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Comparative Study on the Rheological Properties of PS/PP–CaCO3 and PS/PP–Walnut Shell Blends

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ABSTRACT

This study presents a comparative rheological analysis of polystyrene/polypropylene (PS/PP 20/80) blends filled with either calcium carbonate (CaCO3) or walnut shell powder at 8 and 12 wt.% loadings. Rheological properties were investigated using a capillary rheometer at temperatures ranging from 190°C to 220°C. The results demonstrate that adding CaCO3 significantly increases shear stress, apparent viscosity, and flow activation energy (up to 12.9 kJ/mol), enhancing rigidity but impairing processability. In contrast, walnut shell composites exhibited a lubricating effect, reducing viscosity by 15–20%, increasing the melt flow index, and lowering the flow activation energy, thereby promoting easier flow. This is attributed to the thermal softening of lignocellulosic components. The optimal balance for processability was achieved with 8% walnut shell at 220°C, while 12% CaCO3 is recommended for applications requiring higher stiffness. These findings underscore the potential of walnut shell as a sustainable, processability-enhancing filler, presenting a clear trade-off between improved flow and mechanical reinforcement.

KEYWORDS

Agricultural waste, capillary rheometry, melt viscosity, polymer composites, processability enhancement, shear thinning

CITATION

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1. Introduction

The development of polymer blends and composites with tailored properties continues to be a central focus in polymer science. Blending polymers provides a pathway to synergistically combine the complementary mechanical, thermal, and rheological properties of different polymers (Utracki and Wilkie, 2002). In particular, polystyrene (PS) and polypropylene (PP) blends have attracted attention because PS provides rigidity and dimensional stability, while PP contributes ductility, thermal resistance, and low density (Paul and Bucknall, 2000). However, PS and PP are inherently immiscible, which results in phase separation, weak interfacial adhesion, and limited mechanical performance (Huo *et al.*, 2007). This morphological heterogeneity strongly influences rheological behavior, which is critically important for processing methods such as extrusion and injection molding. Recent studies, including work conducted at Damascus University, have underscored that characterizing the rheology of immiscible systems (e.g., polylactic acid/polycarbonate (PLA/PC) blends) under various shear conditions yields insights into their interfacial dynamics and flow behavior (Al-Kateb *et al.*, 2023). Such insights are indispensable for predicting process windows and final performance. To mitigate incompatibility and improve composite properties, fillers are often introduced. Fillers can stabilize interfaces, modify viscosity, or enhance stiffness and thermal behavior (Barnes *et al.*, 1989; Mohamad *et al.*, 2020). Calcium carbonate ($CaCO_3$) is a classical inorganic filler, valued for its abundance, low cost, and beneficial reinforcement effects in polymers (Kloziński, *et al.*, 2023). In PP-based systems, $CaCO_3$ addition typically increases melt viscosity and accentuates non-Newtonian (shear-thinning) behavior through polymer–filler interactions and restricted chain mobility (Arzumanova, 2021; Li *et al.*, 2024). For example, Wang *et al.* (2015) examined dynamic extrusion of $CaCO_3$-filled PP and documented changes in flow behavior with filler concentration. Kloziński *et al.* (2023) also discussed the rheological effects of $CaCO_3$ fillers in PP at high shear rates.

