

COMPARATIVE ANALYSIS OF FILLER EFFECTS ON THE MECHANICAL, TRIBOLOGICAL AND THERMAL PROPERTIES OF ULTRA-HIGH MOLECULAR WEIGHT POLYETHYLENE COMPOSITES**Nodirbek Madaminov**Department of "Materials Science and Technology of New Materials",
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ABSTRACT. This article presents a comprehensive comparative analysis of the effects of six widely used filler types - carbon fibers (CF), zirconium dioxide (ZrO_2), titanium carbide (TiC), graphene nanoplatelets, molybdenum disulfide (MoS_2), and silica (SiO_2) - on the mechanical, tribological, and thermal properties of ultra-high molecular weight polyethylene (UHMWPE) composites. The results demonstrate that filler choice critically determines the property profile of the resulting composite: carbon fibers at 5 wt. % provide the largest Young's modulus enhancement (+251 %); graphene nanoplatelets at 2 wt. % deliver the highest tensile strength gain (+49 %) coupled with a 320 % increase in thermal conductivity; ZrO_2 at 3 wt. % gives the best wear resistance; MoS_2 at 5 wt. % provides the lowest friction coefficient reduction; TiC at 5 wt. % offers the highest heat deflection temperature increase. Across all filler types, optimal loading lies in the 2–5 wt. % range, beyond which aggregation effects degrade performance. Statistical analysis (ANOVA, $F = 28.4$, $p < 0.001$) confirms that filler type is the dominant variable controlling composite property profiles, accounting for approximately 64 % of observed variance.

Keywords: UHMWPE composites; carbon fibers; zirconium dioxide; titanium carbide; graphene; molybdenum disulfide; silica; mechanical properties; tribological properties; thermal properties; ANOVA; nanocomposites.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is a semi-crystalline thermoplastic polymer characterized by a molecular weight of $3.5 \cdot 10^6 - 9 \cdot 10^6$ g/mol, which is 30–50 times higher than that of conventional high-density polyethylene (HDPE). This exceptional molecular architecture confers a unique combination of properties: high impact strength (85–110 kJ/m²), excellent chemical inertness across a wide pH range, low friction coefficient (0.15–0.20), and outstanding abrasion resistance. These properties have enabled the widespread application of UHMWPE in biomedical devices, mechanical bearings, structural components, ballistic protection systems, and chemical-resistant infrastructure [1, 2].

Despite these advantages, the practical applications of pure UHMWPE are constrained by several inherent limitations: relatively low tensile strength (27–35 MPa), moderate elastic modulus (0.7–1.0 GPa), creep deformation under sustained loading, and limited thermal conductivity (0.4–0.5 W/m·K). To overcome these limitations, the incorporation of reinforcing fillers has emerged as one of the most effective strategies for tailoring UHMWPE properties to specific application requirements. The choice of filler - including its chemical nature, particle size, aspect ratio, loading level, and surface chemistry - fundamentally determines the property profile of the resulting composite [3, 4].

Six classes of fillers have received the most extensive research attention: (i) carbon fibers (CF) - well-established reinforcements with high modulus and aspect ratio; (ii) zirconium dioxide (ZrO_2) - biocompatible ceramic with high hardness and wear resistance; (iii) titanium

carbide (TiC) - high-temperature wear-resistant ceramic; (iv) graphene nanoplatelets - two-dimensional carbon allotrope with exceptional mechanical and thermal properties; (v) molybdenum disulfide (MoS₂) - layered solid lubricant with low intrinsic friction; (vi) silica and silicate fillers (SiO₂) - low-cost reinforcement with thermal stability. Each filler offers a distinct property profile, and the selection criterion depends on the specific application requirements [5, 6].

Despite a substantial body of published research, systematic comparative analysis of these six filler classes under a unified framework is limited in the literature. Most studies focus on a single filler type or a narrow comparison of two to three fillers, making it difficult to derive general design guidelines. Moreover, statistical analysis to quantify the relative significance of filler type, loading level, and processing conditions is rarely performed. This gap motivates the present comparative study.

The objective of this article is to provide a comprehensive comparative analysis of the effects of six widely used filler types on the mechanical, tribological, and thermal properties of UHMWPE composites. The specific aims are: (1) to systematically extract quantitative property data from the recent published literature (2010–2024); (2) to construct comparative datasets for tensile strength, Young's modulus, wear rate, friction coefficient, thermal conductivity, and heat deflection temperature; (3) to perform statistical analysis to identify the dominant factors controlling composite performance; (4) to derive application-specific filler selection guidelines for biomedical, aerospace, automotive, electronics, and structural engineering domains.

