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Investigating the tribological properties of thermoplastic polymer composite materials based on local raw materials

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Abstract: This study investigates the tribological and physicomechanical properties of a thermoplastic polymer composite material based on polypropylene, modified with walnut shell pyrolysis residue as a local raw material. The composite's composition consists of 65 wt.% polypropylene, 15 wt.% fine-fraction walnut shell pyrolysis residue, 4 wt.% glycerol monostearate, 1 wt.% zinc oxide, and 15 wt.% R-grade glass fiber. The scientific concept of the research is to reduce the coefficient of friction, increase surface hardness, and ensure the dimensional stability of the material through the synergistic effect of a carbon-rich natural waste-based filler, a glass fiber reinforcing component, and an anti-friction additive within the polypropylene matrix. Composite samples were prepared via the extrusion method. Tribological tests were performed under dry sliding conditions with a contact pressure of 2 MPa and a sliding speed of 0.5 m/s. Furthermore, the material's hardness was assessed using the Shore D method, and its mechanical strength was evaluated by its ultimate tensile strength. The results revealed that the composite with the optimal composition had a coefficient of friction of 0.08, which was significantly lower than that of the comparative sample. For this composition, the ultimate tensile strength was 48.6 MPa, and the coefficient of linear thermal expansion was 0.0001 mm/ (m·°C). The findings indicate that walnut shell pyrolysis residue is significant not only as a simple, low-cost filler in the polypropylene matrix but also as a tribologically active carbon component. Glycerol monostearate, as an additive that reduces friction and facilitates the processing stage, and zinc oxide, as a functional modifier, enhance the operational properties of the composite. R-grade glass fiber increases the load-bearing capacity, hardness, and dimensional stability. The proposed composite material is recommended as a promising material for polymer pipes, protective coatings, and sliding elements that operate in contact with abrasive particles.

Keywords: thermoplastic composite, polypropylene, walnut shell pyrolysis residue, glass fiber, zinc oxide, glycerol monostearate, coefficient of friction, abrasive wear

1. Introduction

Thermoplastic polymer composites are increasingly regarded as promising engineering materials for applications in which the use of conventional metallic materials is limited by cost, density, corrosion resistance or processing complexity. Among thermoplastic matrices, polypropylene (PP) occupies a special position due to its low density, good chemical resistance, relatively low cost, ease of melt processing and wide industrial availability. These advantages make PP attractive for pipes, protective liners, sliding components, guide elements and structural parts operating under moderate mechanical and thermal loads. However, neat polypropylene does not always provide sufficient performance under tribological conditions. Its comparatively low surface hardness, tendency to adhesive wear, viscoelastic deformation under contact pressure and relatively high thermal expansion may reduce dimensional stability and shorten service life in abrasive or sliding-contact environments.

In many engineering systems, especially pneumatic conveying pipes, polymer liners, sliding guides and elements exposed to bulk materials or abrasive particles, the material must simultaneously exhibit low friction, adequate mechanical strength, resistance to surface damage and stable dimensions under temperature variation. Therefore, the development of reinforced and functionally modified PP-based composites with improved tribological behavior is an important scientific and practical task in modern materials engineering. The solution of this task requires not only the selection of a suitable polymer matrix, but also the rational combination of reinforcing fillers, carbonaceous modifiers and processing additives capable of forming a stable structure at the filler–matrix interface.

The development of such composites is closely related to the principles of sustainable materials science. Agricultural wastes and biomass-derived residues can be converted into value-added functional fillers through pyrolysis. As a result of pyrolytic treatment, lignocellulosic materials acquire a carbon-rich porous structure, improved thermal stability and surface characteristics that may promote mechanical interlocking with polymer melts. In comparison with untreated natural fillers, pyrolyzed biomass residues are less hydrophilic and can demonstrate better compatibility with hydrophobic polyolefin matrices. Previous studies on biochar-filled PP composites have shown that carbonaceous fillers may improve stiffness, thermal stability and resistance to degradation, depending on their origin, particle size, pyrolysis temperature and dispersion quality in the polymer matrix [1–3].

