



Nanostructured Fillers for Tailoring the Mechanical Properties of Polypropylene: Recent Advances and Structure-Property Relationships

Gagan Kishor Srivastav^{1,4}, Ravi Raj Verma^{1,2,4}, Amresh Kumar Singh^{3,*}, Pushyamitra Mishra^{1,4,5,*}

¹Department of Chemistry, Shri Lal Bahadur Shastri Degree College, Gonda, U.P., India

²Department of Chemistry, Mahamaya Government Degree College, Mahona, Lucknow, U. P. India

³Kelsey Industries Private Limited, Vapi, Gujarat, India

⁴Dr. Ram Manohar Lohia Avadh University, Ayodhya, Uttar Pradesh, India

⁵Maa Pateswari University, Balrampur, Uttar Pradesh, India

*Corresponding Author Email: pushyamitra@lbsdc.org.in, <https://orcid.org/0000-0002-4702-4734> ;
amreshsingh83@gmail.com

ABSTRACT

Polypropylene (PP) is widely used in engineering applications because of its low density, chemical resistance, processability, and favourable cost-to-performance ratio; however, its mechanical performance is often limited by the trade-off between stiffness, strength, ductility, and toughness. Nanostructured fillers provide an effective strategy for modifying these properties through interfacial reinforcement, stress transfer, crystallization control, and microstructural modification. This review examines recent advances in PP nanocomposites containing carbon-based nanostructures, layered nanomaterials, inorganic nanoparticles, bio-based nanostructures, and hybrid filler systems. Particular emphasis is placed on the relationships among nanofiller architecture, dispersion, interfacial adhesion, orientation, processing conditions, crystallization, and mechanical response. The review compares the mechanisms governing tensile strength, modulus, elongation, impact resistance, fracture behaviour, creep, and fatigue, highlighting the frequent trade-off between stiffness enhancement and toughness retention. Hybrid nanofiller systems and interfacial modification are discussed as approaches for achieving more balanced mechanical performance. Processing–structure–property relationships are further considered to identify the factors controlling reproducibility and scale-up. Finally, challenges associated with dispersion, interfacial engineering, standardized mechanical comparison, sustainability, and predictive modelling are discussed, with emphasis on structure-controlled design of PP nanocomposites for application-specific mechanical performance.

Keywords: Polypropylene; Nanocomposites; Nanostructured Fillers; Mechanical Properties; Interfacial Adhesion; Dispersion; Crystallization; Structure–Property Relationships; Hybrid Nanofillers; Toughening.

1. Introduction

Polypropylene (PP) is a widely used semicrystalline thermoplastic owing to its low density, chemical resistance, processability, and favourable cost–performance balance, supporting applications in packaging, automotive components, fibres, and engineering products (Hossain et al., 2024). However, its non-polar character limits interaction with many reinforcing phases, making simultaneous improvement of stiffness, strength, ductility, and impact resistance difficult. Nanostructured fillers provide an effective route to modify this balance because their nanoscale dimensions and high

interfacial area can influence stress transfer, crystallization, morphology, and deformation behaviour. Their effectiveness depends on dimensionality, aspect ratio, surface chemistry, dispersion, orientation, loading, and interfacial adhesion.

Experimental studies demonstrate that reinforcement is strongly dependent on filler concentration and dispersion. Patti et al. (2015) reported maximum flexural modulus and strength at 0.5 vol% MWCNT, whereas higher loading promoted agglomeration and reduced reinforcing efficiency; functionalized CNTs produced stronger reinforcement at appropriate loading. Similarly, Wang et al. (2020) reported increases of 117% in tensile strength and 116% in tensile modulus for a PP/GNP self-reinforced system containing only 0.062 wt% GNP, with the enhancement associated with graphene orientation during processing. These results illustrate that nanofiller architecture, dispersion, and orientation can be more important than filler loading alone. Different nanofiller classes provide distinct reinforcement mechanisms. Carbon-based structures such as carbon nanotubes (CNTs), graphene, graphene nanoplatelets (GNPs), graphene oxide (GO), and reduced graphene oxide (rGO) offer high-aspect-ratio or high-area reinforcing structures whose mechanical effectiveness depends on geometry, dispersion, orientation, and interfacial interaction. Layered nanomaterials provide another route: Zhu et al. (2011) showed that modified montmorillonite (MMT) formed intercalated and exfoliated structures in PP, influencing mechanical and rheological behaviour; the modified MMT increased Izod impact strength and elongation at break, while PP-g-MA improved tensile strength. Inorganic nanoparticles provide complementary reinforcement, with Awad and Khalaf (2019) demonstrating that nano-SiO₂ modifies the tensile and mechanical behaviour of PP as a function of nanoparticle concentration. More recently, hybrid systems have sought to combine different reinforcement mechanisms. Sinha et al. (2022) reported increased tensile modulus and strength but reduced elongation and toughness in graphene nanoplatelet/TiO₂-filled PP, while Kumar et al. (2024) further examined the coupled mechanical, thermal, and morphological effects of GNP/TiO₂ hybrid fillers. These findings emphasize the distinction between stiffening, strengthening, and toughening. A nanofiller may increase modulus or tensile strength while reducing deformation capacity, whereas appropriate control of dispersion, interfacial adhesion, orientation, and polymer morphology can improve the balance among competing mechanical properties. Processing is therefore an integral structure–property variable because it determines the final dispersion state, filler orientation, interfacial structure, and, in many systems, crystallization behaviour. Despite extensive research, direct comparison among PP nanocomposites remains difficult because reported mechanical performance depends simultaneously on PP grade, filler dimensions and surface chemistry, loading, dispersion, compatibilization, crystallinity, processing history, and testing conditions. This review therefore focuses specifically on nanostructured fillers for modifying the mechanical properties of PP, excluding conventional micron-scale reinforcement. Carbon-based nanostructures, layered nanomaterials, inorganic nanoparticles, bio-derived nanostructures, and hybrid systems are examined through the relationships among nanofiller architecture, dispersion, interfacial interactions, crystallization, processing, and deformation mechanisms, with particular emphasis on reinforcement, stiffening, toughening, and mechanical degradation.

2. Polypropylene–Nanofiller Interface and Reinforcement Mechanisms

The mechanical response of PP nanocomposites is governed strongly by the polymer–nanofiller interface. High intrinsic stiffness or strength of a nanofiller does not automatically produce composite reinforcement; effective stress transfer requires adequate dispersion, interfacial interaction, and a filler morphology capable of sustaining load. Foundational studies established the importance of nanoscale dispersion and interfacial area, while PP-based investigations demonstrated the effects of filler geometry, surface modification, and matrix–filler interactions on mechanical performance (Ray & Okamoto, 2003; Bikiaris, 2010).

2.1 Dispersion and Nanofiller Architecture

Dispersion determines the fraction of nanofiller surface available for interaction with the PP matrix. Poor dispersion produces agglomerates that reduce effective interfacial area and act as stress-concentration sites, whereas uniform dispersion promotes load transfer. This is particularly important for high-aspect-ratio CNTs, graphene sheets, and layered silicates because strong filler–filler interactions favour aggregation during processing. PP/CNT studies show that reinforcement reaches an optimum at appropriate loading, beyond which agglomeration can reduce mechanical performance (Patti et al., 2015). Filler geometry further determines the reinforcement mechanism. One-dimensional CNTs can form elongated

structures and interconnected networks; two-dimensional graphene and layered silicates provide large matrix-contact areas and can generate anisotropic reinforcement when oriented; and approximately zero-dimensional nanoparticles reinforce primarily through particle–matrix interfaces. Consequently, dimensionality, aspect ratio, orientation, dispersion, and loading must be considered together rather than treating chemical composition as the sole descriptor of reinforcement.

2.2 Interfacial Adhesion and Stress Transfer

The polymer–nanofiller interface controls stress transfer from the PP matrix to the reinforcing phase. Because PP is essentially non-polar, direct interaction with many polar inorganic nanoparticles and oxidized carbon nanomaterials is limited. Compatibilization with polypropylene-graft-maleic anhydride (PP-g-MA), surface functionalization, and controlled nanofiller modification are therefore commonly used to improve wetting and interfacial adhesion. PP/graphene studies have demonstrated that improved interfacial compatibility can enhance dispersion and mechanical reinforcement, although excessive functionalization may alter filler structure or promote undesirable interactions (Md Said & Liu, 2021; Hu et al., 2023). Interfacial modification must therefore balance improved matrix–filler interaction with preservation of filler aspect ratio, surface integrity, and dispersibility. The optimum interface is consequently determined by the combined effects of adhesion, dispersion, filler architecture, and structural preservation rather than by functional-group density alone.

2.3 Crystallization and Morphological Modification

Nanofillers can modify PP mechanical behaviour indirectly through changes in semicrystalline morphology. Their surfaces may provide heterogeneous nucleation sites and alter crystallization temperature, crystallinity, crystal morphology, and lamellar organization. In PP/MMT nanocomposites, for example, dispersed silicate layers influence crystallization in addition to providing direct reinforcement (Zhu et al., 2011). Graphene-based nanostructures can similarly modify PP crystallization, so measured modulus and strength may reflect both direct interfacial stress transfer and changes in matrix morphology. Recent PP/graphene work has shown that processing-induced exfoliation and improved interfacial adhesion can simultaneously influence graphene dispersion and the resulting thermo-mechanical response (Hu et al., 2023).

2.4 Reinforcement versus Toughening

Nanofiller incorporation can affect modulus, strength, ductility, and toughness differently. Increased modulus commonly reflects restricted molecular mobility and efficient stress transfer, whereas tensile strength additionally depends on interfacial failure, filler distribution, and damage development. Toughness and impact resistance involve crack initiation, crack deflection, interfacial debonding, plastic deformation, and energy dissipation; therefore, increased stiffness does not necessarily indicate improved toughness. This distinction is illustrated by hybrid-filler studies. Sinha et al. (2022) reported increased tensile modulus and strength in PP hybrid composites accompanied by reductions in elongation and toughness at particular filler combinations. Thus, the design objective is not simply maximum filler loading but controlled nanoscale morphology that balances load transfer, matrix deformation, and damage evolution.

2.5 Processing as a Structure–Property Variable

Processing determines the dispersion, orientation, exfoliation, and interfacial structure ultimately obtained in PP nanocomposites. Melt blending is compatible with conventional PP processing, but molten-PP viscosity and strong nanofiller–nanofiller interactions can hinder homogeneous dispersion. Mixing conditions, residence time, temperature, shear history, and compatibilizer content therefore influence the final nanostructure and mechanical response. Recent strategies increasingly combine processing with interfacial modification or controlled exfoliation. Hu et al. (2023), for example, demonstrated water-phase exfoliation followed by improved interfacial adhesion in PP/graphene nanocomposites. This illustrates that processing and interface engineering should be considered coupled variables. Overall, the mechanical behaviour of PP nanocomposites reflects the combined effects of filler architecture, dispersion, interfacial structure, crystallization, and processing history.