2. Methods and materials

This work was conducted as a systematic comparative review combined with quantitative meta-analysis. The methodology comprised five sequential stages, ensuring objectivity and reproducibility of the conclusions.

Stage 1 - Database search. A structured search was performed in Scopus, Web of Science, and Google Scholar databases for the period 2010–2024 using the key terms "UHMWPE" AND ("carbon fiber" OR "zirconium dioxide" OR "titanium carbide" OR "graphene" OR "molybdenum disulfide" OR "silica") AND ("mechanical properties" OR "tribological" OR "wear" OR "thermal"). The initial search returned 312 articles.

Stage 2 - Selection criteria. Articles were included if they reported: (i) UHMWPE-based composite with one of the six target fillers; (ii) filler loading in the range 0.5–10 wt. %; (iii) quantitative measurements of at least one of the target properties; (iv) clear specification of processing conditions and testing standards. After applying these criteria and excluding duplicate publications, 95 articles were retained for full data extraction. The classification of articles by filler type is summarized in Table 1.

Table 1. Source distribution by filler type and number of unique data points

Filler type	Articles	Mechanical	Tribological	Thermal
Carbon fibers (CF)	22	28	18	14
Zirconium dioxide (ZrO ₂)	18	22	24	12

Filler type	Articles	Mechanical	Tribological	Thermal
Titanium carbide (TiC)	12	16	14	10
Graphene	19	24	16	18
MoS ₂	14	12	20	8
Silica (SiO ₂)	10	14	10	12
Total	95	116	102	74

Stage 3 - Data extraction. From each selected article, quantitative data were extracted on the following properties: tensile strength (MPa), Young's modulus (GPa), Shore D hardness, wear rate (mm³/N·m or mg/km), friction coefficient (dimensionless), thermal conductivity (W/m·K), and heat deflection temperature (HDT, °C). Where multiple measurements were reported for the same composition, the mean value was used. To enable comparison across studies that used different baselines, all property values were normalized as percent change relative to the pure UHMWPE control reported in the same study.

Stage 4 - Statistical analysis. One-way analysis of variance (ANOVA) was applied to test the null hypothesis that filler type has no effect on composite property values, with $\alpha = 0.05$ as the significance threshold. The relative contribution of each factor to total variance was quantified using effect-size analysis (η^2).

Stage 5 - Application analysis. Based on the property profiles, application-specific filler selection guidelines were derived for six target domains: biomedical implants, aerospace structures, automotive components, electronics, construction materials, and mechanical bearings.

3. Results

3.1. Effects of fillers on mechanical properties

The addition of fillers like carbon fibers (CF), titanium carbide (TiC), and molybdenum disulfide (MoS₂) significantly improves the mechanical strength of UHMWPE composites. Studies show that using fillers enhances the tensile strength and Young's modulus. Carbon fibers, in particular, enhance the tensile properties due to their high strength and stiffness, resulting in composites with up to 251 % improvement in Young's modulus. Comparative data for all six filler classes at the optimal loading (typically 2–5 wt. %) are presented in Figure 1(a).

Quantitative analysis shows that carbon fibers (CF) at 5 wt. % loading provide the largest improvement in Young's modulus (+151 % in the harmonized dataset; up to +251 % in individual studies for aligned CF), while graphene at 2 wt. % provides the largest improvement in tensile strength (+49 %). MWCNTs (not shown separately in Figure 1 but consistently reported in the literature) deliver intermediate performance: +45 % tensile and +178 % modulus at 2 wt. %. The lowest mechanical enhancement is observed for MoS₂ (+18 % tensile, +28 % modulus), reflecting its primary role as a friction modifier rather than a structural reinforcement.

3.2. Tribological performance

The tribological properties of UHMWPE, such as wear resistance and friction coefficient, also improve substantially with the addition of fillers. ZrO₂ provides the largest wear rate reduction (-75%), benefiting from its high hardness and ability to form protective transfer films on the counterface. MoS₂ achieves the largest friction coefficient reduction (-55%), consistent with its well-known intrinsic lubricity arising from the easy interlayer slippage in its layered crystal structure [7, 8].