Walnut shell is one of the locally available lignocellulosic wastes and can be considered a promising

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raw material for producing carbon-rich filler. Raw walnut shell powder contains polar functional groups and is usually poorly compatible with non-polar polypropylene. Such incompatibility may lead to weak interfacial adhesion, filler agglomeration and deterioration of mechanical properties. In contrast, walnut shell pyrolysis residue contains a higher carbon fraction and a modified surface structure, which can improve its interaction with the PP matrix. From the materials science point of view, the use of walnut shell pyrolysis residue provides two important advantages: first, it enables the valorization of local agricultural waste; second, it introduces a carbonaceous phase that can contribute to friction reduction and stabilization of the tribological contact zone.

Hybrid reinforcement is another effective approach for improving the performance of polypropylene composites. Short glass fibers are widely used in thermoplastic composites to increase stiffness, tensile strength, load-bearing capacity and dimensional stability. Under tribological contact, glass fibers can partially redistribute the applied load and reduce excessive deformation of the polymer matrix. However, their effect is strongly dependent on fiber content, fiber length, orientation, dispersion quality and interfacial adhesion with the matrix. Excessive fiber content or poor fiber encapsulation may lead to fiber exposure on the worn surface and intensify abrasive interaction with the counter-body. Therefore, an optimal balance between the polymer matrix, carbonaceous filler and fibrous reinforcement is essential for obtaining a low-friction and wear-resistant composite.

In addition to reinforcing components, functional additives play an important role in controlling both processing behavior and service properties of thermoplastic composites. Glycerol monostearate is commonly used as a lubricant, antistatic agent and processing aid in polymer systems. In the molten state, it can reduce internal friction between polymer chains, filler particles and reinforcing fibers, improve melt flow and decrease adhesion of the polymer melt to metallic surfaces of processing equipment. In tribological applications, glycerol monostearate may also contribute to the reduction of sliding friction by improving surface release behavior and supporting the formation of a more stable interfacial layer during dry contact. Zinc oxide is a multifunctional inorganic modifier that can improve thermal stability, UV resistance and surface-related functional properties of PP-based materials [4]. Its presence in the composite may additionally contribute to hardness and stabilization of the polymer-filler system.

The scientific novelty of the present work lies in the development and tribological assessment of a locally sourced polypropylene-based thermoplastic composite containing walnut shell pyrolysis residue, glycerol monostearate, zinc oxide and R-grade glass fiber. The proposed composition is designed to combine the advantages of a PP matrix, a carbon-rich biomass-derived filler, fibrous reinforcement and functional modifiers in one hybrid material system. The research hypothesis is that the synergistic interaction of these components can reduce the coefficient of friction while maintaining mechanical strength and thermal-dimensional stability.

Accordingly, the aim of this study is to investigate the tribological properties of a polypropylene-based thermoplastic polymer composite produced using local raw materials and to evaluate the relationship between composition, processing, friction behavior, mechanical integrity and dimensional stability. The obtained results are expected to provide a scientific basis for the use of walnut shell pyrolysis residue as a functional carbonaceous filler in PP composites intended for polymer pipes, protective liners and sliding elements operating in abrasive particulate environments.

2. Research methodology

In this study, crosslinked polypropylene (PP) was selected as the polymer matrix forming a single continuous thermoplastic phase. In the updated formulation, PP was considered as the only polymer matrix component. The selection of this matrix phase was justified by its relatively low density, chemical stability, ease of processing, and improved resistance to collapse, sliding deformation and load-induced dimensional changes compared with unreinforced polypropylene.

Walnut shell pyrolysis residue with a particle size below 1–2 mm was used as a carbonaceous filler. This filler is a carbon-rich component obtained from locally available agricultural waste, with a reported specific surface area of 874 m^2/g. According to its elemental composition, the pyrolysis residue contains approximately 87 wt.% carbon, while phosphorus, sulfur and other mineral residues are present in smaller amounts. The incorporation of this pyrolysis residue into the composite was aimed at forming a tribologically active carbonaceous phase in the PP matrix, improving surface stability during friction, and enabling the effective utilization of local raw-material resources.

Glycerol monostearate was introduced into the composite as a processing lubricant and anti-friction additive. Its function is to improve the flowability of the molten composition, reduce internal friction between the polymer matrix, filler particles and reinforcing components, and decrease the adhesion of the material to the metallic surfaces of extrusion equipment. Zinc oxide was selected as an inorganic functional modifier. It contributes to the improvement of surface properties, thermal stability and service durability of the composite. R-grade glass fiber was used as the main reinforcing component to enhance stiffness, load-bearing capacity, mechanical strength and thermal-dimensional stability.

