed) specimen reached the highest hardness of 3612, while the second test recorded a value of 2523. The mean value for hardness of the considered specimen is computed to be 3067.5. These results show that the PP/Musa stem ash (mixed) specimen does not allow indentation or deformation to occur as quickly as the other specimens tested. This composite material composition has the potential for applications requiring high hardness and resistance to external forces.

On the other hand, the PP/Musa stem fibre (layered) sample showed a lower hardness level of 316.5 in the first test and 564.3 in the second test. The specimen's average hardness value is 440.4. These findings indicate that the PP/Musa stem fibre (layered) specimen is more susceptible to indentation or deformation than the others. This composite material composition is likely unsuitable for many applications demanding high hardness and resistance to external forces. Regarding the specimens' hardness, helpful information concerning the possible applications of the samples' mechanical properties is provided.

These findings improve comprehension of material performance and potential usage of the examined composite materials. Similar findings for natural fibre-reinforced polymers were reported by Amir et al., (2017) and Arun Sankar et al., (2020).

Table 2: Hardness Value of fabricated composite specimens

Specimen	Hardness Value (HV)		Average Hardness Value
	Hardness Value 1	Hardness Value 2	
PP/ Musa stem ash (layered)	542.3	575.7	559
PP/ Musa stem ash (mixed)	3612	2523	3067.5
PP/Musa stem fiber (layered)	316.5	564.3	440.4

3.2. Surface Roughness

In this study, the Profilometer Perthometer S2 was employed to measure the surface roughness of the specimens accurately. This instrument is capable of providing precise characterization of surface topography. In this work, the chosen test surface was the cross-section of each specimen to elicit an in-depth examination of the roughness parameters. Table 3 shows the measurements made with the Profilometer Perthometer S2, presenting different surface roughness parameters for each specimen individually. Among them are R_a – average roughness, R_q – root mean square roughness, R_{max} – maximum roughness height for the length considered, and R_{sk} – skewness.

For the PP/Musa stem ash (Layer) specimen, the recorded data shows a R_a value of 0.228 µm, an R_q value of 0.290 µm, and a R_{max} value of 2.222 µm. A lower R_a and R_q value indicates a smoother surface, while a higher R_{max} value suggests more significant surface irregularities. Likewise, the PP/Musa stem ash (Mixed) specimen has the values for R_a, R_q, and R_{max} of 0.049µm, 0.071µm, and 0.769µm, respectively, which implies that the values obtained are smoother in comparison to the other specimens, with the R_a and R_q values being relatively lower. The PP/Musa stem fibre (Layer) specimen data gives a R_a value of 0.194µm, R_q value of 0.243µm, and R_{max} of 1.794µm. Such values indicate the surface roughness between the other two specimens, which is of moderate roughness.

As in Figure 1, the majority of these surfaces have been explained, and the surface roughness data is beneficial in characterizing the specimens' surfaces. Comparing various specimens and determining their suitability for particular applications is made simple by the measured parameters, which provide quantifiable information about the roughness. Because smoother surfaces show less wear and friction, lower surface roughness values typically indicate better tribological performance.

Table 3: Surface Roughness results from Profilometer Perthometer S2

Specimen	Spindle speed, rpm	R_a, μm	R_q, μm	R_{max}, μm	R_{sk}
PP/Musa stem ash (Layer)	1250	0.228	0.290	2.222	-
PP/ Musa stem ash (Mixed)	1250	0.049	0.071	0.769	-
PP/Musa stem fiber (Layer)	1250	0.194	0.243	1.794	-

(a) (c) (b)