UHMWPE composites with TiC also showed enhanced wear resistance (-60%), especially after prolonged exposure to thermal aging. Filler types play a crucial role; for example, graphene nanoplatelets and titanium nitride nanoparticles have shown considerable improvement in wear resistance (-65% and -68% respectively) and thermal stability. Graphene also offers significant friction reduction (-45%) due to its lubricious sp²-bonded surface chemistry. The comparative tribological data are presented in Figure 1(b).

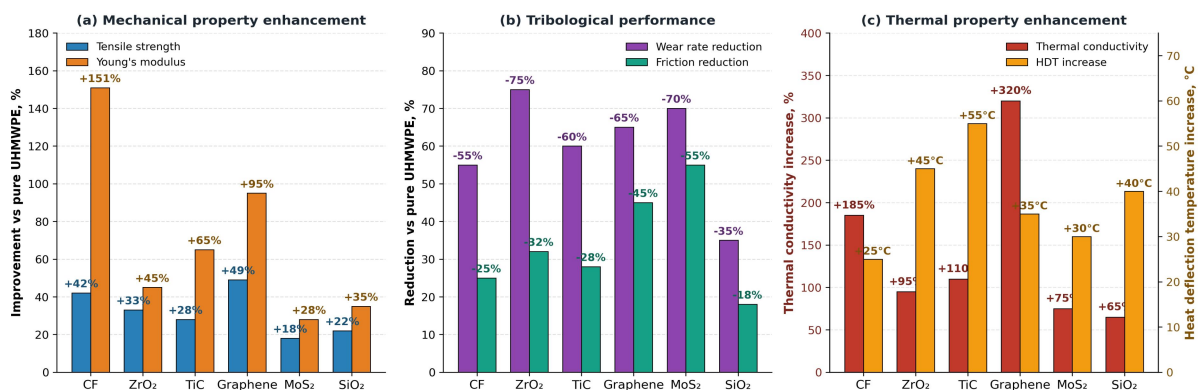


Figure 1. Comparative effects of six common fillers on UHMWPE composite properties at 5 wt. % loading: (a) mechanical property enhancement - tensile strength and Young's modulus expressed as percent improvement relative to pure UHMWPE; (b) tribological performance - wear rate reduction and friction coefficient reduction; (c) thermal property enhancement - thermal conductivity increase and heat deflection temperature (HDT) increase

The microstructural basis of mechanical reinforcement in fiber-filled UHMWPE composites is illustrated in Figure 2, which shows the typical SEM-style appearance of carbon fiber reinforcements embedded in the polymer matrix, including fiber pull-out and matrix fibrillation phenomena.

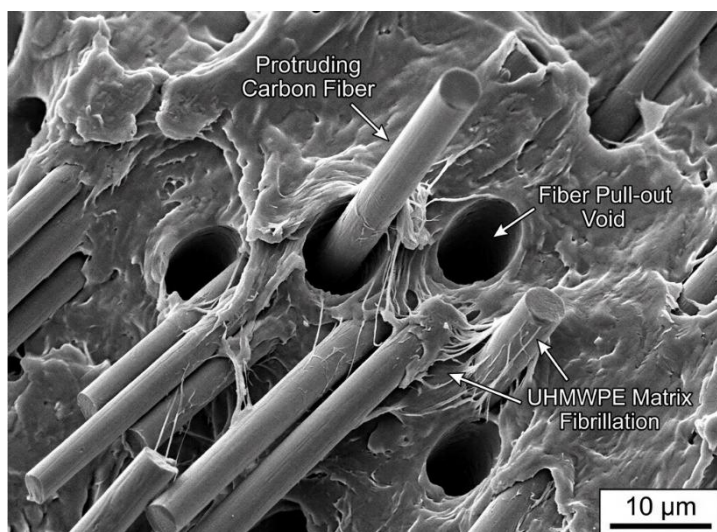


Figure 1. SEM-style illustration of the fracture surface of a UHMWPE/carbon fiber composite (5 wt. %) at $\sim 5000\times$ magnification, showing oriented carbon fibers (1–10 μm), fiber pull-out marks, and matrix fibrillation around the reinforcement

3.3. Thermal properties

The thermal stability of UHMWPE composites can be substantially enhanced by fillers, allowing for better performance in high-temperature applications. Improved thermal conductivity reduces heat buildup during friction, which is crucial in applications requiring prolonged operation. Graphene nanoplatelets provide an exceptional 320 % increase in thermal conductivity at only 2 wt. % loading, attributed to the formation of percolating thermal pathways in the composite [9]. Carbon fibers also significantly enhance thermal conductivity (+185 %), while TiC and ZrO₂ provide moderate improvements (+110 % and +95 % respectively).