Table 1

Optimized formulation of the PP-based thermoplastic polymer composite

Component	**Function in the composite**	**Content, wt.%**
Crosslinked polypropylene (PP)	Thermoplastic matrix and continuous load-bearing phase	65
Walnut shell pyrolysis residue, <1–2 mm	Local carbonaceous filler and tribological modifier	15
Glycerol monostearate	Processing lubricant, anti-friction additive and release aid	4
Zinc oxide	Inorganic modifier for stability and surface functionality	1
R-grade glass fiber	Reinforcement for stiffness, strength and dimensional stability	15

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2.2. Preparation of walnut shell pyrolysis residue

Walnut shell was selected as a locally available agricultural waste and was pre-treated to obtain a carbonaceous functional filler. First, the raw material was cleaned from mechanical impurities, dried and subjected to pyrolysis under oxygen-limited conditions. As a result of pyrolysis, the lignocellulosic raw material was converted into a carbon-rich solid residue. The obtained product was ground and sieved to separate a fraction smaller than 1–2 mm.

The main purpose of pyrolysis was to reduce the hydrophilicity typical of raw walnut shell powder, increase the carbon content, and improve interfacial compatibility with the hydrophobic PP matrix. This is important because polar functional groups in natural lignocellulosic fillers can lead to weak adhesion with non-polar polyolefin matrices such as PP. After pyrolysis, the chemical nature and microstructure of the filler surface are modified, which can promote mechanical interlocking with the polymer melt and improve interfacial bonding.

Before composite preparation, the pyrolysis residue was dried to remove moisture. This step is essential because excessive moisture during melt processing may cause porosity, local degradation, gas release and the formation of interfacial defects.

2.3. Composite compounding and specimen preparation

The PP-based thermoplastic composite was prepared under laboratory conditions by melt compounding followed by extrusion. In the first stage, calculated amounts of crosslinked PP and walnut shell pyrolysis residue were introduced into the mixing zone. The mixture was heated to 160–170 °C to melt the PP matrix. Within this temperature range, melting of the polymer matrix, wetting of carbonaceous filler particles and penetration of the polymer melt into the micro-pores of the filler surface are expected to occur. This may strengthen mechanical interlocking at the filler–polymer interface and improve the structural integrity of the composite.

After the initial mixing stage, the composite mass was cooled to approximately 50 °C. In the next stage, zinc oxide and R-grade glass fiber were added. The mixture was homogenized for 5 min to ensure uniform distribution of the functional modifier and reinforcing fibers throughout the matrix volume. Then, glycerol monostearate in the molten state was introduced, and mixing was continued until a homogeneous composite mass was obtained.

The prepared composite mass was extruded through a die in the form of strands, cooled to approximately 30 °C and cut into granules with a diameter of 2–4 mm and a length of 3–5 mm. In the subsequent stage, the composite granules were processed by extrusion to obtain test specimens in the form of tapes with an approximate thickness of 0.5 mm. During the preparation of test tapes, the temperature zones of the extrusion unit were set at 120, 140, 160 and 180 °C, respectively.

Table 2

Technological processing route of the PP-based thermoplastic composite

Stage	Temperature or condition	Purpose
Initial mixing of matrix and carbonaceous filler	160–170 °C	Melting of the PP matrix and wetting of pyrolysis residue particles with polymer melt
Cooling before addition of ZnO and glass fiber	~50 °C	Reducing thermal influence and creating controlled mixing conditions
Mixing of ZnO and R-grade glass fiber	5 min	Uniform distribution of the functional modifier and reinforcing fibers in the matrix
Addition of glycerol monostearate	Molten additive	Improving melt flow and reducing internal and external friction
Strand extrusion and granulation	Cooling to ~30 °C	Obtaining granules for subsequent specimen preparation
Extrusion of test tapes	120/140/160/180 °C by zones	Formation of 0.5 mm thick test tapes

2.4. Testing equipment

The experimental methodology was developed based on laboratory equipment intended for the preparation of the composite material and the determination of its tribological and physico-mechanical properties. A laboratory melt-compounding and extrusion unit was used for specimen preparation. This equipment allows thermoplastic composite components to be mixed under controlled temperature conditions, converted into a molten state, homogenized, and formed into granules or test tapes.