Driven by sustainability goals, researchers are increasingly exploring bio-derived fillers. Walnut shell powder, a lignocellulosic byproduct, is an attractive renewable filler due to its low cost, biodegradability, and structural composition (lignin, cellulose, hemicellulose) (Tsegaye, *et al.*, 2023). Its incorporation in polymer matrices can influence melt rheology not only via physical interactions but also through chemical or thermal softening of its lignocellulosic constituents (Fazeli *et al.*, 2024). A recent review, "Review of Bio-Fillers Dedicated to Polymer Compositions" (2025), addresses the roles and challenges of bio-fillers in polymers, including issues of dispersion, interfacial compatibility, moisture sensitivity, and rheological impacts. In addition, the review "Lignin beyond the status quo: recent and emerging composite advances" (2024) provides a modern perspective on how lignin-modified materials behave within polymer matrices. Although many studies have explored $CaCO_3$-reinforced PP and referenced bio-fillers separately, direct, side-by-side rheological comparisons of PS/PP blends filled with $CaCO_3$ versus walnut shell under identical processing and measurement conditions remain scarce. In addition, few works have quantitatively correlated multiple rheological metrics such as apparent viscosity, shear-thinning index, activation energy, and melt flow index in hybrid or bio-filled polymer composites (Lee, *et al.*, 2023). This study aims to fill that gap by investigating PS/PP (80/20) blends incorporating either $CaCO_3$ or walnut shell at two loadings (8% and 12% by weight), using capillary rheometry and MFI tests to evaluate how filler type and concentration influence the flow curves, viscosity, shear-thinning behavior, die swell, and temperature sensitivity.

Because rheological parameters directly affect processability (flow stability, shear sensitivity, energy consumption), linking them to filler selection is of practical significance. The results aim to inform the design of sustainable polymer composites that balance processability, mechanical performance, and environmental considerations.

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2. Materials and Methods

2.1. Polymer Materials:

Polystyrene (PS): Type SABIC® 125 PS, with a density of 1.05 g/cm³, supplied by Saudi Basic Industries Corporation (SABIC), Kingdom of Saudi Arabia.

Polypropylene (PP): Type PETOPLEN EH 251, produced by PETKIM Petrokimya Holding A.S., Turkey.

2.2. Fillers:

Calcium Carbonate ($CaCO_3$): A high-purity (≥ 99%) $CaCO_3$ powder supplied by Riedel-de Haën AG (Germany) was used. According to the manufacturer's specifications, the powder features a fine particle size range of 1–5 micrometers and a primary calcite crystal structure. No surface treatment was applied to the powder prior to use.

Walnut Shell Powder: Walnut shells were collected from local natural sources. They were washed, dried at 80°C for 24 hours, and then mechanically ground and sieved to pass through a 75-micrometer sieve (200 mesh) to achieve a consistent particle size distribution. The particles did not undergo any chemical surface treatment. Walnut shell powder is a lignocellulosic material composed primarily of cellulose, hemicellulose, and lignin, components known to thermally soften and influence flow properties.

2.3. Methodology:

The blends were prepared by melt extrusion using a 20/80 PS/PP ratio with filler loadings of 8% and 12% by weight. These specific loadings were selected because preliminary tests indicated that lower concentrations (e.g., 4%) resulted in properties very similar to the unfilled blend, providing an insufficient basis for comparison, while higher loadings posed processing challenges. Thus, 8% and 12% represent an optimal range to clearly observe the filler's influence. $CaCO_3$ and walnut shell powders were used as reinforcing agents. After extrusion, the blends were pelletized and reprocessed for testing. Rheological measurements were carried out using a capillary rheometer at four temperatures (190, 200, 210, and 220 °C) under applied loads of 1–4 kg. All rheological tests were performed in triplicate, and the calculated coefficient of variation (CV) for all measured parameters was below 7.4%, confirming the high reproducibility of the data.

The apparent shear stress τ_a, apparent shear rate γ_a, and apparent viscosity η_a were calculated according to the following standard rheological relations for capillary (Macosko, 1994; Dealy and Wang, 2013):

$$\tau_a = \frac{\Delta pR}{2L} \quad (1)$$

$$\gamma_a = \cdot\frac{4Q}{\pi R^3} \quad (2)$$

$$\eta_a = \frac{\tau_a}{\gamma_a} \quad (3)$$

where:

- Δp: is the pressure drop across the capillary,
- R: is the radius of the capillary die,
- L: is the length of the capillary die,
- Q: is the volumetric flow rate.