3. Carbon-Based Nanostructured Fillers

Carbon nanotubes (CNTs), graphene and graphene nanoplatelets (GNPs), graphene oxide (GO), and reduced graphene oxide (rGO) provide distinct carbon-based architectures for modifying PP. Their different dimensionality, aspect ratio, surface chemistry, dispersion, orientation, and morphology govern stress transfer, crystallization, and mechanical

response. Consequently, reinforcement efficiency depends not only on the intrinsic properties of the carbon phase but also on how its nanoscale structure is established within the PP matrix.

3.1 Carbon Nanotubes

CNTs provide one-dimensional, high-aspect-ratio reinforcement capable of forming interconnected structures within PP. Early studies established their ability to increase PP stiffness and mechanical strength and showed that functionalization can improve dispersion and mechanical performance (Bikiaris, 2010; Spitalsky et al., 2008). Zhou et al. (2012) demonstrated directly that CNT dispersion strongly affects performance: more uniformly dispersed CNTs produced greater improvements in tensile and impact strength, while rheological behaviour indicated network formation above a concentration-dependent percolation threshold. CNT loading therefore does not produce a continuously increasing mechanical response. Patti et al. (2015) reported maximum flexural modulus and strength at 0.5 vol% MWCNT, followed by deterioration at higher concentrations associated with agglomeration. Functionalized CNTs provided stronger reinforcement at appropriate loading, confirming the combined importance of dispersion and matrix–CNT interaction. Novais et al. (2012) further showed that CNT functionalization route and twin-screw processing conditions influence dispersion in PP; polypropylene-functionalized nanotubes exhibited improved dispersion stability during melt processing and remelting. CNTs can also influence the semicrystalline PP matrix through heterogeneous nucleation and changes in molecular mobility. Thus, the mechanical response of PP/CNT nanocomposites reflects the combined effects of CNT-mediated load transfer, network formation, interfacial interaction, and modification of PP morphology.

3.2 Graphene and Graphene Nanoplatelets

Graphene and GNPs provide two-dimensional reinforcing structures with large lateral dimensions and high interfacial area. Their effectiveness depends strongly on platelet thickness, lateral size, dispersion, orientation, loading, and matrix–filler interaction. Al-Saleh et al. (2019) reported increased tensile strength with increasing GNP content from 1 to 5 wt%, accompanied by a substantial reduction in elongation at break; PP-g-MA increased tensile strength, whereas POE-g-MA produced a different response. These findings demonstrate that both filler loading and compatibilizer chemistry influence the balance between reinforcement and ductility. Platelet geometry is an additional structure–property variable. Liang (2019) showed that GNP size and loading affect tensile behaviour and that the response also depends on strain rate. Sutar et al. (2021) found that thinner GNPs with the same lateral dimensions provided better dispersion and higher tensile and flexural properties, whereas thicker platelets produced higher impact strength under the conditions studied. GNP incorporation also affected the β -crystalline structure of PP and increased crystallization temperature, demonstrating that platelet dimensions can simultaneously influence dispersion, crystallization, and mechanical performance. Thus, graphene content alone is an inadequate descriptor of reinforcement efficiency; platelet thickness, lateral dimensions, orientation, aggregation, processing, and interfacial compatibility must be considered together.

3.3 Graphene Oxide and Reduced Graphene Oxide

GO and rGO provide additional control over the PP–graphene interface because their surface chemistry differs from that of relatively unmodified graphene. GO contains oxygen-containing functional groups that facilitate chemical modification, whereas reduction removes part of this functionality and partially restores the conjugated carbon structure. Their mechanical performance therefore depends on surface chemistry, dispersion, and preservation of the reinforcing structure. Chammingkwan et al. (2016) demonstrated this interfacial approach by grafting terminally hydroxylated PP onto GO before melt mixing. The modified GO exhibited reduced restacking and agglomeration and stronger interaction with PP, with the highest tensile-strength improvement obtained at 1 wt% PP-modified GO. Comparison of GNP, partially reduced GO, and fully reduced GO further showed that surface chemistry and reduction state influence PP nanocomposite behaviour. The distinction between GO and rGO therefore extends beyond oxygen content: functional-group density, defect structure, layer organization, and dispersion collectively determine the balance between interfacial adhesion and preservation of the graphitic reinforcing structure. Functionalization is most effective when it improves PP–filler interaction without excessively disrupting the structural characteristics responsible for reinforcement. Recent processing research has further demonstrated that graphene exfoliation and interfacial adhesion can be controlled simultaneously. Hu et al. (2023)

developed an *insitu* water-phase exfoliation and interfacial-adhesion strategy for PP/graphene nanocomposites, illustrating the transition from simple filler incorporation toward deliberate control of graphene dispersion and interface structure.

3.4 Comparative Structure–Property Relationships

The three carbon-based filler groups demonstrate that reinforcement is controlled by architecture as much as by chemical composition. CNTs provide high-aspect-ratio one-dimensional networks; graphene and GNPs provide two-dimensional platelet reinforcement whose effectiveness is highly sensitive to thickness, lateral dimensions, and orientation; and GO/rGO provide greater opportunities for surface and interfacial engineering. Across these systems, excessive loading or poor processing promotes aggregation and stress concentration, whereas controlled dispersion and appropriate interfacial adhesion improve stress transfer. The mechanical response is therefore governed by the interaction of filler geometry, dispersion, orientation, surface chemistry, crystallization, and processing rather than by filler loading alone. These relationships provide the basis for comparing carbon-based nanostructures with layered, inorganic, bio-derived, and hybrid fillers considered in subsequent sections.

Table 1. Representative experimental evidence for carbon-based nanostructured fillers in PP

Nanofiller	PP system / modification	Loading	Property investigated	Principal reported result	Structure–property interpretation
MWCNT	PP/MWCNT; pristine and amino-functionalized CNTs	Up to 2.5 vol%	Flexural modulus and strength	Both modulus and strength reached a maximum at 0.5 vol% CNT; higher loading reduced the benefit	Increasing agglomeration at higher loading reduced reinforcement efficiency; functionalized CNTs enhanced the response [40]
MWCNT	PP/pristine and purified CNTs	Up to several wt%	Tensile and impact strength; rheology	Both tensile and impact strength improved with CNT addition; better CNT dispersion produced greater improvement. Percolation occurred at about 3 wt% for pristine CNTs and 1.5 wt% for purified CNTs	Dispersion controls effective reinforcement and formation of CNT networks [53]
CNT	PP/CNT; chemically functionalized CNTs	4 wt%	Dispersion and mechanical behaviour	Functionalization route strongly affected CNT dispersion; PP-functionalized CNTs showed distinctive dispersion and remained stable after remelting	Chemical compatibility and processing history control dispersion stability [39]
GNP	PP/GNP with PP-g-MA or POE-g-MA	1–5 wt%	Tensile strength and elongation	Tensile strength increased with GNP loading, while elongation at break decreased; compatibilizer type altered the mechanical response	Reinforcement is accompanied by a ductility trade-off; matrix–GNP compatibility is important [4]
GNP	PP/GNP	<0.4 wt% optimum range for impact response	Izod and Charpy impact strength	Impact strength increased below 0.4 wt% GNP, then decreased with increasing GNP content	Low loading can promote toughening, whereas higher loading promotes detrimental structural effects; GNP size also matters [27]
GNP	PP/GNP of different platelet sizes	Variable	Tensile properties	Young's modulus, yield strength and fracture strength increased with increasing tension rate, while elongation at break decreased; GNP size and content also significantly affected the response	Mechanical response depends on filler geometry as well as loading and strain rate [28]

Nanofiller	PP system / modification	Loading	Property investigated	Principal reported result	Structure–property interpretation
GNP	PP/GNP with different platelet thicknesses	Variable	Tensile, flexural and impact properties	Thinner GNPs showed better dispersion and higher tensile/flexural performance; thicker GNPs showed higher impact performance under the reported conditions	Platelet thickness affects dispersion, crystallization and deformation mechanisms [46]
PP-modified GO	PP/PP-GO	1 wt%	Tensile strength	Highest tensile-strength improvement at 1 wt% PP-GO	Covalent PP grafting suppressed GO restacking/agglomeration and strengthened PP–GO interfacial bonding [10]
Mildly oxidized graphene	PP/MAPP-modified graphene	5 wt%	Tensile strength and Young's modulus	Tensile strength increased by 21.5% and Young's modulus by 50.7%	High exfoliation, homogeneous dispersion and improved interfacial compatibility enhanced reinforcement [14]

Note: The table summarizes representative results reported in the cited original studies. Reported values are specific to the PP grade, nanofiller characteristics, processing conditions, loading and mechanical-testing conditions used in each study and therefore should not be interpreted as directly standardized cross-study comparisons.

4. Nanoclays and Other Layered Nanostructures

Layered and tubular aluminosilicate nanostructures provide alternatives to carbon-based fillers for modifying PP. Their high aspect ratio and surface area can influence stress transfer, crystallization, and deformation, but their mechanical effectiveness depends strongly on dispersion, interfacial compatibility, morphology, and processing. Montmorillonite (MMT) provides a two-dimensional layered architecture, whereas halloysite nanotubes (HNTs) provide a naturally occurring tubular structure.

4.1 Montmorillonite Nanoclay

MMT consists of stacked aluminosilicate layers that can form intercalated or partially exfoliated structures in PP. Early studies established that organo-modification and melt intercalation, particularly with functionalized PP, can produce useful PP/MMT nanocomposites (Manias et al., 2001). Because hydrophilic clay surfaces interact poorly with non-polar PP, compatibilization and surface modification are important for effective polymer–clay interaction. Zhu et al. (2011) confirmed intercalated and exfoliated structures in modified-MMT/PP systems using XRD and TEM. Modified MMT increased impact strength and elongation at break, while PP-g-MA improved tensile strength, demonstrating that mechanical performance depends on the combined effects of layer separation, interfacial adhesion, and matrix morphology rather than exfoliation alone. MMT also acts as a nucleating phase and modifies PP semicrystalline morphology under mechanical loading; consequently, direct filler reinforcement may compete with changes in the crystalline matrix (Zhu et al., 2011). A recent PP-random-copolymer/MMT study further reported effective intercalation and dispersion at low loading, whereas higher concentrations promoted agglomeration and reduced elongation and impact strength; approximately 1 wt% MMT produced the most favourable combination of mechanical and crystallization behaviour (Delli et al., 2026). Thus, controlled dispersion rather than maximum clay loading determines the optimum response.

4.2 Halloysite Nanotubes

HNTs are naturally occurring tubular aluminosilicates with a hollow lumen and elongated one-dimensional morphology, providing a reinforcement mechanism distinct from platelet-shaped MMT. Early PP/HNT studies showed that surface-treated HNTs could be dispersed in PP while influencing crystallization and mechanical properties (Ning et al., 2007). Prashantha et al. (2011) demonstrated that untreated and quaternary-ammonium-treated HNTs could be incorporated through a masterbatch route. HNT addition increased crystallinity and crystallization temperature and improved tensile and flexural strength and modulus without significant ductility loss; approximately 6 wt% HNT gave the most favourable overall response, with surface treatment further improving performance through stronger matrix–nanotube

interaction. Processing also strongly affects dispersion: Lecouvet et al. (2011) showed that water-assisted extrusion combined with PP-g-MA produced substantially better HNT dispersion than conventional processing or either treatment alone, accompanied by improved viscoelastic and thermo-mechanical properties. More recent work has continued to examine surface treatment, with Awad (2024) reporting modified HNT-filled PP prepared by melt extrusion and observing homogeneous nanotube dispersion together with changes in mechanical and rheological properties. Overall, HNT performance depends on the coupled effects of concentration, surface treatment, dispersion, and matrix–nanotube interaction.