An INtest-type tribological testing unit was used to evaluate sliding friction and wear behavior. This device makes it possible to determine the coefficient of friction of the composite material under controlled load and sliding speed. Surface hardness was measured using a digital Shore D durometer. The durometer was used to evaluate the local hardness of the extruded or molded specimen surface. The set of equipment is shown in Figure 1.

Fig. 1. Main equipment used in the experimental methodology: extrusion unit, tribological testing unit and digital Shore D hardness tester

2.5. Tribological testing procedure

The tribological properties of the composite specimens were evaluated under dry sliding conditions using a laboratory tribological testing unit. The coefficient of friction, μ, was selected as the main tribological parameter. The tests were carried out at a contact pressure of 2 MPa and a sliding speed of 0.5 m/s. These parameters represent a relatively severe contact regime for thermoplastic composites intended to operate in contact with abrasive particles, bulk materials or viscous technological media.

Before testing, the surface of each specimen was cleaned, conditioned at laboratory temperature and fixed in the sample holder of the testing device. The counter-body was positioned to ensure stable and uniform contact with the specimen surface. The coefficient of friction was recorded after the initial running-in period under steady-state sliding conditions. The final value was evaluated as the average of the data obtained during the stable friction regime.

When experimental mass-loss data are available, the specific wear rate of the composite can be determined using the following expression:

$$Ws = \Delta m / (\rho \cdot F \cdot L) \quad (1)$$

where Ws is the specific wear rate, Δm is the mass loss during testing, ρ is the composite density, F is the normal load, and L is the sliding distance.

In this manuscript, the coefficient of friction is presented as the main validated tribological indicator. For the final journal version, it is recommended to conduct at least three repeated tests for each composition, report the mean value and standard deviation, and additionally determine wear volume based on mass loss or 3D profilometry.

2.6. Hardness, mechanical and thermal-dimensional characterization

The surface hardness of the composite material was determined using a digital Shore D hardness tester. During measurement, the indenter was placed perpendicular to the specimen surface, and the hardness value was recorded after stabilization of the display reading. For the final scientific manuscript, it is recommended to perform measurements at no fewer than five different points for each specimen and present the average value together with the standard deviation.

Mechanical integrity was evaluated by determining the tensile failure stress of the specimens. This parameter makes it possible to assess the strength level formed as a result of the interaction between the carbonaceous filler, glass fiber, functional modifiers and the PP matrix. Thermal-dimensional stability was evaluated using the coefficient of linear thermal expansion and expressed in mm/(m·°C). This parameter is particularly important for polyolefin-based materials because high thermal expansion may lead to geometrical changes, internal stresses and reduced joint stability under service conditions.

In addition, pressure resistance and joint stability were considered as engineering performance criteria for pipe-type products. These indicators allow assessment not only of the laboratory tribological properties of the composite material, but also of its suitability for practical operation under real service conditions.

3. Results and Discussion

3.1. Composition design and interfacial justification

The composition design strategy was based on the combined action of a crosslinked polypropylene thermoplastic matrix, carbon-rich walnut shell pyrolysis residue, R-grade glass fiber and a small amount of functional modifiers. Crosslinked PP served as a continuous load-bearing thermoplastic phase, providing melt processability, chemical stability and resistance to deformation under mechanical loading. Walnut shell pyrolysis residue was introduced as a locally sourced, low-cost and carbon-rich filler capable of improving the tribological response of the polymer matrix.

From the materials science point of view, the efficiency of this filler is associated with its high carbon content and porous surface morphology. During melt compounding, the molten PP can partially penetrate the micro-pores and surface irregularities of the pyrolysis residue, promoting mechanical interlocking at the filler–matrix interface. Such interfacial interaction is important for maintaining mechanical integrity and reducing the probability of filler pull-out during sliding contact. This mechanism is consistent with the behavior reported for biochar-filled PP composites, where the infiltration of molten polymer into the porous carbonaceous filler improves interfacial bonding and contributes to enhanced composite performance [4-6].

R-grade glass fiber was used as the main reinforcing component. Its role is to increase stiffness, restrict matrix deformation under contact pressure and redistribute the applied load from the polymer surface to the internal structure of the composite. A glass fiber content of 15 wt.% was considered sufficient to provide reinforcement without excessive fiber exposure on the worn surface. Excessive fiber exposure may intensify local abrasive interaction with the counter-body and reduce the anti-friction efficiency of the composite.