The melt flow index (MFI) was determined according to ASTM D1238 (ASTM International, 2013), using a standard die under a specified load. The MFI value is expressed as the mass of polymer extruded in 10 minutes:

$$MF = \frac{W\times 600}{t} \quad (4)$$

where:

- W: is the mass of the extrudate in grams,
- t: represents time in seconds, and the time taken is 10 seconds.

The die swell ratio (B), which characterizes the elastic recovery of the melt, was evaluated from the diameter of the extrudate (D) and the diameter of the capillary die (D_0) (Tanner, 2000):

$$B = \frac{D}{D_0} \quad (5)$$

The flow activation energy (E_a) was calculated using the Arrhenius equation, which relates the melt viscosity to temperature (Rudolph and Osswald, 2014):

$$\eta_a = A \times e^{\frac{E_a}{RT}} \quad (6)$$

where:

- η_a: is the viscosity at a constant shear stress,
- A: is the pre-exponential factor,
- E_a: is the flow activation energy (J/mol),
- R: is the universal gas constant (8.314 J/mol·K),
- T: is the absolute temperature (K).

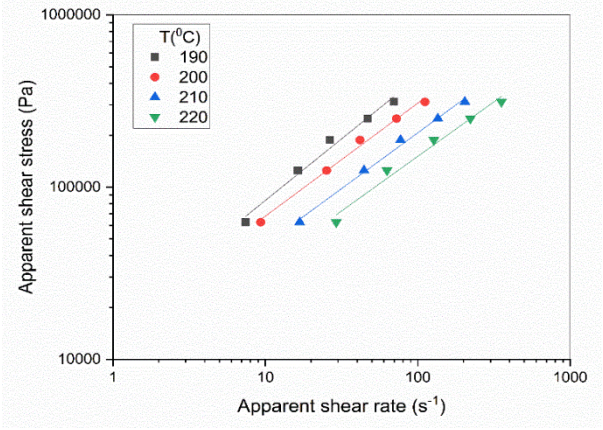
It is important to note that in this study, apparent rheological values were used. This methodological choice follows earlier studies that emphasize the comparative evaluation of apparent values in filled polymer systems (Rueda, 2017; Montfort *et al.*, 1978).

3. Results and Discussion

3.1. Shear Stress vs. Shear Rate (Flow Curves):

Figure 1 illustrates the flow curves (apparent shear stress vs. apparent shear rate) for the unfilled PS/PP (80/20) blend, establishing the baseline rheological behavior of the polymer matrix prior to the addition of any fillers.

Figure 1. Comparative flow curves (apparent shear stress, τ_a, vs. apparent shear rate, γ_a) for unfilled PS/PP (20/80) blend at different temperatures.

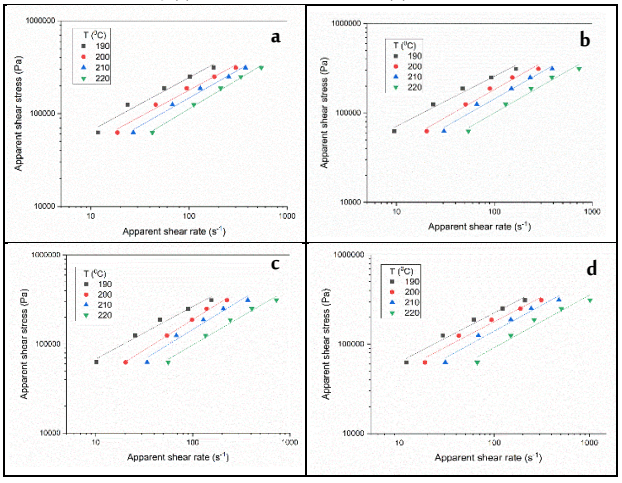


The results presented in Figure 2. and the data in Table 1 provide a clear picture of the melt's rheological behavior. All samples exhibited non-Newtonian pseudoplastic behavior, where the apparent shear stress τ_a increases with the apparent shear rate γ_a in a non-linear relationship. However, fundamental differences were observed between systems filled with $CaCO_3$ and those filled with walnut shell particles, as well as when compared to the unfilled PS/PP (20/80) blend.