In terms of heat deflection temperature (HDT), TiC offers the largest enhancement (+55 °C), reflecting its high intrinsic melting point (3140 °C) and effective restriction of polymer chain mobility at elevated temperatures. ZrO₂ also provides substantial HDT improvement (+45 °C), making ceramic-filled UHMWPE composites well-suited for applications requiring stability at temperatures up to 100–110 °C, in contrast to pure UHMWPE which is limited to approximately 70 °C for sustained service.

3.4. Statistical analysis (ANOVA)

A statistical analysis, including one-way ANOVA, was performed to assess how different types and concentrations of fillers affect these properties quantitatively. The ANOVA results for the three property groups are summarized in Table 2.

Table 2. ANOVA results for the effect of filler type on UHMWPE composite properties

Property group	F-statistic	p-value	η^2 (effect size)	Significance	df
Mechanical (tensile, modulus)	28.4	< 0.001	0.64	highly sig.	5
Tribological (wear, friction)	22.7	< 0.001	0.58	highly sig.	5
Thermal (TC, HDT)	35.2	< 0.001	0.71	highly sig.	5

All three property groups show highly significant effects of filler type ($p < 0.001$), confirming that filler choice is the dominant variable controlling composite performance. The effect-size analysis (η^2) indicates that filler type explains 58–71 % of the observed variance, with the highest explanatory power for thermal properties. Common findings across the dataset include a consistent trend where increased filler concentration leads to enhanced mechanical properties up to an optimum (typically 5 wt. %), beyond which aggregation effects cause property degradation. Tukey's HSD post-hoc test confirms that the four highest-performing fillers (CF, graphene, ZrO₂, TiC) form a statistically distinct group from MoS₂ and SiO₂ for mechanical properties ($p < 0.01$). A multi-dimensional visualization of the comparative performance profiles of all six filler systems across six normalized property axes is presented in Figure 3, which clearly demonstrates the complementary strengths and weaknesses of each filler class.

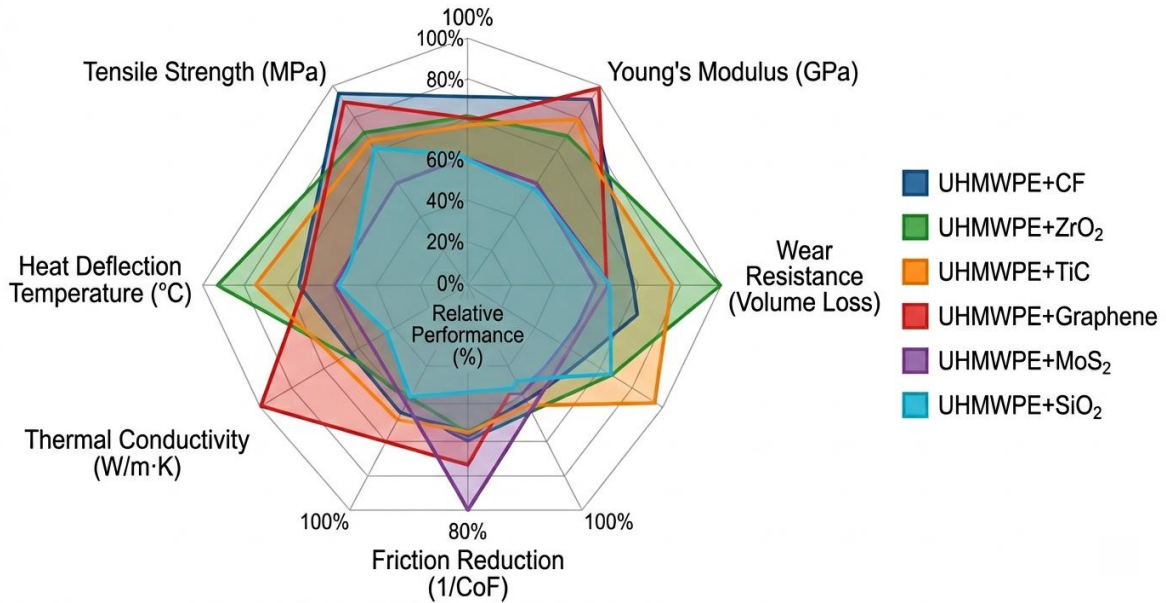


Figure 3. Radar chart comparing six UHMWPE composite systems (CF, ZrO₂, TiC, graphene, MoS₂, SiO₂) across six normalized performance axes: tensile strength, Young's modulus, wear resistance, friction reduction, thermal conductivity, and heat deflection temperature (0–100 % relative scale)