Glycerol monostearate was incorporated as a processing lubricant and anti-friction additive. It improves melt flow, reduces internal friction during processing and may contribute to lower friction during dry sliding. Zinc oxide acted as a multifunctional inorganic modifier, contributing to surface stability, local hardness and thermal resistance. As a result, the developed hybrid composite system is expected to reduce friction through three main mechanisms: increased surface stiffness, reduced adhesive interaction and formation of a more stable transfer layer during sliding.

Table 3

Compared compositions used to determine the optimized formulation

Composition	PP, wt. %	Walnut shell pyrolysis residue, wt.%	GMS, wt. %	ZnO, wt. %	R-grade glass fiber, wt. %
C1	68	10	12	2	8
C2	65	12	10	1	12
C3 — optimized	65	15	4	1	15
C4	58	10	9	3	20
C5	55	12	12	1	20

3.2. Friction behavior under dry sliding conditions

The coefficient of friction values are summarized in Table 4 and illustrated in Figure 2. Among all compared formulations, the optimized C3 composition demonstrated the lowest coefficient of friction, μ = 0.08, under a contact pressure of 2 MPa and a sliding speed of 0.5 m/s. For comparison, the reference D2 composition showed a coefficient of friction of μ = 0.21 under the same testing conditions. This indicates that the optimized PP-based composite reduced friction by approximately 61.9% relative to the reference composition.

The other experimental compositions showed higher friction values: 0.16 for C1, 0.18 for C2, 0.14 for C4 and 0.18 for C5. These results demonstrate that a simple increase in lubricant content or glass fiber content does not automatically lead to the lowest coefficient of friction. The most effective result was obtained only when the amounts of walnut shell pyrolysis residue, glycerol monostearate and R-grade glass fiber were balanced. In particular, the combination of 15 wt.% pyrolysis residue, 4 wt.% glycerol monostearate and 15 wt.% glass fiber provided the most favorable tribological behavior.

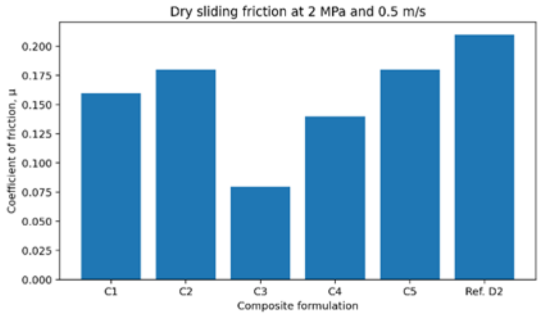

Fig. 2. Coefficient of friction of the experimental compositions and reference D2 at 2 MPa and 0.5 m/s

The reduced friction of the C3 composition can be explained by the synergistic interaction between the carbonaceous filler and the processing lubricant. Walnut shell pyrolysis residue may act as a carbon-based micro-reinforcing filler and support the formation of a carbon-rich tribolayer at the sliding interface. Such a tribolayer can reduce direct adhesive interaction between the PP surface and the counter-body. Glycerol monostearate can decrease friction associated with polymer chain mobility and improve surface release behavior. At the same time, glass fibers increase the rigidity of the surface layer and reduce the real contact area caused by viscoelastic deformation of the polymer matrix.

The higher glass fiber content in C4 and C5 did not result in the lowest friction. This may be associated with partial exposure of fibers on the contact surface, which can produce local abrasive interaction and partially compensate for the anti-friction effect of the carbonaceous filler and lubricant. Therefore, the C3 formulation represents the most balanced composition in terms of friction reduction and structural stability.

3.3. Mechanical integrity and hardness

Tribological performance cannot be evaluated separately from mechanical integrity. A composite material with low friction but insufficient strength would not be suitable for pipe liners, sliding guides, protective coatings or structural elements operating in abrasive environments. Therefore, tensile failure stress and surface hardness are important parameters for evaluating the practical applicability of the developed PP-based composite.

The optimized C3 composition showed a tensile failure stress of 48.6 MPa, which was higher than the values obtained for all other experimental compositions and significantly higher than the reference value of 28.5 MPa. The increase in tensile failure stress relative to the reference composition was approximately 70.5%. This result confirms that the reduction in friction was not achieved at the expense of weakening the polymer composite. On the contrary, the balanced combination of carbonaceous filler, glass fiber and functional modifiers improved both friction behavior and mechanical strength.