Examination of the flow curves reveals that the incorporation of either filler type moved the curves toward higher shear stress values

compared to the unfilled base blend, indicating an increase in shear stress at any given shear rate. This effect was most pronounced in $CaCO_3$-filled systems, which recorded higher stress levels than both the walnut shell-filled composites and the unfilled blend at equivalent loadings. This is attributed to the rigid and hard nature of $CaCO_3$ particles, which severely restricts polymer chain mobility, thereby increasing flow resistance, as commonly observed in particulate-filled polymer systems (Pukanszky, 1990). In contrast, the addition of porous, organic walnut shell particles resulted in a comparatively smaller increase in shear stress relative to the base blend, suggesting different interfacial interactions, which is a known characteristic of lignocellulosic fillers that can lead to weaker adhesion and potential lubricity (Fu *et al.*, 2008).

Figure 2. Comparative flow curves (apparent shear stress, τ_a, vs. apparent shear rate, γ_a) for PS/PP (20/80) blends at different temperatures. (a) Filled with 8% $CaCO_3$, (b) filled with 12% $CaCO_3$, (c) filled with 8% walnut shell, (d) filled with 12% walnut shell.



These qualitative observations are in full agreement with the quantitative analysis of the flow behavior index (n) presented in Table 1. While all n values below 1 confirm pseudoplasticity for all melts, the relatively lower n values for the $CaCO_3$ composites (ranging between 0.558 and 0.636) compared to the unfilled blend (ranging from 0.633 to 0.714) reflect a higher degree of shear-thinning behavior (i.e., greater sensitivity of viscosity to changes in shear rate). This explains the sharp decline observed in the initial part of the flow curves for these samples (Figure 2a and 2b), where the structure of rigid, mobility-restricting particles breaks down significantly under increasing shear. Conversely, the higher n values recorded for many walnut shell composites (reaching 0.683 at 8% and 200 °C) indicate less severe pseudoplasticity, making their behavior closer to that of the unfilled blend. This is visually evident in the flow curves (c and d of Figure 2) as a more gradual decrease in viscosity with increasing shear rate.

Furthermore, the effect of temperature shows consistency between the tabular data and the figures. For $CaCO_3$-filled systems, increasing temperature steadily increased the value of n (e.g., from 0.572 at 190°C to 0.636 at 220°C for the 8% sample), indicating a shift towards more Newtonian-like behavior due to enhanced polymer chain mobility, a trend also observed though less pronounced in the unfilled blend. For walnut shell composites, the effect of temperature was less regular, reflecting the more complex nature of the interactions between the polymer and the organic filler.

In summary, there is complete agreement between the quantitative (n values) and qualitative (flow curve offset) analyses. The unfilled PS/PP (20/80) blend serves as a reference with moderate pseudoplastic behavior. Filler incorporation increases flow resistance and accentuates pseudoplasticity. The low n values in $CaCO_3$ systems correspond to flow curves with a steep slope, while the higher n values in walnut shell systems correspond to straighter, more gradual curves, conclusively confirming the difference in flow mechanisms between the two filler types compared to the base polymer (Rudolph and Osswald, 2014).

Table 1. Flow behavior index (n) values for PS/PP blends filled with $CaCO_3$ and walnut shell powder at different temperatures and filler loadings.