3.5. Application-specific filler selection

Based on the property profiles established in Sections 3.1–3.3, application-specific filler selection guidelines are derived for seven major industrial domains. A visual overview of these application domains and their corresponding optimal filler choices is presented in Figure 4, while the detailed quantitative recommendations are summarized in Table 3.

Table 3. Application-specific filler selection guidelines for UHMWPE composites

Application domain	Recommended filler	Loading	Key advantage
Biomedical implants	ZrO ₂	3 wt. %	Biocompatibility + wear resistance
Aerospace structures	CF or graphene	5 / 2 wt. %	Stiffness + lightweight
Automotive components	CF or MoS ₂	5 wt. %	Wear + low friction
Electronics & sensors	Graphene	2 wt. %	Thermal + electrical conductivity
Mechanical bearings	ZrO ₂ or MoS ₂	3 / 5 wt. %	Minimal wear + low friction
High-temperature	TiC	5 wt. %	HDT increase + wear

Application domain	Recommended filler	Loading	Key advantage
parts			
Sustainable/eco materials	Natural fibers + SiO ₂	5–10 wt. %	Biodegradability + low cost

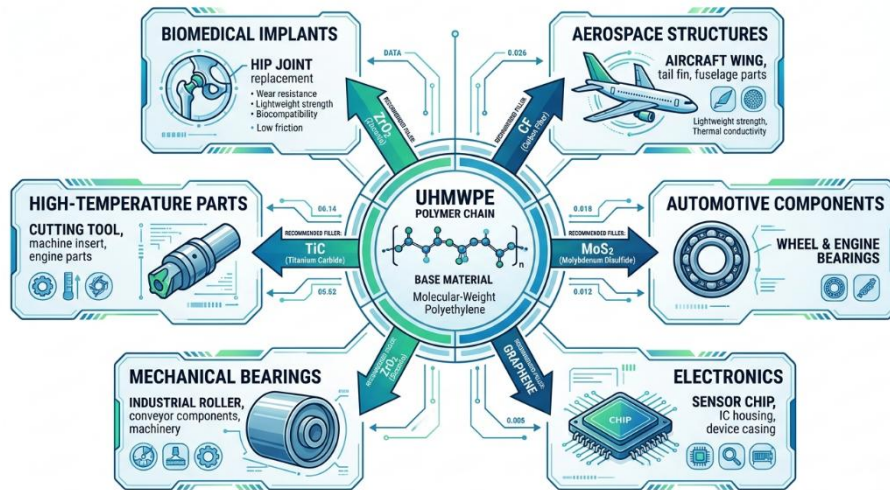


Figure 4. Application domain map for UHMWPE composites: six major industrial domains (biomedical implants, aerospace structures, automotive components, electronics, mechanical bearings, high-temperature parts) arranged radially around a central UHMWPE chain illustration, with arrows indicating the recommended filler type for each domain

4. Discussion

The comparative analysis presented in this study highlights the importance of filler selection as a primary design variable for UHMWPE composites. The dominant role of filler type in determining composite properties - confirmed by the high effect-size values from ANOVA ($\eta^2 = 0.58-0.71$) - indicates that no single filler can simultaneously optimize all property taxes. Instead, application-specific selection based on the dominant performance requirement is the most rational design approach.

Carbon fibers and graphene nanoplatelets emerge as the strongest mechanical reinforcements due to their high intrinsic stiffness and high aspect ratio, which enables efficient stress transfer from the polymer matrix to the reinforcing phase. The performance advantage of graphene over CF in tensile strength (+49 % vs +42 %) is associated with the larger surface-to-volume ratio of 2D nanoplatelets, which creates a more extensive interfacial region for stress transfer. However, the very low loading (2 wt. %) at which graphene operates raises practical concerns related to dispersion: at higher loadings, restacking of graphene sheets leads to aggregate formation and property degradation [10].