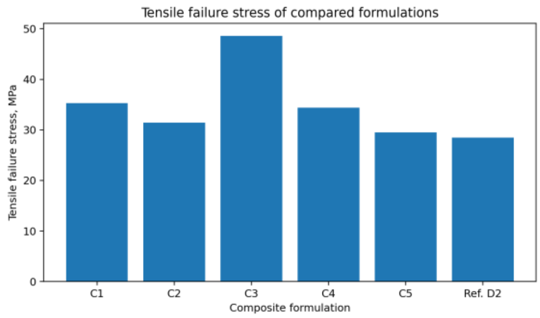

Fig. 3. Tensile failure stress of the compared compositions

The improved mechanical performance of the C3 composition may be attributed to more effective load transfer between the PP matrix, walnut shell pyrolysis residue and R-grade glass fibers. The carbon-rich filler can contribute to interfacial mechanical interlocking, while the glass fibers provide reinforcement and restrict deformation. Zinc oxide particles may additionally increase local stiffness, whereas the PP matrix maintains the necessary toughness and thermoplastic processability.

Surface hardness was evaluated using a digital Shore D hardness tester. For a complete journal version, it is recommended to provide at least five measurements for each sample and report the mean value together with the standard deviation. From the materials science perspective, increased surface hardness is expected to reduce scratching by abrasive particles and limit deformation under the counter-body during sliding. In the developed composite, surface hardness is mainly supported by the combined effect of R-grade glass fiber, zinc oxide particles and carbonaceous pyrolysis residue.

3.4. Thermal-dimensional stability and pressure-related performance

Thermal expansion is one of the critical limitations of PP-based components, particularly in pipe-type structures and elements subjected to temperature variation. As shown in Figure 4, the optimized C3 composite exhibited a linear thermal expansion coefficient of 0.0001 mm/(m·°C), while the reference D2 composition showed a much higher value of 0.024 mm/(m·°C). This significant reduction indicates that the hybrid filler system effectively restricts the mobility of PP molecular chains during heating.

The low thermal expansion coefficient of the optimized composite is primarily associated with the presence of dimensionally stable phases within the thermoplastic matrix. R-grade glass fibers, zinc oxide particles and walnut shell pyrolysis residue act as reinforcing and stabilizing components. Their distribution in the PP matrix reduces the tendency of the polymer phase to undergo excessive thermal expansion. This is especially important for polymer pipes and structural elements where dimensional changes may lead to internal stresses, joint instability and leakage.

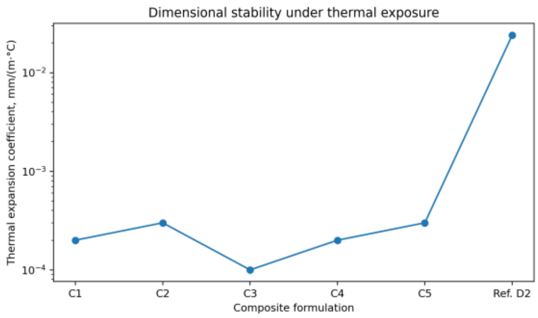

Fig. 4. Thermal expansion coefficient of the compared compositions, presented on a logarithmic scale

The C3 composition also demonstrated favorable pressure-related performance. During the leak-tightness test at 1.5 times the working pressure and 20 °C, the optimized composite showed no leakage. The resistance of pipe joints under an internal pressure of 1 MPa at 60–80 °C reached 200 h, compared with 143 h for the reference composition. In addition, joint resistance under tensile loading above 40 °C reached 22 h. These engineering indicators confirm that the improved friction behavior of the C3 composition was achieved not by compromising structural performance, but due to the synergistic effect of the hybrid filler system and PP matrix.