4.3 Structure–Property Considerations

MMT and HNTs demonstrate the importance of nanofiller geometry in determining reinforcement mechanisms. MMT relies on intercalation/exfoliation and development of an effective polymer–silicate interface, whereas HNTs provide elongated tubular reinforcement. In both systems, aspect ratio, orientation, dispersion, surface chemistry, and interfacial adhesion determine mechanical response (Manias et al., 2001; Ning et al., 2007; Prashantha et al., 2011). Excessive filler concentration can promote agglomeration and reduce effective interfacial area, while nanofiller-induced crystallization may either enhance reinforcement or alter matrix strength and deformability (Zhu et al., 2011; Prashantha et al., 2011). The optimum response therefore requires sufficient dispersion and matrix coupling without excessive restriction of PP deformation. Overall, stiffness, strength, ductility, and impact behaviour arise from the combined effects of nanostructure development, interface, dispersion, crystallization, and processing history rather than filler loading alone (Zhu et al., 2011; Prashantha et al., 2011; Lecouvet et al., 2011; Awad, 2024).

Table 2. Representative experimental evidence for layered and tubular nanostructures in PP

Nanofiller	PP system / modification	Loading	Property / structural observation	Principal reported result	Structure–property interpretation
MMT	Modified MMT/PP	—	Mechanical properties, crystallization, rheology	Modified MMT produced intercalated/exfoliated structures; impact strength and elongation increased, while PP-g-MA improved tensile strength	Mechanical response depends on layer separation, interfacial adhesion, and PP crystallization [54]
MMT	PP/MMT	—	Semicrystalline structure under mechanical loading	MMT altered the semicrystalline structure and deformation response of PP under mechanical loading	Filler–matrix interaction and mechanically induced morphological evolution contribute to the observed response [45]
MMT	PP-random-copolymer/MMT	~1 wt% optimum	Intercalation, dispersion, mechanical and crystallization behaviour	Low loading promoted effective intercalation and dispersion; higher loading produced agglomeration and reduced elongation and impact strength; ~1 wt% gave the most favourable overall response	Controlled dispersion rather than maximum clay concentration determines the optimum mechanical response [11]
HNT	PP/HNT, untreated and surface-treated	~6 wt% optimum	Tensile/flexural strength and modulus; crystallization	HNT increased crystallinity, crystallization temperature, tensile/flexural strength and modulus without significant ductility loss; ~6 wt% was favourable	Tubular geometry, dispersion and surface treatment improve matrix–nanotube interaction [41]
HNT	PP/HNT with PP-g-MA; water-assisted extrusion	—	Dispersion, viscoelastic and thermomechanical behaviour	Water-assisted extrusion combined with PP-g-MA produced substantially better HNT dispersion and improved associated properties	Processing and compatibilization jointly control nanotube dispersion and performance [24]

Nanofiller	PP system / modification	Loading	Property / structural observation	Principal reported result	Structure–property interpretation
HNT	Modified HNT/PP prepared by melt extrusion	0.5–3 wt%	Dispersion, mechanical and rheological properties	Homogeneous nanotube dispersion was observed, together with measurable changes in mechanical and rheological response	Dispersion and filler–matrix interactions influence the mechanical and rheological response of PP composites [6].

Note: The table summarizes representative experimental results reported in the cited studies. Reported loading levels and mechanical responses are specific to the PP grade, nanofiller characteristics, surface treatment, processing conditions, specimen preparation, and testing methods used in each study and therefore should not be interpreted as directly standardized cross-study comparisons. “—” indicates that a specific loading level was not reported or was not used as the principal comparison in the cited study.

5. Inorganic Nanoparticles

Inorganic nanoparticles provide chemically diverse reinforcement routes for PP. Unlike high-aspect-ratio carbon and layered fillers, many inorganic particles are approximately equiaxed and influence mechanical behaviour through interfacial interactions, restriction of polymer-chain mobility, heterogeneous nucleation, and modification of local deformation. Nano-SiO₂, nano-CaCO₃, TiO₂, ZnO, and Al₂O₃ have all been investigated, but their effects depend strongly on particle size, surface chemistry, dispersion, loading, and processing history.

5.1 Nano-SiO₂

Nano-SiO₂ provides high polymer–particle interfacial area and readily modifiable surface chemistry. Awad and Khalaf (2019) demonstrated that modified nanosilica alters tensile strength, modulus, and elongation of PP, showing that its mechanical effect depends on appropriate incorporation. In PP–nanosilica foams, Kumar et al. (2020) further showed that silica affects crystallinity, melt rheology, cellular morphology, and mechanical behaviour, indicating that reinforcement can arise from both direct particle–matrix interaction and changes in matrix morphology. The importance of interfacial chemistry is also evident from atomistic simulations. Sorkin et al. (2021) found that functionalized silica surfaces enhanced interaction with PP and increased the calculated mechanical response relative to unfunctionalized silica. Thus, nanosilica effectiveness depends on dispersion, surface chemistry, interphase formation, and matrix morphology rather than loading alone (Awad & Khalaf, 2019; Kumar et al., 2020; Sorkin et al., 2021).

5.2 Nano-CaCO₃

Nano-CaCO₃ provides substantially greater polymer–particle interfacial area than conventional micron-scale CaCO₃. Wang et al. (2002) demonstrated that high-speed mixing can reduce aggregation and improve PP/nano-CaCO₃ mechanical performance, highlighting the tendency of high-surface-energy nanoparticles to aggregate during melt processing. Karamipour et al. (2011) examined 5–15 wt% nano-CaCO₃ and observed increased storage modulus together with increasing particle coalescence at higher loading, demonstrating the simultaneous effects of reinforcement and particle–particle interaction. Nano-CaCO₃ can also contribute to toughening in multiphase PP. Liang et al. (2016) showed that PP/poly(ethylene-co-octene) (POE)/nano-CaCO₃ composites exhibit mechanical responses governed by interactions among the PP matrix, elastomeric phase, and nanoparticles. Appropriate phase structure and interfacial adhesion can therefore improve impact toughness without severe loss of stiffness or tensile strength, through mechanisms distinct from rigid-particle reinforcement of single-phase PP.

5.3 TiO₂, ZnO and Al₂O₃ Nanoparticles

Metal-oxide nanoparticles provide additional routes for modifying PP stiffness, viscoelasticity, crystallinity, and strength, but their effects are strongly dependent on dispersion, concentration, and processing. Aydemir et al. (2016) reported that nano-TiO₂ incorporation by extrusion and injection moulding modified PP mechanical properties and thermal stability, while Bendaoued et al. (2022) showed that 20–30 nm TiO₂ affected crystallinity, rheology, and viscoelastic properties as a function of concentration. Kumar et al. (2021) found that increasing TiO₂ content increased hardness and compressive strength, whereas optimum flexural performance occurred at lower loading and impact strength did not improve correspondingly, illustrating the trade-off between stiffness-related properties and impact resistance. For nano-ZnO, Mohagheghian et al. (2011) observed relatively uniform dispersion at 5–15 wt% together with particle coalescence and

changes in rheological and dynamic mechanical behaviour. Nano- Al_2O_3 likewise exhibits strong loading and dispersion dependence. Mirjalili et al. (2012) reported increased storage modulus and crystallinity, with stronger effects when a dispersant was used, whereas Mirjalili et al. (2014) found improved tensile and flexural properties at moderate loading followed by deterioration at higher concentrations because of agglomeration.

5.4 Mechanical Balance and Interfacial Effects

Inorganic nanoparticles commonly produce a concentration-dependent balance among stiffness, strength, ductility, and toughness. At relatively low concentrations, well-dispersed particles increase interfacial area and can restrict local polymer deformation; at higher concentrations, particle–particle interactions and aggregation generate stress-concentration regions and reduce load-transfer efficiency (Karamipour et al., 2011; Mirjalili et al., 2014). Interphase structure is therefore critical: silica functionalization influences stress transfer (Sorkin et al., 2021), while dispersant-assisted Al_2O_3 dispersion alters crystallinity, modulus, tensile strength, and flexural properties (Mirjalili et al., 2012, 2014). Overall, inorganic nanoparticles provide diverse routes for tailoring PP, but their mechanical effectiveness is system-specific. Nano- SiO_2 is particularly sensitive to interfacial chemistry and dispersion; nano- CaCO_3 can provide reinforcement and nanoparticle-assisted toughening in multiphase systems; and TiO_2 , ZnO , and Al_2O_3 can modify stiffness, viscoelastic behaviour, crystallinity, and selected strength or toughness characteristics. Across these systems, dispersion, interfacial structure, loading, and matrix morphology remain the principal variables governing mechanical response (Kumar et al., 2020; Karamipour et al., 2011; Mohagheghian et al., 2011; Mirjalili et al., 2014).

Table 3. Representative experimental evidence for inorganic nanoparticles in polypropylene

Nanofiller	PP system / modification	Loading	Property investigated	Principal reported result	Structure–property interpretation
Nano- SiO_2	Modified nano- SiO_2 /PP	—	Tensile strength, modulus and elongation	Nano- SiO_2 incorporation altered tensile strength, modulus and elongation, with the response depending on incorporation and interfacial interaction	Mechanical effectiveness depends on dispersion, surface chemistry and polymer–particle interaction [5]
Nano- SiO_2	PP/nano- SiO_2 foams	—	Crystallinity, rheology, cellular morphology and mechanical properties	Silica affected crystallinity, melt rheology and cellular morphology, thereby modifying mechanical behaviour	Reinforcement arises from both particle–matrix interaction and changes in PP morphology and foam structure [21]
Nano- CaCO_3	PP/nano- CaCO_3	5–15 wt%	Storage modulus and particle morphology	Storage modulus increased with nano- CaCO_3 incorporation, while particle coalescence increased with loading	Reinforcement competes with particle–particle interaction and aggregation at higher loading [18]
Nano- CaCO_3	PP/nano- CaCO_3 prepared using high-speed mixing	—	Mechanical performance and dispersion	High-speed mixing reduced nanoparticle aggregation and improved mechanical performance	Processing-induced dispersion is critical because high nanoparticle surface energy promotes aggregation [48]
Nano- CaCO_3	PP/POE/nano- CaCO_3	—	Tensile, flexural and impact behaviour	Mechanical response changed with elastomer fraction and nanoparticle incorporation; appropriate phase structure supported impact toughening without severe loss of stiffness or tensile performance	Toughening results from interaction among PP, elastomeric phase, nanoparticles and interfaces rather than rigid-particle reinforcement alone [29]
TiO_2	PP/nano- TiO_2	—	Mechanical properties and thermal stability	Nano- TiO_2 incorporation modified mechanical properties and thermal stability; response depended on processing and loading	Particle dispersion and matrix–particle interaction influence reinforcement and thermal response [7]