Temperatures	PS/PP (20/80) blends	PS/PP (20/80) blends			
		$CaCO_3$		Walnut Shell	
		8%	12%	8%	12%
190 °C	0.714 ± 0.053	0.572 ± 0.062	0.558 ± 0.047	0.588 ± 0.050	0.550 ± 0.047
200 °C	0.656 ± 0.030	0.571 ± 0.043	0.622 ± 0.050	0.683 ± 0.024	0.554 ± 0.051
210 °C	0.647 ± 0.028	0.601 ± 0.038	0.621 ± 0.048	0.670 ± 0.068	0.582 ± 0.056
220 °C	0.633 ± 0.050	0.636 ± 0.026	0.628 ± 0.053	0.635 ±0.048	0.586 ± 0.071

* Note: All values are reported as estimate ± standard error. The power-law model fittings exhibited high correlation coefficients ($R^2 > 0.99$). *

3.2. Analysis of Viscosity Curves and the Effect of Additives:

The apparent viscosity η_a curves, derived from the relationship between shear stress and shear rate, provide deeper insight into the flow behavior of PS/PP blends filled with $CaCO_3$ and walnut shell particles. Figure 3 illustrates the variation in viscosity as a function of shear rate for different filler types, loadings, and temperatures. All systems exhibited distinct shear-thinning behavior, consistent with n values of less than 1. However, the extent of shear thinning and the absolute viscosity values were significantly influenced by the filler type and concentration, particularly when compared to the unfilled base blend (Figure 3a). The incorporation of $CaCO_3$ led to a substantial increase in the overall melt viscosity compared to walnut shell fillers at equivalent loadings, especially at low shear rates. The unfilled blend exhibited the lowest viscosity values, followed by the walnut shell-filled composites, with the $CaCO_3$-filled samples showing the highest viscosity values (Figure 3b–3e). This significant increase is attributed to the resistant network formed by the rigid $CaCO_3$ particles within the polymer matrix, hindering chain mobility, as commonly reported for mineral-filled thermoplastics (Pukanszky, 1990). In contrast, walnut shell composites displayed a less pronounced viscosity increase compared to the base blend. The organic, porous structure of walnut shell particles likely results in different polymer-filler interactions; lignocellulosic fillers often exhibit lower reinforcing efficiency and can affect flow differently due to their complex structure and potential thermal softening (Fu *et al.*, 2008). This aligns with the higher n values observed for walnut shell composites, indicating a lower degree of shear sensitivity and making their rheological behavior closer to the unfilled blend than to the $CaCO_3$-filled samples.

3.3. Flow Activation Energy (Ea):

The values of the flow activation energy (Ea), derived from the Arrhenius plots (Figure 4) and shown in Table 2 show a fundamental difference in the thermal response of the filled samples, reflecting the nature of polymer–filler interactions at the molecular level.

Table 2. Activation energy values (Ea.τ) (kJ/mol) for polystyrene/polypropylene blends with calcium carbonate and walnut shell particles at 8% and 12% concentrations, under constant shear stress.

The blend (PP/PS) (80/20) was added to...	$\tau = 6.2 \times 10^4$ (Pa)	$\tau = 12.4 \times 10^4$ (Pa)	$\tau = 18.7 \times 10^4$ (Pa)	$\tau = 24.9 \times 10^4$ (Pa)	$\tau = 31.2 \times 10^4$ (Pa)
(%8) $CaCO_3$	9.570 ± 0.26	10.058± 0.42	9.137 ± 0.06	9.007± 0.99	8.159 ± 0.879
(%12)$CaCO_3$	12.875 ± 0.98	12.277 ± 0.14	12.197 ± 0.49	10.69 ± 0.31	10.90 ± 0.97
(%8) Walnut Shells	12.85 ± 0.592	12.10 ± 1.37	12.08 ± 1.42	11.22 ± 1.13	11.65 ± 1.12
(%12) Walnut Shells	12.85 ± 1.38	12.28 ± 1.65	11.05 ± 0.66	10.33 ± 1.60	11.73 ± 1.53

* Note: Values represent the mean ± standard error derived from triplicate measurements. The Arrhenius model fittings for the temperature dependence of viscosity yielded high linear correlation coefficients ($R^2 > 0.98$) for all reported activation energies. *

For the $CaCO_3$ samples, an increase in Ea value was observed with increasing filler loading (from 8% to 12%) under most shear stress values. This increase indicates a higher energy barrier required to initiate melt flow, attributed to the polar nature and hard, inorganic surface of $CaCO_3$ particles. These particles form stronger physical bonds with the polymer chains, hindering their thermal motion and making the system more temperature-sensitive. This aligns with studies showing that rigid inorganic fillers increase the difficulty of polymer chain relaxation (Pukanszky, 1990).