Table 4

Comparative properties of experimental compositions and reference D2

Property	C1	C2	C3 optimized	C4	C5	Reference D2
Tensile failure stress, MPa	35.3	31.4	48.6	34.4	29.5	28.5
Coefficient of friction at 2 MPa and 0.5 m/s	0.16	0.18	0.08	0.14	0.18	0.21
Thermal expansion coefficient, mm/(m·°C)	0.0002	0.0003	0.0001	0.0002	0.0003	0.024
Leak-tightness at 1.5 working pressure and 20 °C	Leakage after 25 s	Leakage after 25 s	No leakage	No leakage	Leakage after 20 s	Leakage after 8 s
Joint resistance at 1 MPa and 60–80 °C	175 h	175 h	200 h	170 h	170 h	143 h
Joint resistance under tensile load above 40 °C	10 h	10 h	22 h	8 h	8 h	—

3.5. Proposed wear mechanism

The proposed wear mechanism of the optimized PP-based hybrid composite is presented in Figure 5. During the initial running-in stage, the surface asperities of the composite come into contact with the counter-body. A small amount of polymer-rich material may be transferred to the sliding interface. The presence of carbon-rich walnut shell

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pyrolysis residue can stabilize this interfacial layer and reduce adhesive interaction between the sliding surfaces.

At the same time, R-grade glass fibers carry part of the normal load and restrict the penetration of the counter-body into the polymer matrix. This reduces the depth of surface deformation and limits the formation of severe wear grooves. Zinc oxide particles may contribute to local hardness and thermal stability, while glycerol monostearate reduces internal friction and surface adhesion tendency. As a result, the composite reaches a more stable friction regime with a lower steady-state coefficient of friction.

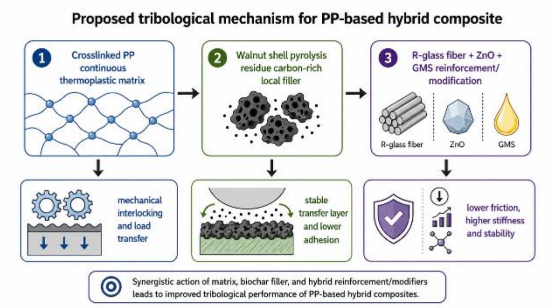

Fig. 5. Proposed mechanism for friction reduction and stability improvement in the PP-based hybrid thermoplastic composite

3.6. Sustainability and engineering significance

The use of walnut shell pyrolysis residue has practical significance beyond friction reduction. It expands the raw-material base for polymer composites by converting agricultural waste into a functional carbonaceous filler. This approach is consistent with the principles of circular economy and sustainable materials engineering, since it reduces dependence on conventional mineral fillers and creates added value from low-cost local resources.

The optimized composition does not rely on excessively high glass fiber content, which is also important from a processing point of view. Moderate fiber loading helps maintain melt processability and reduces the risk of excessive abrasive action on extrusion equipment. At the same time, the combination of glass fiber, carbonaceous filler, zinc oxide and glycerol monostearate provides a balanced relationship between mechanical strength, low friction and dimensional stability.

From an engineering application perspective, the developed composite is promising for polymer pipes, protective liners and structural elements used for transporting bulk materials, fibrous materials or viscous technological fluids containing abrasive particles. A low coefficient of friction can reduce energy losses and surface heating during material movement. High tensile strength and low thermal expansion improve dimensional stability, while pressure resistance indicates potential suitability for pipe-type systems. However, the final field of application should be selected after additional long-term tests, including abrasive wear, fatigue, water absorption, thermal aging and chemical resistance under service-specific conditions.

4. Conclusion

1. The PP-based thermoplastic composite containing 65 wt.% crosslinked polypropylene, 15 wt.% walnut shell pyrolysis residue, 4 wt.% glycerol monostearate, 1 wt.% zinc oxide and 15 wt.% R-grade glass fiber demonstrated the most balanced performance among the compared compositions.

2. Under dry sliding conditions at a contact pressure of 2 MPa and a sliding speed of 0.5 m/s, the optimized composition showed a coefficient of friction of 0.08, while the reference composition showed a value of 0.21. This corresponds to an approximately 61.9% reduction in friction.

3. The same optimized composition exhibited a tensile failure stress of 48.6 MPa, which was approximately 70.5% higher than the reference value. This confirms that friction reduction was achieved without weakening the composite structure.

4. The coefficient of linear thermal expansion decreased to 0.0001 mm/(m·°C), indicating high dimensional stability. The optimized composite also showed no leakage during the leak-tightness test and demonstrated improved pressure-related durability.

5. The observed performance improvement is attributed to the synergistic interaction of the crosslinked PP matrix, carbon-rich walnut shell pyrolysis residue, R-grade glass fiber reinforcement, glycerol monostearate lubrication and zinc oxide modification.

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