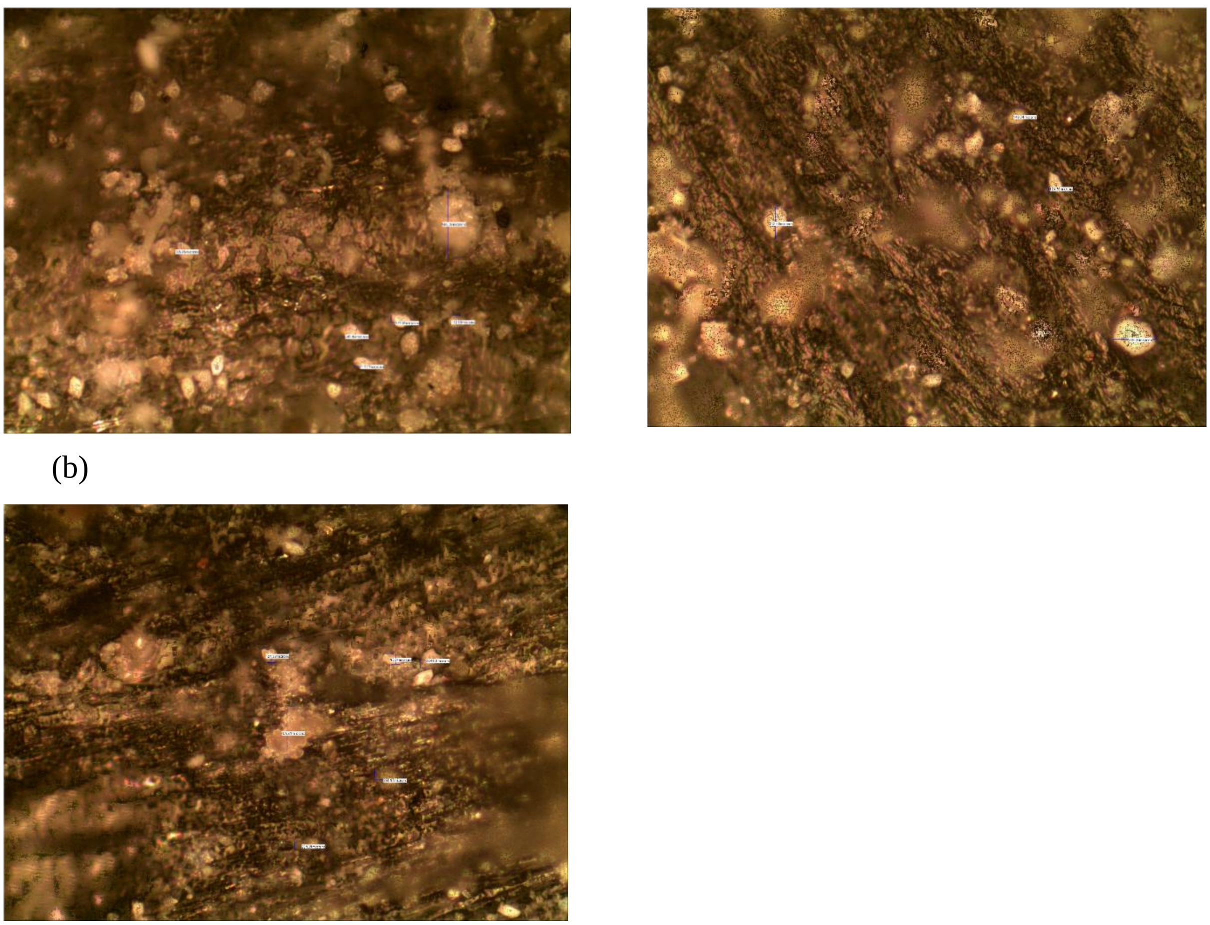

Figure 1: Surface Roughness results from Profilometer Perthometer S2 (a) PP/Musa stem ash (Layer) (b) PP/ Musa stem ash (Mixed) (c) PP/Musa stem fibre (Layer)

3.3. Surface Morphology

A 20x magnification factor was used in this study to carefully examine the specimens' cross-sections. With this degree of magnification, the researchers were able to examine the specimen surfaces in great detail and spot any small deficiencies or characteristics.

Furthermore, each specimen's three-dimensional surface was examined, offering a thorough comprehension of its structure and topography.