Nanofiller	PP system / modification	Loading	Property investigated	Principal reported result	Structure–property interpretation
TiO ₂	PP/TiO ₂	20–30 nm particles; variable concentration	Crystallinity, rheology and viscoelastic properties	TiO ₂ concentration affected PP crystallinity, rheological behaviour and viscoelastic response	TiO ₂ influences PP through both particle–matrix interactions and modification of matrix morphology [8]
TiO ₂	Injection-moulded PP/TiO ₂	Variable	Hardness, compressive, flexural and impact properties	Increasing TiO ₂ increased hardness and compressive strength; optimum flexural performance occurred at lower loading, while impact strength did not improve correspondingly	Demonstrates a trade-off between stiffness-related properties and impact resistance [22]
ZnO	PP/nano-ZnO	5–15 wt%	Rheological and dynamic mechanical properties	Relatively uniform dispersion was observed, with particle coalescence at different degrees; ZnO altered rheological and dynamic mechanical behaviour	Dispersion and particle–particle interactions strongly influence viscoelastic response [37]
Nano-Al ₂ O ₃	PP/nano- α -Al ₂ O ₃ with dispersant	—	Storage modulus and crystallinity	Storage modulus and crystallinity increased, with stronger effects when a dispersant was used	Improved dispersion increases effective interfacial interaction and reinforcement efficiency [32]
Nano-Al ₂ O ₃	PP/nano- α -Al ₂ O ₃	Moderate to higher loading	Tensile and flexural properties	Tensile and flexural properties improved at moderate loading but declined at higher concentration	Excessive loading promotes agglomeration and reduces reinforcement efficiency [34]

Note: The table summarizes representative experimental results reported in the cited studies. Reported loading levels and mechanical responses are specific to the PP grade, nanoparticle characteristics, surface treatment, processing conditions, specimen preparation, and testing methods used in each study and therefore should not be interpreted as directly standardized cross-study comparisons. “—” indicates that a specific loading level was not reported or was not the principal comparison in the cited study.

6. Bio-Based Nanostructures

Growing interest in sustainable materials has increased attention to bio-derived nanostructures as reinforcing phases for polypropylene (PP). Cellulose nanocrystals (CNCs), cellulose nanofibres (CNFs), and chitin- or chitin-derived nanostructures offer low density, high specific surface area, and favourable stiffness-to-weight characteristics. Their nanoscale dimensions and, particularly for nanofibres, high aspect ratios make them attractive reinforcements; however, their hydrophilic character creates a fundamental compatibility problem with non-polar PP, making interfacial engineering essential.

6.1 Cellulose Nanocrystals and Nanofibres

CNCs are relatively short, rod-like crystalline particles, whereas CNFs are longer, entangled fibrillar structures containing crystalline and less-ordered regions. Both provide high stiffness and extensive surface area, but these properties cannot be fully exploited in PP without adequate dispersion and matrix coupling. Untreated cellulose tends to form hydrogen-bonded aggregates and interacts poorly with non-polar PP, limiting stress transfer. Consequently, surface modification, compatibilization, and polymer grafting have been emphasized for improving PP/cellulose dispersion and interfacial adhesion (Borysiak et al., 2016; Herrera-Franco & Valadez-González, 2005). PP-g-MA is particularly relevant because its polar groups can interact with hydroxyl-rich cellulose while retaining compatibility with PP. Improved coupling can increase stiffness and strength when dispersion is adequate, whereas excessive interfacial restriction or aggregation can reduce elongation. The mechanical response therefore reflects a balance between adhesion and matrix mobility. Cellulose nanostructures can also act as heterogeneous nucleation sites and modify PP crystallization, so their mechanical contribution may combine direct reinforcement, interfacial stress transfer, and changes in semicrystalline morphology.

6.2 Chitin and Chitin-Derived Nanostructures

Chitin nanofibres and nanocrystals provide renewable nanoscale reinforcement containing hydroxyl and acetamide functionalities that permit chemical modification and interfacial interaction. Their fibrillar or crystalline structures can

potentially increase polymer stiffness, but their polarity also limits compatibility with non-polar PP. Compared with cellulose/PP systems, direct PP/chitin nanocomposite research remains less developed; therefore, claims of superior mechanical performance should be made cautiously. Available evidence nevertheless indicates that dispersion, surface modification, and interfacial adhesion are critical. Processing is also important because cellulose- and chitin-based structures can be affected by moisture and thermal history. Drying, residence time, melt temperature, and shear must therefore be controlled to prevent degradation or moisture-induced aggregation before mechanical testing.

6.3 Mechanical and Processing Considerations

The principal advantages of bio-based nanostructures are low density, renewable origin, and nanoscale reinforcement potential, offering opportunities for lightweight PP formulations with reduced dependence on mineral or fossil-derived reinforcements. Their practical performance, however, is constrained by moisture sensitivity, aggregation, matrix incompatibility, and thermal-processing limitations. Their structure–property behaviour therefore depends on coupled effects of surface modification, interfacial adhesion, dispersion, orientation, and PP crystallization. Excessive filler loading can promote filler–filler association and reduce reinforcement efficiency. Bio-based nanostructures should consequently be evaluated not only by intrinsic mechanical properties but also by their ability to combine nanoscale reinforcement with low density and renewable feedstocks. Their principal challenge is achieving sufficient polymer–nanofiller coupling while preserving processability and ductility, requiring improved surface functionalization, moisture management, controlled dispersion, and processing strategies that preserve nanoscale structure.

7. Hybrid Nanofiller Systems

Hybrid nanofiller systems combine two or more nanostructures with different geometries, surface characteristics, or reinforcement mechanisms to modify the balance among stiffness, strength, ductility, and toughness. However, hybridization does not inherently produce synergy; the resulting behaviour depends on filler proportions, dispersion, spatial organization, interfacial interactions, and processing history (Infurna et al., 2020; Bian et al., 2017).

7.1 Carbon–Carbon Nanofiller Combinations

CNT–graphene and CNT–GNP combinations exploit complementary one- and two-dimensional architectures. CNTs can bridge neighbouring graphene or GNP structures and potentially reduce sheet restacking, thereby promoting more continuous nanoscale reinforcement networks. Infurna et al. (2020) demonstrated in PP prepared by twin-screw extrusion that combined CNT/GNP systems produced favourable changes in mechanical, morphological, electrical, and degradation behaviour, with performance depending on filler aspect ratio, loading, and dispersion. Al-Saleh (2015) likewise showed that CNTs could bridge GNP particles in melt-mixed PP and improve carbon-filler connectivity. The relative CNT proportion influenced the resulting properties, demonstrating that hybrid performance depends not only on total filler concentration but also on the geometry and ratio of the individual components. Excessive loading, however, can increase filler–filler association and reduce the effective PP–nanofiller interface (Infurna et al., 2020; Al-Saleh, 2015).

7.2 Carbon–Inorganic Hybrid Nanofillers

Combining carbon nanostructures with inorganic nanoparticles can integrate high-aspect-ratio reinforcement with modified surface interactions, crystallization, and local morphology. Bian et al. (2017) reported that a functionalized graphene/SiO₂ hybrid incorporated into PP was more uniformly distributed than graphene alone, with SiO₂ limiting graphene-sheet aggregation. At optimized low loading, tensile and impact strength increased relative to neat PP and graphene-only PP, attributed to improved dispersion, interfacial interactions, and heterogeneous nucleation. PP/GNP/TiO₂ systems provide another example. Sinha et al. (2022) found that GNP/TiO₂/maleated-PP formulations increased tensile modulus and strength but reduced elongation and toughness. Kumar et al. (2024) similarly reported increases in tensile modulus and yield strength with GNP/TiO₂ hybridization, while higher filler contents promoted agglomeration and declining mechanical performance. Thus, hybrid benefit depends strongly on spatial organization: controlled association can limit carbon-sheet restacking, whereas uncontrolled filler–filler interactions can generate larger aggregates and stress concentrations.

7.3 Hybrid Nanostructures and Mechanical Balance

Hybridization is particularly relevant when attempting to balance stiffness and toughness, but PP studies show that improvement in one property does not necessarily produce simultaneous improvement in all mechanical characteristics. Sinha et al. (2022) observed increased modulus and strength but reduced elongation and toughness, whereas Bian et al. (2017) reported simultaneous increases in tensile and impact strength for an appropriately designed graphene/SiO₂ hybrid at low loading. Mechanical synergy must therefore be demonstrated rather than assumed. Appropriate evaluation requires comparison with single-filler controls at comparable total filler concentrations and under equivalent processing and testing conditions. Otherwise, apparent improvements may arise from altered dispersion, crystallinity, filler orientation, or matrix morphology. Potential mechanisms include improved stress transfer, filler-network formation, crack deflection or bridging, localized matrix deformation, and crystallization modification.

7.4 Processing and Interfacial Compatibility

Hybrid systems introduce additional processing complexity because different nanofillers may possess different surface energies, aggregation tendencies, and dispersion requirements. Melt processing remains particularly relevant for PP, while twin-screw extrusion studies demonstrate that shear history and processing conditions influence CNT–GNP dispersion and structure (Infurna et al., 2020). Functionalization and compatibilization can further modify polymer–filler and filler–filler interactions, although inappropriate modification may produce undesirable aggregation. The sequence and conditions of filler incorporation therefore become important structure–property variables. Uniform dispersion is generally desirable, but controlled association can sometimes be beneficial when one nanofiller bridges or separates structures formed by another. The resulting architecture must nevertheless remain sufficiently fine and well bonded to PP to support effective stress transfer.

7.5 Critical Perspective

The principal value of hybrid nanofillers is their ability to combine complementary nanoscale reinforcement mechanisms. PP studies of CNT–GNP, graphene–SiO₂, and GNP–TiO₂ systems demonstrate that appropriately selected combinations can modify mechanical behaviour beyond that obtained with some individual fillers, but the outcome remains strongly dependent on composition, dispersion, and interface quality (Al-Saleh, 2015; Bian et al., 2017; Infurna et al., 2020; Sinha et al., 2022; Kumar et al., 2024). Hybridization should therefore not be treated as a universal solution. A poorly dispersed hybrid can perform less effectively than a well-dispersed single-filler composite. Future studies should establish quantitative relationships among hybrid architecture, dispersion, interfacial structure, crystallization, and deformation mechanisms, using three-dimensional structural characterization, mechanical testing, and multiscale modelling to distinguish genuine synergy from improvements caused primarily by altered dispersion or matrix morphology.

Table 4. Representative experimental evidence for hybrid nanofiller systems in polypropylene and their structure–property relationships.