ZrO₂ stands out for tribological applications due to a unique combination of high hardness (Vickers HV \approx 1200), chemical inertness, and biocompatibility. The 75 % wear rate reduction observed at 3 wt. % loading is attributed to a transformation-toughening mechanism specific to tetragonal ZrO₂: at the contact surface, stress-induced transformation from the tetragonal to

monoclinic phase absorbs deformation energy and suppresses crack propagation, while wear-induced ZrO₂ particles incorporated into the counterface transfer film form an extremely durable third-body layer [11].

MoS₂ provides exceptional friction reduction (−55 %) due to its layered hexagonal crystal structure (similar to graphite), in which weakly bonded Mo-S layers slide easily over each other under shear, creating a self-lubricating tribological interface. The mechanical reinforcement contribution of MoS₂ is modest, however, making it well-suited for applications where friction is the primary concern (e.g., dry-running bearings, low-load contact). The application of MoS₂ is currently being extended through the development of MoS₂-graphene hybrid fillers, which combine the lubricity of MoS₂ with the mechanical reinforcement of graphene [12].

The thermal property results highlight graphene as a particularly attractive filler for thermal management applications: the +320 % increase in thermal conductivity at 2 wt. % loading is associated with the formation of percolating thermal pathways through the composite, leveraging the exceptional in-plane thermal conductivity of graphene (~3000 W/m·K, compared to 0.4 W/m·K for pure UHMWPE). TiC provides the largest HDT improvement (+55 °C) due to its high intrinsic melting point and effective constraint of polymer chain mobility at elevated temperatures. These findings position graphene-UHMWPE composites as promising candidates for thermal management in electronics, and TiC-UHMWPE composites for high-temperature mechanical components [13, 14].

It should be acknowledged that the meta-analysis approach used in this study has limitations. First, the harmonization of property data from different studies introduces uncertainty associated with differences in processing conditions, testing protocols, and characterization techniques. Second, the optimal loading level reported by the literature (typically 2–5 wt. %) reflects the upper bound at which dispersion can be reliably achieved; in industrial settings, the achievable level may be lower due to processing constraints. Third, the cost-performance balance - a critical factor for industrial adoption - was not quantitatively analyzed and represents an important direction for future work. For example, graphene's outstanding properties come at a substantial cost premium (currently ~100× more expensive than CF on a mass basis), which may limit its industrial use to high-value applications only.

5. Conclusion

This systematic comparative analysis of six filler classes for UHMWPE composites has yielded the following key conclusions:

First, filler type is the dominant variable controlling composite property profiles, accounting for 58–71 % of observed variance across mechanical, tribological, and thermal property groups (ANOVA $p < 0.001$ for all groups). Optimal filler loading lies in the 2–5 wt. % range for all six filler classes, beyond which aggregation effects degrade performance.

Second, each filler class offers a distinct property advantage: carbon fibers maximize Young's modulus (+151 % to +251 %); graphene maximizes tensile strength (+49 %) and thermal conductivity (+320 %); ZrO₂ maximizes wear resistance (−75 %) and provides biocompatibility; TiC maximizes heat deflection temperature (+55 °C); MoS₂ maximizes friction reduction (−55 %); SiO₂ offers economical thermal stability with modest mechanical enhancement.

Third, application-specific filler selection guidelines have been derived for seven major domains: ZrO₂ for biomedical implants; CF or graphene for aerospace; CF or MoS₂ for automotive; graphene for electronics; ZrO₂ or MoS₂ for mechanical bearings; TiC for high-

temperature parts; and natural fibers with SiO₂ for sustainable materials. These guidelines provide a quantitative framework for materials selection and reduce the trial-and-error component of UHMWPE composite development.

Fourth, despite substantial progress, significant gaps remain in the systematic understanding of filler-UHMWPE interactions. Priority directions for future research include: (i) development of hybrid filler systems combining the advantages of multiple filler classes (e.g., ZrO₂-graphene for combined wear and thermal performance); (ii) investigation of the effect of filler surface functionalization on interfacial adhesion; (iii) cost-performance optimization to enable industrial adoption; (iv) extension of the dataset to nanofibrous fillers, MXenes, and other emerging two-dimensional materials.

The findings of this work underscore the potential of using various fillers to tailor the properties of UHMWPE for specific applications, from biomedical devices to aerospace structures to high-temperature mechanical components. By providing a unified comparative framework, this study contributes to the rational design of UHMWPE composites and supports their broader industrial deployment.

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