Table 4: Gap length from each specimen

Specimen	Gap Length
PP/Musa stem ash (Layer)	249.99 microns
PP/ Musa stem ash (Mixed)	230.08 microns
PP/Musa stem fibre (Layer)	237.19 microns

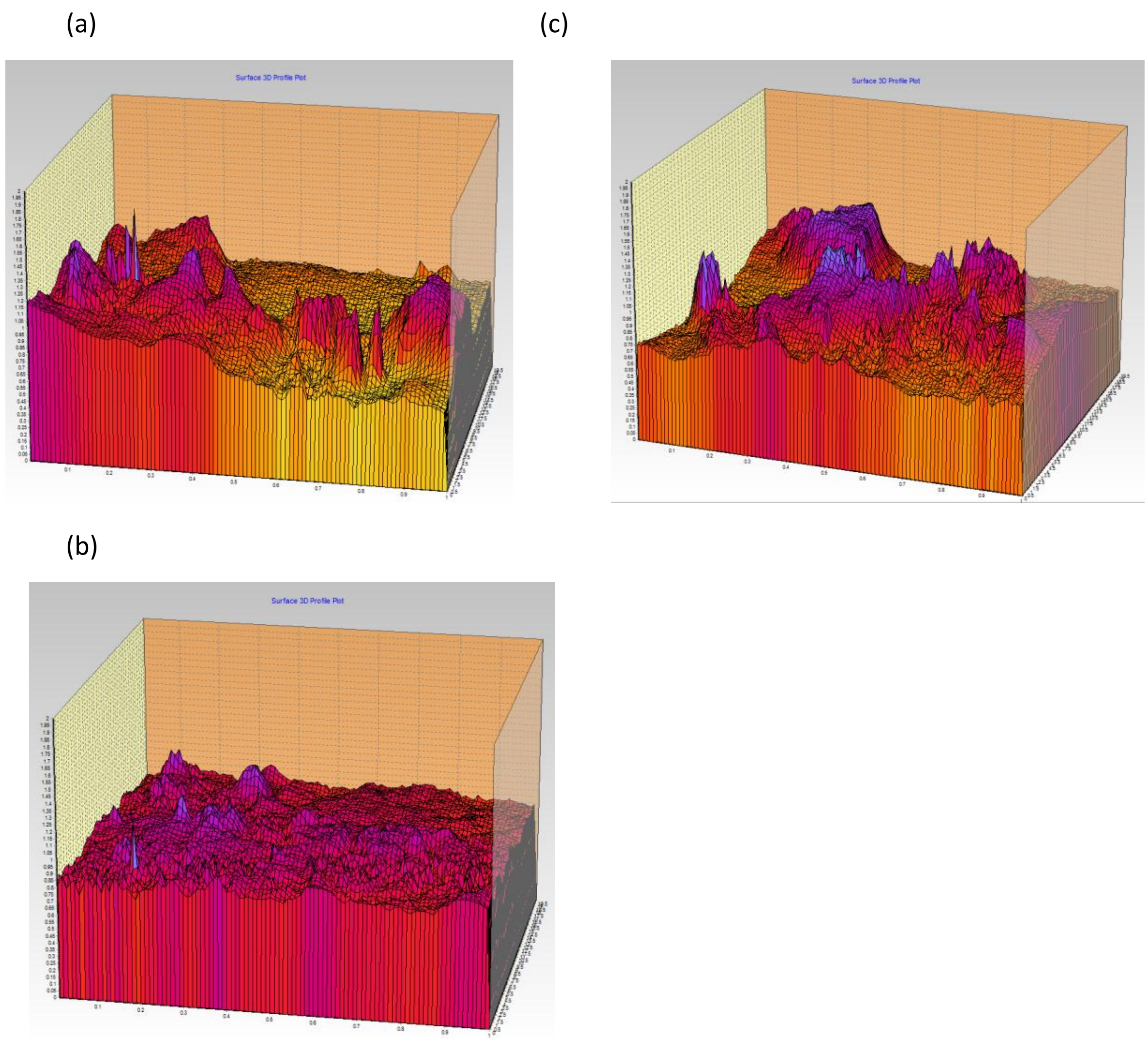

Figure 2: Gap length **(a)** PP/Musa stem ash (Layer) **(b)** PP/ Musa stem ash (Mixed) **(c)** PP/Musa stem fibre (Layer)