Figure 3. Comparative flow curves (apparent shear stress, τ_a, vs. apparent shear rate, γ_a) for PS/PP (20/80) blends at various temperatures. (a) Unfilled base blend, (b) filled with 8% $CaCO_3$, (c) filled with 12% $CaCO_3$, (d) filled with 8% walnut shell, (e) filled with 12% walnut shell.

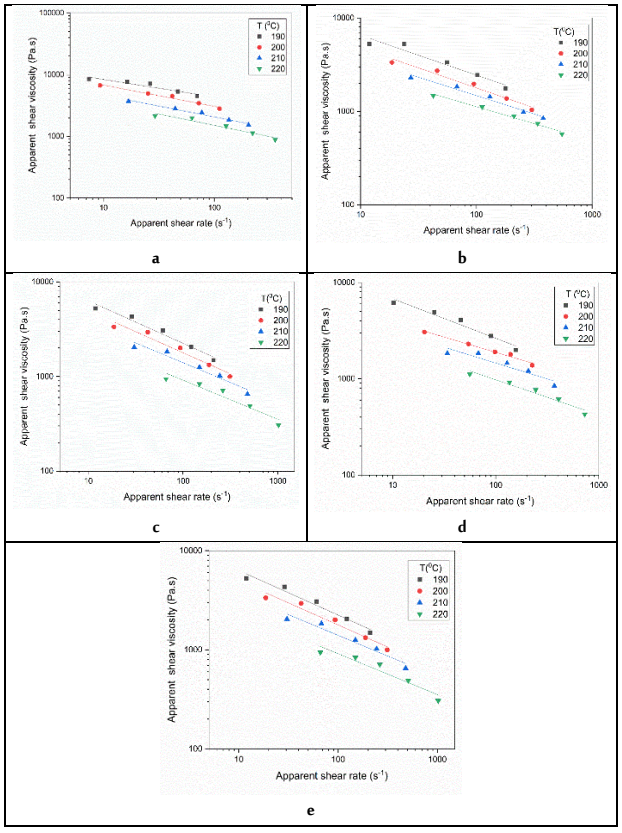
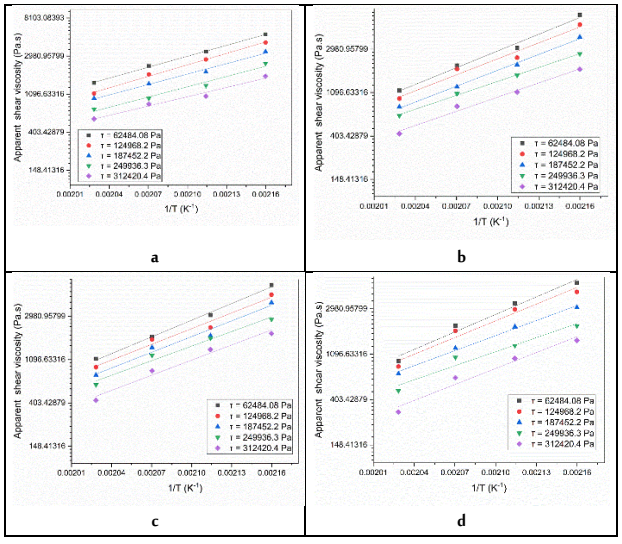


Figure 4. Arrhenius plots of apparent viscosity (η_a) versus inverse absolute temperature (1/T) for PS/PP (20/80) blends under constant shear stress. (a) Filled with 8% $CaCO_3$, (b) filled with 12% $CaCO_3$, (c) filled with 8% walnut shell, (d) filled with 12% walnut shell.