Hybrid nanofiller	PP system / modification	Loading	Property investigated	Principal reported result	Structure–property interpretation
CNT + GNP	PP/CNT–GNP hybrid	Variable	Mechanical and multifunctional properties	Combined CNT/GNP systems produced favourable changes in mechanical and morphological behaviour; response depended on filler ratio and dispersion	CNTs can bridge graphene structures and reduce sheet restacking, but excessive filler–filler interaction can promote aggregation [15]
CNT + GNP	Melt-mixed PP/CNT–GNP	Variable	Mechanical and electrical behaviour	CNT addition modified the connectivity of the graphene network and the resulting composite response	Complementary 1D/2D architectures can form more continuous reinforcement networks when appropriately proportioned [2]
GNP + TiO ₂	PP/GNP/TiO ₂ with maleated PP	Variable	Tensile modulus, strength, elongation and toughness	Tensile modulus and strength increased, whereas elongation and toughness decreased at the investigated hybrid compositions	Hybrid reinforcement can enhance load transfer but does not necessarily overcome the stiffness–toughness trade-off [43]

Hybrid nanofiller	PP system / modification	Loading	Property investigated	Principal reported result	Structure–property interpretation
GNP + TiO ₂	PP/GNP–TiO ₂ hybrid	Variable	Tensile, thermal and morphological behaviour	Hybridization increased tensile modulus and yield strength; excessive filler content promoted agglomeration and reduced mechanical performance	Mechanical benefit depends on controlled dispersion and filler–filler interaction rather than hybridization alone [23]

Note: The table summarizes representative experimental results reported in the cited studies. Loading levels and mechanical responses are specific to the PP grade, filler characteristics, composition, processing conditions, specimen preparation and testing methods used in each study and therefore should not be interpreted as standardized cross-study comparisons.

8. Processing–Structure–Property Relationships

Processing is a fundamental component of the PP nanocomposite structure–property relationship because it determines nanofiller dispersion, orientation, interfacial contact, and, in many systems, PP crystalline morphology. Consequently, identical filler type and nominal concentration can produce substantially different mechanical responses under different processing histories. Studies of PP/clay, PP/CNT, and PP/graphene systems demonstrate that processing modifies nanostructure, crystallization, and mechanical performance (Modesti et al., 2005; Zhou et al., 2012; Triantou et al., 2017).

8.1 Melt Processing

Melt blending is particularly important for PP because it is compatible with extrusion and injection moulding. Shear promotes aggregate breakup and redistribution while influencing the orientation of anisotropic fillers; the resulting dispersion depends on temperature, residence time, screw speed, mixing intensity, and filler-addition sequence. Zhou et al. (2012) showed that improved CNT dispersion enhanced tensile and impact properties, whereas Al-Saleh (2015) found that increasing melt-mixing time and rotation speed improved dispersion without producing proportional increases in tensile strength and modulus. Thus, processing effects can be property-specific. Excessive shear may also alter CNT length and aspect ratio. Multilayer coextrusion provides an alternative approach: Miquelard-Garnier et al. (2013) demonstrated improved CNT dispersion and substantial increases in Young's modulus at low CNT loading without significant loss of elongation.

8.2 Compatibilization and Interfacial Modification

Because PP is non-polar, compatibilization is particularly important for polar or chemically dissimilar nanofillers. PP-g-MA improves compatibility by combining a PP-compatible backbone with polar functional groups capable of interacting with nanofiller surfaces. Modesti et al. (2005) demonstrated that barrel temperature and screw speed influenced PP/clay morphology, while PP-g-MA promoted exfoliation and improved mechanical properties. The study also showed that lower processing temperatures could increase viscosity and shear sufficiently to promote clay exfoliation, demonstrating that compatibilizer concentration and processing conditions are interdependent. For graphene, Hu et al. (2023) combined water-phase exfoliation with interfacial-adhesion improvement, illustrating the close coupling between accessible filler surface area and effective stress transfer.

8.3 Dispersion and Orientation

Dispersion is a principal structural variable governing PP nanocomposite performance. Improved dispersion increases polymer–filler contact and stress transfer, whereas excessive filler–filler interactions at higher concentrations promote aggregation and reduce reinforcement efficiency (Zhou et al., 2012; Al-Saleh, 2015). For anisotropic fillers, processing-induced orientation can increase mechanical response along the alignment direction while introducing anisotropy. Mi et al. (2023) demonstrated that compression moulding, conventional injection moulding, and interval injection moulding produced different CNT dispersion and orientation states with corresponding mechanical changes. Li et al. (2017) deliberately manipulated MWCNT dispersion and orientation through microlayer extrusion; increasing the number of layers produced substantial increases in tensile strength, Young's modulus, and elongation at break. For layered clays, processing additionally controls intercalation and exfoliation, determining the effective interfacial area and stress-transfer efficiency (Manias et al., 2001; Modesti et al., 2005).

8.4 Processing and Crystallization

Processing affects mechanical behaviour indirectly through PP crystallization. Nanofillers can provide heterogeneous nucleation sites, while shear influences polymer-chain orientation and crystal development. Changes in crystallinity, crystal size, lamellar organization, and molecular orientation can consequently alter mechanical properties. In PP/clay systems, processing and intercalation conditions influence the resulting morphology (Manias et al., 2001). In PP/CNT systems, Li et al. (2017) associated improved filler dispersion and orientation during microlayer extrusion with changes in crystallization and mechanical behaviour. Triantou et al. (2017) further showed that re-extrusion of PP/GNP composites altered crystalline-phase content and increased elastic modulus, demonstrating that repeated thermal and shear histories can change mechanical performance without changing nominal filler concentration. Increased crystallinity, however, does not necessarily improve every mechanical property because the final response also depends on interfacial reinforcement, molecular orientation, and deformation of the amorphous phase.

8.5 Processing–Property Trade-Offs

Optimum processing conditions are property-specific. A route that maximizes tensile modulus may not maximize impact resistance because strong filler orientation or increased matrix constraint can reduce energy-dissipation mechanisms. Similarly, improved dispersion may be accompanied by changes in crystallization or orientation that influence ductility. The PP/CNT literature illustrates this distinction: Zhou et al. (2012) reported simultaneous tensile and impact improvements with better dispersion, whereas Al-Saleh (2015) observed improved dispersion without proportional tensile-property gains. Consequently, literature comparisons should account for extrusion temperature, screw speed, mixing time, injection conditions, PP grade, compatibilizer concentration, specific mechanical energy, and specimen orientation rather than comparing filler type and loading alone.

8.6 Toward Controlled Nanostructure Formation

Recent processing strategies increasingly seek controlled nanofiller organization rather than simply higher filler loading. Compatibilizer-assisted melt processing, controlled shear, multilayer and microlayer extrusion, surface functionalization, and hybrid-filler approaches can manipulate dispersion, orientation, and interfacial architecture. The objective is not necessarily maximum dispersion, but a stable nanoscale structure that maintains sufficient polymer–filler contact while preserving an architecture capable of effective load transfer. The required structure depends on filler geometry: approximately isotropic nanoparticles primarily require suppression of aggregation, whereas CNTs, graphene sheets, and layered silicates additionally require control of orientation, network formation, intercalation, or exfoliation. Processing therefore provides the practical link between nanofiller characteristics and the structure responsible for mechanical performance, making processing history, dispersion, orientation, interfacial structure, and crystallinity essential variables in meaningful literature comparisons (Modesti et al., 2005; Zhou et al., 2012; Miquelard-Garnier et al., 2013; Mi et al., 2023).

Table 5. Representative experimental evidence linking processing conditions, nanostructure and mechanical response in polypropylene nanocomposites.

Processing / strategy	PP nanocomposite	Structural effect	Mechanical/property response	Structure–property interpretation
Twin-screw melt extrusion; functionalization	PP/CNT	Functionalization route altered CNT dispersion and dispersion stability during remelting	Improved dispersion was associated with improved reinforcement efficiency	Chemical compatibility and processing history jointly determine effective CNT–PP interaction [39]
Controlled melt mixing	PP/CNT	Improved CNT dispersion with increasing mixing intensity/time	Better dispersion improved tensile and impact behaviour, although processing effects were not proportional for all properties	Mechanical response depends on effective interfacial area rather than processing intensity alone [53]
Melt mixing; processing-condition variation	Compatibilized PP nanocomposites	Processing temperature and screw speed altered morphology/exfoliation	Changes in morphology were accompanied by changes in mechanical properties	Processing conditions and compatibilizer concentration act as coupled variables controlling interfacial structure [36]

Processing / strategy	PP nanocomposite	Structural effect	Mechanical/property response	Structure–property interpretation
Multilayer coextrusion	PP/MWCNT	Improved CNT dispersion and orientation through controlled layer formation	Substantial increases in Young's modulus at low CNT loading without significant loss of elongation	Spatial control of CNT distribution can improve reinforcement while limiting the usual ductility penalty [31]
Microlayer extrusion	PP/MWCNT	Controlled CNT dispersion and orientation	Tensile strength, Young's modulus and elongation increased with increasing number of layers	Processing-induced nanoscale organization can modify mechanical response without simply increasing filler concentration [26]
Water-assisted extrusion + compatibilization	PP/HNT	Improved HNT dispersion	Improved associated viscoelastic and thermomechanical behaviour	Processing and interfacial modification jointly control nanotube dispersion and matrix–filler interaction [24]
Water-phase exfoliation + interfacial modification	PP/graphene	Improved graphene exfoliation and polymer–graphene adhesion	Enhanced mechanical performance associated with improved dispersion and interfacial interaction	Accessible graphene surface area and interface quality are coupled processing–structure variables [14]
Re-extrusion / thermal–shear history	PP/GNP	Altered crystalline-phase content and nanostructure	Elastic modulus increased after re-extrusion	Mechanical properties can change through processing-induced matrix morphology even at unchanged nominal filler concentration [47]

Note: The table summarizes representative experimental evidence from the cited studies. Processing conditions, PP grade, filler loading, specimen preparation and testing methods differ among studies; therefore, the listed responses are intended to demonstrate processing–structure–property relationships rather than provide standardized numerical rankings.

9. Mechanical Performance: From Stiffening to Toughening

The mechanical response of PP nanocomposites reflects the combined effects of nanofiller reinforcement, interfacial stress transfer, dispersion, crystallization, orientation, and deformation mechanisms. Nanofillers commonly increase stiffness, but changes in tensile strength, ductility, impact resistance, and fracture behaviour are less consistent and depend strongly on filler type, loading, dispersion, and interface. For example, PP/MWCNT systems may show simultaneous increases in strength and modulus with reduced elongation and impact resistance, whereas appropriately selected GNP contents can improve impact strength before aggregation becomes dominant (Mansor et al., 2019; Liang, 2019). Mechanical assessment should therefore consider strength, stiffness, ductility, impact and fracture behaviour, and, where relevant, long-term deformation.