The recorded data in Table 4 provides information about the gap length found for each specimen. Gap length refers to the distance between two distinct points on the surface, indicating any gaps or voids in the material. It is an important indicator for evaluating the specimen's integrity and quality. The measured value for the PP/Musa stem ash (Layer) sample indicates a gap with a 249.99 micron extent. It demonstrates how the material's mechanical and tribological response properties may be impacted by structural holes or pores. Similarly, the gap length of the PP/Musa stem ash (Mixed) sample is roughly 230.08 microns. This measurement shows whether there are any voids or gaps in the specimen's structure, which may have an impact on how well it performs overall. The gap length of the PP/Musa stem fiber (Layer) specimen is 237.19 microns. This measurement implies that the material contains voids or gaps, which could affect the material's mechanical characteristics and suitability for particular uses.

As in Figure 2, significant information about the specimens' quality and homogeneity can be collected by looking at the gap length. The strength, resilience to deterioration, and durability of the material can all be impacted by gaps or voids. When assessing the specimens' performance and deciding whether they are appropriate for different applications, these factors must be taken into account.

4. CONCLUSIONS

The study focused on polypropylene's mechanical properties and tribological performance with Musa stem ash reinforcement (PP/Musa). The Vickers hardness test, surface roughness test, and surface morphology analysis results indicate its suitability for wear and tear industries due to its minor surface roughness compared to pure polypropylene and other polymers. It suggests potential applications that can replace existing wear and tear products. The polymer exhibits favorable tribological properties, mainly mixed polypropylene with banana stem ash reinforcement (PP/Musa). Its low surface roughness and self-lubricating nature make it an ideal material that does not require additional lubrication to function effectively.

The following point can be concluded:

- The hardness test results for the mixture PP/Musa specimen show a very high value of 3067.5HV. This demonstrates an object's capacity to withstand permanent deformation under a force of 10kN in loading without an indenter. The microscopic observation notes the evenness of the surface, which is further beneficial for tribological applications in higher-resistance surfaces to abrasion. In addition to the surface roughness measurement, it was confirmed that the specimen had the lowest surface finish compared with the other specimens.
- The layered PP/Musa stem ash specimen exhibits a lower hardness value of 559HV than the mixed PP/Musa stem ash. It also demonstrates a relatively rough surface, as confirmed by the surface profilometry analysis, which shows the highest roughness among the three specimens.
- The layered PP/Musa stem fibre specimen was the weakest of the three and could not be recommended for practical applications. It had voids inside the specimen and a rough surface morphology. Even if it is second in the surface roughness test according to the surface profilometry test, it cannot be used in tribological applications concerning wear and tear.

In general, mixed PP/Musa stem ash specimens have been found to possess the highest hardness, the most favorable surface morphology, and the roughest surface, which makes them suitable for tribological applications that require high performance in terms of resistance to wear and tear.

Author Contributions:

Conceptualization, E.E.M.N. and C.G.N.; methodology, E.E.M.N. and C.G.N.; validation, E.E.M.N.; formal analysis, C.G.N.; investigation, C.G.N.; resources, E.E.M.N. ; data curation, C.G.N.; writing—original draft preparation, M.F.B. ; writing—review and editing, M.F.B., and E.E.M.N.; visualization, E.E.M.N., C.G.N., and M.F.B.; supervision, E.E.M.N.; project ad-ministration, E.E.M.N.; funding acquisition, E.E.M.N. All authors have read and agreed to the published version of the manuscript.

Informed consent

Not applicable.

Ethical approval

The ethical guidelines for plant materials are followed in the study for collection, identification & experimentation.

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Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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