In contrast, the samples filled with walnut shells showed an opposite or irregular trend, where Ea values decreased or varied with increasing filler content. A deeper analysis of the chemical composition of walnut shells reveals the precise mechanism behind this lubricating effect. The key lignocellulosic components—namely lignin and hemicellulose—contain low-molecular-weight compounds (e.g., phenolic acids) that act as inherent plasticizers (Faruk *et al.*, 2012). At the elevated processing temperatures (190–220 °C), these components undergo thermal softening, migrating to the polymer–polymer and polymer–filler interfaces. This migration facilitates chain slippage during flow, thereby reducing internal friction and effectively lowering the energy barrier for viscous flow, as reflected in the decreased Ea values (Tsegaye, *et al.*, 2023). Furthermore, the porous and organic nature of walnut shell particles results in weaker polymer–filler adhesion compared to the strong polar interactions of $CaCO_3$. This weaker interface, while reducing reinforcement efficiency, significantly diminishes the constraints on polymer chain mobility (Fu *et al.*, 2008). Consequently, the filler particles act more as passive, slippage-inducing sites within the matrix rather than as strong reinforcing anchors, which further contributes to the reduced flow activation energy and enhanced processability observed in these biocomposites. Notably, the processing temperature range (190–220°C) employed in this study remains below the significant thermal degradation threshold of walnut shell components (typically above 250°C) (Tsegaye, *et al.*, 2023), ensuring that the observed effects are primarily due to thermal softening rather than decomposition. This lubricating effect overcomes any restriction of movement caused by the particles themselves (Pukanszky, 1990).

In summary, the differences in Ea reflect the different mechanisms of influence: mobility restriction by the inorganic filler versus flow facilitation by the thermally softenable organic filler.

3.4. Melt Flow Index (MFI):

The Melt Flow Index (MFI) results (Figure 5) confirm the conclusions drawn from the viscosity analysis, but from a perspective more relevant to industrial processing applications. The notable increase in MFI values with increasing walnut shell loading indicates a significant improvement in the processability of the molten blend. This result directly reflects the lubricating and thermoplastifying effect of the lignocellulosic components, which reduce internal friction and allow easier flow under pressure, thereby reducing energy consumption in processes such as extrusion and injection molding (Kuram, 2022). Conversely, the slight or stable increase in MFI for $CaCO_3$-containing blends at the same loading levels confirms $CaCO_3$'s role as a stiffness-enhancing filler. The rigid particles increase dimensional stability and mechanical resistance, but at the cost of increased melt viscosity and thus greater difficulty in flow under low shear conditions (characteristic of MFI tests) (Rothon, 2003). Therefore, the choice of filler depends on the final objective: walnut shells to improve processability, and $CaCO_3$ to enhance mechanical properties and stability.

3.5. Die Swell coefficient of swelling (B):

The die swell coefficient (B) (Figure 6) provides valuable insight into the melt elasticity, a property distinct from plastic viscosity. The greater reduction in values of B observed in samples filled with walnut shells indicates a significant decrease in the melt's elastic recovery. This is due to the mechanical nature of the porous organic particles, which are less capable of storing elastic energy during deformation compared to the elastic polymer chains. Upon exiting the die, the stored elastic energy is lower, resulting in less die swell.

This aligns with the known behavior of organic fillers that dampen elasticity (Ak, 1994). In contrast, samples filled with $CaCO_3$ showed a smaller reduction in the (B) coefficient. This phenomenon is explained by the rigid structure of the inorganic particles, which can form a rigid network that interacts with the polymer chains and allows for partial transmission of elastic stress. Even though present, the rigid particles do not absorb elastic energy as effectively as the elastic polymer matrix, but they may allow for greater limited elastic recovery compared to the energy-absorbing porous particles (Landel and Nielsen, 1993). This difference highlights another distinction: walnut shells reduce elastic recovery (beneficial for reducing post-extrusion deformation), while $CaCO_3$ maintains a degree of the inherent melt elasticity associated with the base polymer behavior.