9.1 Tensile Strength and Young's Modulus

Young's modulus is generally among the properties most readily improved by nanofillers because rigid phases restrict local chain mobility and carry part of the applied load. High-aspect-ratio CNTs and graphene are particularly effective when adequately dispersed and oriented, with PP/MWCNT studies demonstrating substantial increases in tensile and flexural modulus depending on loading and dispersion (Zhou et al., 2012). Tensile strength is more sensitive to interfacial adhesion because efficient load transfer requires sufficient matrix–filler interaction. Functionalized graphene and surface-modified inorganic fillers demonstrate that improved interfacial coupling can enhance stress transfer (Hu et al., 2023; Sorkin et al., 2021). However, strength does not increase indefinitely with filler concentration: aggregation generates filler-rich stress-concentration regions and promotes premature failure. Liang (2019) showed that PP/GNP tensile behaviour depends on GNP concentration, platelet size, and deformation rate.

9.2 Elongation and Ductility

Rigid nanofillers frequently reduce elongation at break through restricted chain mobility, increased matrix constraint, filler-rich domains, and premature damage at poorly dispersed particles or interfaces. The PP/MWCNT results reported by Mansor et al. (2019), in which strength and modulus increased while elongation decreased substantially, illustrate this trade-off. Reduced ductility is not necessarily detrimental where dimensional stability and rigidity are primary requirements, but applications involving impact, cyclic loading, or large deformation require a more balanced response. Consequently, the optimum nanocomposite formulation is application-dependent rather than defined by a single mechanical property.

9.3 Impact Strength and Toughness

Impact resistance requires energy dissipation rather than simply resistance to elastic deformation. Poorly dispersed rigid particles can act as crack-initiation sites, whereas appropriately distributed nanostructures may promote crack deflection, crack bridging, controlled interfacial debonding, and localized matrix deformation. PP/POE/nano-CaCO₃ systems illustrate the role of multiphase structure, where interactions among nanoparticles, elastomeric domains, and PP modify deformation and energy absorption (Liang et al., 2016). In PP/GNP composites, Liang (2019) reported increases in Izod and Charpy impact strength at low GNP concentration, followed by reductions above approximately 0.4 wt%; platelet dimensions also affected impact-fracture toughness. Thus, high tensile modulus does not necessarily imply high toughness.

9.4 Fracture Behaviour

Fracture performance depends on both damage initiation and crack propagation. Well-dispersed nanostructures can deflect or bridge cracks, while controlled interfacial debonding can dissipate energy. Conversely, large aggregates are more likely to act as critical flaws than as toughening structures. PP/GNP studies demonstrate that platelet size and loading influence impact-fracture behaviour, while PP/MWCNT systems show that nanotube geometry can similarly affect impact fracture strength (Liang, 2019; Liang, 2018/2019). Fracture behaviour is therefore particularly sensitive to nanocomposite morphology: a material may show substantially higher modulus but little improvement, or deterioration, in impact resistance if reinforcement introduces stress concentrations or excessively restricts plastic deformation.

9.5 Fatigue and Creep Behaviour

Nanofiller effects extend to long-term deformation. Restriction of chain mobility and formation of reinforcing networks can reduce creep under sustained loading. PP/MWCNT experiments showed reduced creep strain and improved recovery with increasing CNT content, particularly at elevated temperature (Jia et al., 2011). The source manuscript also reports more recent modelling and experimental evidence for improved creep resistance in CNT- and reduced-graphene-oxide-filled PP, while indicating that excessive filler contents can reduce these benefits through interfacial detachment, void formation, aggregation, or imperfect interfaces. Thus, short-term reinforcement mechanisms can contribute to long-term deformation resistance, but the relationship is not necessarily monotonic. Creep and recovery should therefore be evaluated as functions of filler concentration, dispersion, interfacial quality, and temperature rather than inferred directly from tensile modulus.

9.6 Balancing Strength, Stiffness and Toughness

Mechanical optimization is inherently multivariable. Increasing nanofiller concentration may improve modulus while reducing ductility; stronger interfacial adhesion may improve load transfer while increasing matrix constraint; and increased crystallinity may enhance stiffness while altering plastic deformation and fracture. The PP/MWCNT and PP/GNP systems illustrate this balance: MWCNT incorporation can increase strength and modulus while reducing elongation and impact resistance, whereas appropriately selected GNP concentrations can improve impact strength without necessarily maximizing tensile reinforcement (Mansor et al., 2019; Liang, 2019). Nanofiller systems should therefore be evaluated in terms of the combined responses of strength, stiffness, ductility, and toughness, with creep and fatigue included where long-term service is relevant.

9.7 Structure–Property Interpretation

Across the nanofiller classes considered, high-aspect-ratio CNTs and graphene can provide efficient stiffness and load transfer when adequately dispersed and oriented; layered MMT combines interfacial reinforcement with modification

of crystallization and semicrystalline morphology; inorganic nanoparticles such as SiO_2 and CaCO_3 influence interfacial stress transfer and local deformation; and bio-derived nanostructures offer potentially sustainable reinforcement but require greater attention to compatibility and moisture. Overall, mechanical behaviour is governed by the coupled effects of nanofiller geometry, surface chemistry, dispersion, interfacial adhesion, crystallization, orientation, and processing history. Consequently, apparently similar PP nanocomposites can exhibit substantially different tensile, impact, fracture, and long-term responses. Mechanical-property values should therefore be interpreted within their structural and processing context rather than as isolated measures of filler effectiveness. This would allow more reliable relationships between nanofiller distribution and mechanical response to be established.

10. Challenges and Research Opportunities

Despite substantial progress in PP nanocomposites, reproducible mechanical enhancement remains limited by the coupled effects of dispersion, interfacial structure, processing, morphology, and testing conditions. Future research must therefore move beyond empirical optimization of filler loading toward quantitative control of nanostructure and its relationship with mechanical performance.

10.1 Dispersion and Agglomeration

Achieving uniform nanofiller dispersion remains one of the principal challenges in PP nanocomposites. High surface energy and strong filler–filler interactions promote aggregation, particularly at higher concentrations, reducing the effective polymer–filler interfacial area and generating stress-concentration regions. CNT studies demonstrate that improved dispersion can enhance tensile and impact properties, whereas excessive aggregation reduces reinforcement efficiency (Zhou et al., 2012). Similar effects occur in graphene, inorganic nanoparticles, and layered fillers, where the optimum mechanical response is generally associated with a sufficiently dispersed nanoscale structure rather than maximum filler concentration.

Dispersion is also strongly dependent on processing and interfacial modification. Compatibilization can improve polymer–filler interaction and suppress aggregation, while processing conditions determine the shear, residence time, and thermal history available for aggregate breakup and redistribution (Modesti et al., 2005). Atomistic analysis further indicates that interfacial structure and filler functionalization influence deformation and failure at the nanoscale (Sorkin et al., 2021). Future studies should therefore combine quantitative dispersion characterization with mechanical testing rather than treating filler loading as the primary structural variable. Three-dimensional characterization techniques and standardized measures of aggregate size, orientation, and spatial distribution would allow more reliable relationships between nanofiller distribution and mechanical response to be established.

10.2 Interfacial Engineering

The non-polar nature of PP limits interaction with many inorganic, carbonaceous, and bio-derived nanofillers. Compatibilization and surface functionalization can improve stress transfer, but excessive modification may introduce additional interfaces, alter filler morphology, or change intrinsic filler properties. The objective should therefore be controlled interfacial coupling rather than maximum functionalization. PP/silica modelling demonstrates that surface functionalization alters interfacial adhesion and deformation/failure behaviour, while graphene and layered-silicate studies show that compatibilization influences both dispersion and stress transfer (Sorkin et al., 2021; Hu et al., 2023; Modesti et al., 2005). Future work should systematically separate surface chemistry, interfacial adhesion, and dispersion through controlled model systems in which individual variables can be varied independently.

10.3 Balancing Stiffness and Toughness

Simultaneously improving stiffness, strength, ductility, and impact resistance remains a persistent challenge. Rigid fillers commonly increase modulus while reducing elongation, and aggregation can further impair impact performance (Mansor et al., 2019; Liang, 2019). Hybrid structures and controlled interfaces may moderate this trade-off, but increases in an individual tensile property should not be interpreted as overall mechanical improvement. Claims of simultaneous strengthening and toughening should therefore be supported by fracture and impact measurements, energy-dissipation and damage analyses, and appropriate single-filler controls at equivalent total filler concentrations and identical processing conditions.

10.4 Processing Reproducibility and Scale-Up

Laboratory processing does not necessarily reproduce industrial nanostructures. Mixer or extruder geometry, shear history, residence time, temperature profile, cooling rate, and injection conditions can alter filler distribution, orientation, and PP crystallization (Modesti et al., 2005; Miquelard-Garnier et al., 2013; Mi et al., 2023). More systematic reporting of specific processing energy, screw configuration and speed, residence time, temperature history, filler-addition sequence, and moulding conditions is therefore needed. Establishing processing–morphology relationships under representative industrial extrusion and injection conditions would improve reproducibility and scale-up.

10.5 Standardization of Mechanical Comparisons

Quantitative comparison across published PP nanocomposites is complicated by differences in PP grade, molecular characteristics, filler dimensions and surface treatment, loading, specimen preparation, testing standards, strain rate, and environmental conditions. Percentage improvement relative to neat PP alone can therefore obscure differences in absolute performance. Meaningful reporting should include absolute mechanical properties together with filler loading, particle dimensions/aspect ratio, surface treatment, dispersion state, PP grade, processing history, specimen orientation, testing standard, strain rate, and environmental conditions. Such standardization would facilitate comparison among carbon, layered, inorganic, and bio-derived nanostructures.

10.6 Multiscale Modelling and Data-Driven Design

Molecular dynamics, micromechanical modelling, finite-element analysis, and data-driven methods can connect nanoscale structure with macroscopic mechanical behaviour. Atomistic approaches provide information on polymer–filler interactions, interfacial adhesion, chain mobility, and failure, while continuum and micromechanical models address filler distribution, orientation, and volume fraction (Sorkin et al., 2021). Predictive accuracy nevertheless depends on reliable experimental inputs. Poorly characterized dispersion, uncertain interface properties, or inconsistent mechanical measurements can produce precise but physically unreliable predictions. Greater integration of quantitatively characterized experiments with multiscale modelling is therefore required. Machine-learning methods may further identify relationships among filler geometry, surface chemistry, loading, processing, crystallinity, and mechanical response, but their usefulness will depend on sufficiently large and standardized datasets.

10.7 Sustainability and Practical Considerations

Bio-derived nanostructures may reduce dependence on mineral or fossil-derived reinforcement, but sustainability cannot be judged solely from renewable origin. Surface modification, compatibilizer production, drying, energy-intensive processing, nanofiller preparation, recyclability, and end-of-life behaviour must also be considered. Carbon-based and inorganic systems similarly require attention to material recovery, recyclability, occupational exposure, and environmental fate as applications move toward larger-scale manufacturing. Future assessment should therefore combine mechanical performance with material and processing inputs through integrated performance–sustainability metrics.

10.8 Research Priorities

Future PP nanocomposite research should move from empirical filler selection toward controlled nanostructure design, emphasizing surface-engineered fillers, spatially controlled hybrid architectures, aggregation-resistant processing, and data-driven optimization of filler concentration and interfacial chemistry. Equally important is standardized quantitative characterization linking morphology and dispersion to mechanical response. Complete structure–processing–property datasets would help distinguish genuine reinforcement from changes arising primarily from matrix morphology, crystallinity, or processing history. The central objective is therefore to establish predictable relationships between nanoscale architecture and application-specific combinations of strength, stiffness, ductility, toughness, and long-term durability through coordinated advances in surface engineering, structural characterization, processing control, standardized testing, and multiscale modelling.

11. Conclusions

Nanostructured fillers provide an effective route for tailoring the mechanical behaviour of polypropylene (PP) beyond the limitations of the unmodified polymer. Across carbon-based nanostructures, layered nanomaterials, inorganic nanoparticles, bio-derived nanostructures, and hybrid systems, the literature demonstrates their potential to modify tensile

strength, stiffness, ductility, impact resistance, and fracture behaviour. However, the magnitude and direction of these changes depend strongly on nanofiller characteristics, PP matrix structure, and processing conditions. A consistent finding across the different nanofiller classes is that dispersion and interfacial adhesion are central determinants of reinforcement efficiency. High intrinsic strength or stiffness of a nanofiller does not, by itself, guarantee improved composite performance. Effective stress transfer requires adequate interfacial interaction, whereas excessive filler–filler interactions can promote agglomeration and stress-concentrating defects. Nanofiller geometry is equally important because CNTs, graphene-based structures, layered silicates, tubular nanostructures, and approximately spherical nanoparticles interact with PP through different combinations of surface area, aspect ratio, orientation, interfacial contact, and network formation. Mechanical behaviour is also closely coupled with PP crystallization and morphology. Nanofillers can act as heterogeneous nucleation sites and modify crystalline development, while melt processing simultaneously affects filler dispersion, orientation, polymer-chain organization, and crystallization. Consequently, mechanical-property improvements should not be attributed solely to direct nanofiller reinforcement; they generally represent the combined effects of interfacial stress transfer, nanofiller reinforcement, and modification of PP microstructure. An important limitation remains the frequent trade-off between stiffness and toughness. Nanofillers that substantially increase modulus and strength may reduce elongation or impact resistance by restricting polymer-chain mobility, promoting localized stress concentration, or forming poorly dispersed domains. Hybrid architectures and improved interfacial engineering provide potential routes for moderating these competing effects, but hybridization does not inherently produce synergy. Meaningful improvement requires controlled dispersion, appropriate filler–filler and filler–matrix interactions, and suitable spatial organization of the reinforcing phases. Future development should therefore progress beyond empirical optimization of filler loading toward structure-controlled nanocomposite design. Quantitative characterization of dispersion and orientation, systematic analysis of interfacial structure and crystallization, tensile and fracture characterization, long-term mechanical testing, and multiscale modelling should be increasingly integrated to establish predictive structure–property relationships. Such an approach would enable PP nanocomposites to be designed for application-specific combinations of stiffness, strength, ductility, toughness, and durability rather than optimized for a single mechanical parameter.

Overall, nanofiller effectiveness in PP is determined not by filler identity alone but by the interaction among nanofiller architecture, surface chemistry, dispersion, interfacial structure, processing history, and polymer morphology. Controlling these interconnected variables is therefore fundamental to achieving reproducible and balanced mechanical performance. Future PP nanocomposite development will increasingly depend on quantitative links between nanoscale structure, processing conditions, polymer morphology, and macroscopic mechanical response, enabling more predictable and application-oriented material design.

ACKNOWLEDGEMENT

The authors sincerely acknowledge the support and encouragement received from their respective institutions and colleagues during the preparation of this review article.

REFERENCES

- [1] Al-Saleh, M. H. (2015a). Electrically conductive carbon nanotube/polypropylene nanocomposite with improved mechanical properties. *Materials & Design*, 85, 76–81. <https://doi.org/10.1016/j.matdes.2015.06.162>
- [2] Al-Saleh, M. H. (2015b). Electrical and mechanical properties of graphene/carbon nanotube hybrid nanocomposites. *Synthetic Metals*, 209, 41–46. <https://doi.org/10.1016/j.synthmet.2015.06.023>
- [3] Al-Saleh MH. Effect of processing conditions on the dispersion, electrical, and mechanical properties of carbon nanotube/polypropylene nanocomposites. *Journal of Reinforced Plastics and Composites*. 2015;34(9):742-749. doi:[10.1177/0731684415579214](https://doi.org/10.1177/0731684415579214)
- [4] Al-Saleh, M. A., Yussuf, A. A., Al-Enezi, S., Kazemi, R., Wahit, M. U., Al-Shammari, T., & Al-Banna, A. (2019). Polypropylene/graphene nanocomposites: Effects of GNP loading and compatibilizers on the mechanical and thermal properties. *Materials*, 12(23), 3924. <https://doi.org/10.3390/ma12233924>
- [5] Awad, S. A., & Khalaf, E. M. (2019). Investigation of improvement of properties of polypropylene modified by nano silica composites. *Composites Communications*, 12, 59–63. <https://doi.org/10.1016/j.coco.2018.12.008>

- [6] Awad, S. A. (2024). Improvement of the Thermal and Mechanical Properties of Polypropylene/Modified Halloysite Nanotubes Composites. *Journal of Macromolecular Science, Part B*, 63(10), 791–802. <https://doi.org/10.1080/00222348.2021.1938367>
- [7] Aydemir, D., Uzun, U. Z., Gümüş, H., Yıldız, S., Gümüş, S., Bardak, T., & Gündüz, G. (2016). Nanocomposites of polypropylene/nano titanium dioxide: Effect of loading rates of nano titanium dioxide. *Materials Science (Medžiagotyra)*, 22(3), 364–369. <https://doi.org/10.5755/j01.ms.22.3.8217>
- [8] Bendaoued, A., Messaoud, M., Harzallah, O., Bistac, S., & Salhi, R. (2022). Use of thermal, dynamic, and mechanical analysis for characterizing sol-gel nano-TiO₂ and PP@TiO₂ advanced materials. *Journal of Sol-Gel Science and Technology*, 102(2), 372–385. <https://doi.org/10.1007/s10971-022-05724-0>
- [9] Bikiaris, D. (2010). Can nanoparticles really enhance thermal stability of polymers? Part I: An overview on thermal decomposition of polymer nanocomposites. *Materials*, 3(4), 2884–2946. <https://doi.org/10.3390/ma3042884>
- [10] Chammingkwan, P., Matsushita, K., Taniike, T., & Terano, M. (2016). Enhancement in mechanical and electrical properties of polypropylene using graphene oxide grafted with end-functionalized polypropylene. *Materials*, 9(4), 240. <https://doi.org/10.3390/ma9040240>
- [11] Delli, E., Gkiliopoulos, D., Bikiaris, D. N., Vourlias, G., Kehagias, T., & Chrissafis, K. (2026). The effect of montmorillonite concentration on the properties of random polypropylene/montmorillonite nanocomposites. *Polymer*, 343, 129482. <https://doi.org/10.1016/j.polymer.2025.129482>
- [12] Harada, K., Chu, P., Xu, K., & Fujimori, A. (2023). Polypropylene-based nanocomposite with improved mechanical properties: Effect of cellulose nanofiber and polyrotaxane with partial miscibility. *Polymer Composites*, 44(5), 2977–2987. <https://doi.org/10.1002/pc.27295>
- [13] Hossain, M. T., Shahid, M. A., Mahmud, N., Habib, A., Rana, M. M., Khan, S. A., & Hossain, M. D. (2024). Research and application of polypropylene: A review. *Discover Nano*, 19(1), Article 2. <https://doi.org/10.1186/s11671-023-03952-z>
- [14] Hu, B., Shao, Y., & Lu, H. (2023). Straightforward strategy toward in situ water-phase exfoliation and improved interfacial adhesion to fabricate high-performance polypropylene/graphene nanocomposites. *ACS Applied Materials & Interfaces*, 15(31), 37903–37915. <https://doi.org/10.1021/acsami.3c06185>
- [15] Infurna, G., Teixeira, P. F., Dintcheva, N. T., Hilliou, L., La Mantia, F. P., & Covas, J. A. (2020). Taking advantage of the functional synergism between carbon nanotubes and graphene nanoplatelets to obtain polypropylene-based nanocomposites with enhanced oxidative resistance. *European Polymer Journal*, 133, 109796. <https://doi.org/10.1016/j.eurpolymj.2020.109796>
- [16] Jia, Y., Peng, K., Gong, X.-L., & Zhang, Z. (2011). Creep and recovery of polypropylene/carbon nanotube composites. *International Journal of Plasticity*, 27(8), 1239–1251. <https://doi.org/10.1016/j.iijplas.2011.02.004>
- [17] Jung, K. H., et al. (2020). Synergistic effect of cellulose nanofiber and nanoclay as distributed phase in a polypropylene based nanocomposite system. *Polymers*, 12(10), 2399. <https://doi.org/10.3390/polym12102399>
- [18] Karamipour, S., Ebadi-Dehaghani, H., Ashouri, D., & Mousavian, S. (2011). Effect of nano-CaCO₃ on rheological and dynamic mechanical properties of polypropylene: Experiments and models. *Polymer Testing*, 30(1), 110–117. <https://doi.org/10.1016/j.polymertesting.2010.10.009>
- [19] Khoshkava, V., & Kamal, M. R. (2014). Effect of cellulose nanocrystals (CNC) particle morphology on dispersion and rheological and mechanical properties of polypropylene/CNC nanocomposites. *ACS Applied Materials & Interfaces*, 6(10), 8146–8157. <https://doi.org/10.1021/am500577e>
- [20] Khoshkava, V., Ghasemi, I., & Kamal, M. R. (2015). Effect of cellulose nanocrystals (CNC) on isothermal crystallization kinetics of polypropylene. *Thermochimica Acta*, 608, 30–39. <https://doi.org/10.1016/j.tca.2015.04.007>
- [21] Kumar, A., Patham, B., Mohanty, S., & Nayak, S. K. (2020). Polypropylene–nano-silica nanocomposite foams: Mechanisms underlying foamability, and foam microstructure, crystallinity and mechanical properties. *Polymer International*, 69(4), 373–386. <https://doi.org/10.1002/pi.5959>
- [22] Kumar, D., Srivastav, A., & Gautam, V. (2021). Investigation on mechanical and thermo-mechanical properties of injection molded PP-TiO₂ composites. *Materials Today: Proceedings*, 44(6), 4607–4611. <https://doi.org/10.1016/j.matpr.2020.10.912>
- [23] Kumar, R., Mishra, S. K., Raj, U., Sengupta, S., Chatterjee, R., Pandey, S., Hasnain, S. M. M., Ragab, A. E., Deifalla, A. F., & Jayapalan, S. (2024). Influence of graphene nanoplatelets (GnPs) and titanium dioxide (TiO₂) hybrid fillers on the mechanical, thermal, and morphological performance of polypropylene (PP) based hybrid composites. *Polymers and Polymer Composites*, 32. <https://doi.org/10.1177/09673911241260160>
- [24] Lecouvet, B., Sclavons, M., Bourbigot, S., Devaux, J., & Bailly, C. (2011). Water-assisted extrusion as a novel processing route to prepare polypropylene/halloysite nanotube nanocomposites: Structure and properties. *Polymer*, 52(19), 4284–4295. <https://doi.org/10.1016/j.polymer.2011.07.021>

- [25] Li, C. S.-Y., Sun, Y.-C., Guan, Q., & Naguib, H. (2016). Effects of chitin nanowhiskers on the thermal, barrier, mechanical, and rheological properties of polypropylene nanocomposites. *RSC Advances*, 6, 72086–72095. <https://doi.org/10.1039/C6RA11623J>
- [26] Li, C., Jiao, Z., Xiong, L., & Yang, W. (2017). Properties of polypropylene/multiwall carbon nanotube composite films prepared by microlayer extrusion. *Journal of Plastic Film & Sheeting*, 33(2), 191–206. <https://doi.org/10.1177/8756087916652931>
- [27] Liang, J.-Z. (2019a). Impact fracture behavior and morphology of polypropylene/graphene nanoplatelets composites. *Polymer Composites*, 40(S1), E511–E516. <https://doi.org/10.1002/pc.24826>
- [28] Liang, J.-Z. (2019b). Effects of tension rates and filler size on tensile properties of polypropylene/graphene nanoplatelets composites. *Composites Part B: Engineering*, 167, 241–249. <https://doi.org/10.1016/j.compositesb.2018.12.035>
- [29] Liang, J.-Z., Zhu, B., & Ma, W.-Y. (2016). Morphology and mechanical properties of PP/POE/nano-CaCO₃ composites. *Polymer Composites*, 37(2), 539–546. <https://doi.org/10.1002/pc.23210>
- [30] Manias, E., Touny, A., Wu, L., Strawhecker, K., Lu, B., & Chung, T. C. (2001). Polypropylene/montmorillonite nanocomposites: Review of the synthetic routes and materials properties. *Chemistry of Materials*, 13(10), 3516–3523. <https://doi.org/10.1021/cm0110627>
- [31] Miquelard-Garnier, G., Guinault, A., Fromonteil, D., Delalande, S., & Sollogoub, C. (2013). Dispersion of carbon nanotubes in polypropylene via multilayer coextrusion: Influence on the mechanical properties. *Polymer*, 54(16), 4290–4297. <https://doi.org/10.1016/j.polymer.2013.06.007>
- [32] Mirjalili, F., Chuah, L., Khalid, M., & Hasmaliza, M. (2012). Effects of nano α -Al₂O₃ fillers and dispersant on thermal and dynamic mechanical properties of polypropylene/nano α -Al₂O₃ composite. *Journal of Thermoplastic Composite Materials*, 25(4), 453–467. <https://doi.org/10.1177/0892705711421805>
- [33] Mirjalili, F., Chuah, L., Danafar, F., Soltani, M., & Chen, P. (2013). The effect of dispersant on toughening mechanism and structure behaviors of polypropylene nanocomposites reinforced with nano α -alumina particles. *Journal of Thermoplastic Composite Materials*, 26(10), 1377–1392. <https://doi.org/10.1177/0892705712454288>
- [34] Mirjalili, F., Chuah, L., & Salahi, E. (2014). Mechanical and morphological properties of polypropylene/nano α -Al₂O₃ composites. *The Scientific World Journal*, 2014, Article 718765. <https://doi.org/10.1155/2014/718765>
- [35] Md Said NH, Liu W-W, Khe C-S, Lai C-W, Zulkepli NN, Aziz A. Review of the past and recent developments in functionalization of graphene derivatives for reinforcement of polypropylene nanocomposites. *Polymer Composites*. 2021; 42: 1075–1108. <https://doi.org/10.1002/pc.25922>
- [36] Modesti, M., Lorenzetti, A., Bon, D., & Besco, S. (2005). Effect of processing conditions on morphology and mechanical properties of compatibilized polypropylene nanocomposites. *Polymer*, 46(23), 10237–10245. <https://doi.org/10.1016/j.polymer.2005.08.035>
- [37] Mohagheghian, M., Ebadi-Dehaghani, H., Ashouri, D., & Mousavian, S. (2011). A study on the effect of nano-ZnO on rheological and dynamic mechanical properties of polypropylene: Experiments and models. *Composites Part B: Engineering*, 42(7), 2038–2046. <https://doi.org/10.1016/j.compositesb.2011.04.043>
- [38] Ning, N.-Y., Yin, Q.-J., Luo, F., Zhang, Q., Du, R.-N., & Fu, Q. (2007). Crystallization behavior and mechanical properties of polypropylene/halloysite composites. *Polymer*, 48(25), 7374–7384. <https://doi.org/10.1016/j.polymer.2007.10.005>
- [39] Novais, R. M., Simon, F., Paiva, M. C., Covas, J. A., et al. (2012). The influence of carbon nanotube functionalization route on the efficiency of dispersion in polypropylene by twin-screw extrusion. *Composites Part A: Applied Science and Manufacturing*, 43(12), 2189–2198. <https://doi.org/10.1016/j.compositesa.2012.08.004>
- [40] Patti, A., Barretta, R., Marotti de Sciarra, F., Mensitieri, G., Menna, C., & Russo, P. (2015). Flexural properties of multi-wall carbon nanotube/polypropylene composites: Experimental investigation and nonlocal modeling. *Composite Structures*, 131, 282–289. <https://doi.org/10.1016/j.compstruct.2015.05.002>
- [41] Prashantha, K., Lacrampe, M.-F., & Krawczak, P. (2011). Processing and characterization of halloysite nanotubes filled polypropylene nanocomposites based on a masterbatch route: Effect of halloysites treatment on structural and mechanical properties. *Express Polymer Letters*, 5(4), 295–307. <https://doi.org/10.3144/expresspolymlett.2011.30>
- [42] Ray, S. S., & Okamoto, M. (2003). Polymer/layered silicate nanocomposites: A review from preparation to processing. *Progress in Polymer Science*, 28(11), 1539–1641. <https://doi.org/10.1016/j.progpolymsci.2003.08.002>
- [43] Sinha, R., Sengupta, S., & Jayapalan, S. (2022). Effect of hybrid fillers on the mechanical behavior of polypropylene based hybrid composites. *Journal of the Indian Chemical Society*, 99(2), 100317. <https://doi.org/10.1016/j.jics.2021.100317>

- [44] Sorkin, V., Pei, Q. X., Liu, P., Thitsartarn, W., He, C. B., & Zhang, Y. W. (2021). Atomistic-scale analysis of the deformation and failure of polypropylene composites reinforced by functionalized silica nanoparticles. *Scientific Reports*, 11, 23108. <https://doi.org/10.1038/s41598-021-02460-3>
- [45] Stribeck, N., Zeinolebadi, A., Ganjaee Sari, M., Botta, S., Jankova Atanasova, K., Hvilsted, S., Drozdov, A., Klitkou, R., Potarniche, C.-G., deClaville Christiansen, J., & Ermini, V. (2012). Properties and semicrystalline structure evolution of polypropylene/montmorillonite nanocomposites under mechanical load. *Macromolecules*, 45(2), 962–973. <https://doi.org/10.1021/ma202004f>
- [46] Sutar, H., Mishra, B., Senapati, P., Murmu, R., & Sahu, D. (2021). Mechanical, thermal, and morphological properties of graphene nanoplatelet-reinforced polypropylene nanocomposites: Effects of nanofiller thickness. *Journal of Composites Science*, 5(1), 24. <https://doi.org/10.3390/jcs5010024>
- [47] Triantou, M., Todorova, N., Giannakopoulou, T., Vaimakis, T., & Trapalis, C. (2017). Mechanical performance of re-extruded and aged graphene/polypropylene nanocomposites. *Polymer International*, 66(12), 1716–1724. <https://doi.org/10.1002/pi.5353>
- [48] Wang, G., Chen, X. Y., Huang, R., & Zhang, L. (2002). Nano-CaCO₃/polypropylene composites made with ultra-high-speed mixer. *Journal of Materials Science Letters*, 21(13), 985–986. <https://doi.org/10.1023/A:1016044204168>
- [49] Wang, J., Song, F., Ding, Y., & Shao, M. (2020). The incorporation of graphene to enhance mechanical properties of polypropylene self-reinforced polymer composites. *Materials & Design*, 195, 109073. <https://doi.org/10.1016/j.matdes.2020.109073>
- [50] Wang, L., Okada, K., Sodenaga, M., Hikima, Y., Ohshima, M., Sekiguchi, T., & Yano, H. (2018). Effect of surface modification on the dispersion, rheological behavior, crystallization kinetics, and foaming ability of polypropylene/cellulose nanofiber nanocomposites. *Composites Science and Technology*, 168, 412–419. <https://doi.org/10.1016/j.compscitech.2018.10.023>
- [51] Wang, L., Okada, K., Hikima, Y., Ohshima, M., Sekiguchi, T., & Yano, H. (2019). Effect of cellulose nanofiber (CNF) surface treatment on cellular structures and mechanical properties of polypropylene/CNF nanocomposite foams via core-back foam injection molding. *Polymers*, 11(2), 249. <https://doi.org/10.3390/polym11020249>
- [52] Wu, C., Wu, R., & Tam, L.-H. (2022). The creep behavior of semicrystalline carbon nanotube/polypropylene nanocomposite: A coarse-grained molecular study. *Polymer Degradation and Stability*, 196, 109834. <https://doi.org/10.1016/j.polymdegradstab.2022.109834>
- [53] Zhou, K., Gu, S.-Y., Zhang, Y.-H., & Ren, J. (2012). Effect of dispersion on rheological and mechanical properties of polypropylene/carbon nanotubes nanocomposites. *Polymer Engineering & Science*, 52(7), 1485–1494. <https://doi.org/10.1002/pen.23098>
- [54] Zhu, S., Chen, J., Zuo, Y., Li, H., et al. (2011). Montmorillonite/polypropylene nanocomposites: Mechanical properties, crystallization and rheological behaviors. *Applied Clay Science*, 52(1–2), 171–178. <https://doi.org/10.1016/j.clay.2011.02.021>

Cite this Article:

Srivastav, G. K., Verma, R. R., Singh, A. K., Mishra, P. (2026). Nanostructured Fillers for Tailoring the Mechanical Properties of Polypropylene: Recent Advances and Structure-Property Relationships. *International Journal of Scientific Research in Modern Science and Technology (IJSRMST)*, 5(8), 18–39.

Journal URL: <https://ijrmst.com/> DOI: <https://doi.org/10.59828/ijrmst.v5i8.453>.



This work is licensed under a [Creative Commons Attribution-Non-Commercial 4.0 International License](https://creativecommons.org/licenses/by-nc/4.0/).

© The Author(s) 2026. IJSRMST Published by Surya Multidisciplinary Publication.

Disclaimer/Publisher's Note: The author(s) are solely responsible for the content and claims of this article. The publisher and editors assume no legal liability for any errors, copyright violations, or damages arising from its use.