Figure 5. Melt Flow Index (MFI) as a function of apparent shear stress (τ_a) for PS/PP (20/80) blends at different temperatures. (a) Filled with 8% $CaCO_3$, (b) filled with 12% $CaCO_3$, (c) filled with 8% walnut shell, (d) filled with 12% walnut shell.

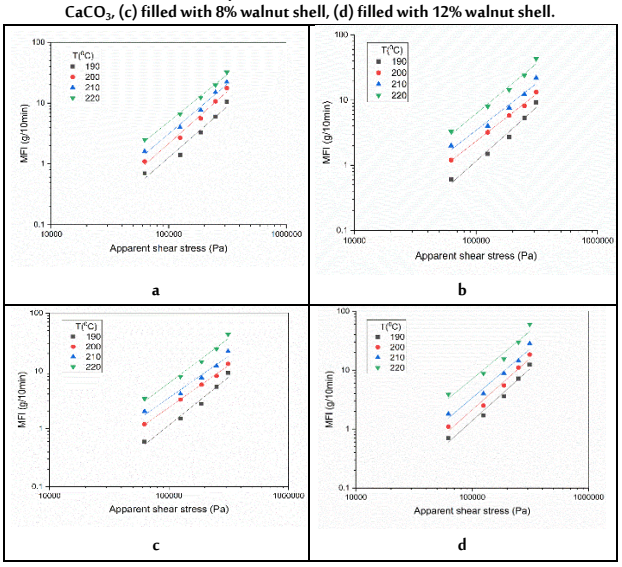
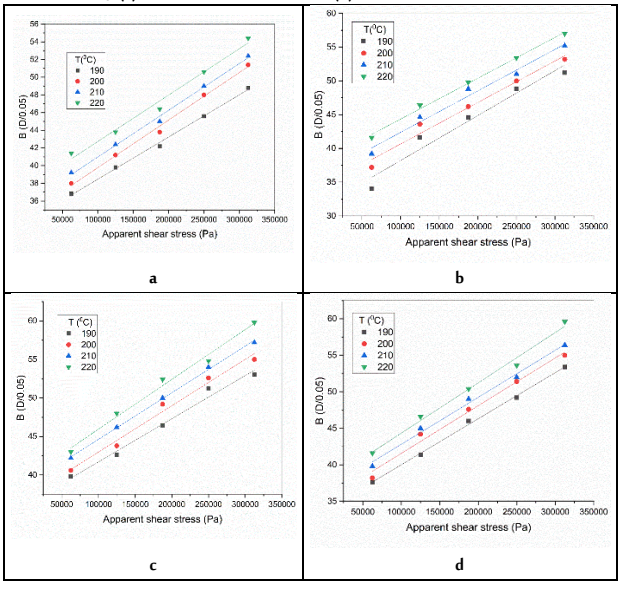


Figure 6. Die swell coefficient (B) as a function of apparent shear stress (τ_a) for PS/PP (20/80) blends at different temperatures. (a) Filled with 8% $CaCO_3$, (b) filled with 12% $CaCO_3$, (c) filled with 8% walnut shell, (d) filled with 12% walnut shell.



3.6. Implications for Mechanical Performance and Processing:

The distinct rheological behaviors observed for $CaCO_3$ and walnut shell composites have direct implications for their mechanical performance and optimal industrial processing conditions. The significant increase in melt viscosity, shear stress, and flow activation energy in $CaCO_3$-filled blends indicates the formation of a rigid filler network within the polymer matrix. This network restricts polymer chain mobility not only during flow but also upon solidification, which is expected to translate into enhanced mechanical stiffness, higher tensile modulus, and improved dimensional stability in the final product (Pukanszky, 1990). Consequently, these composites are highly suitable for applications requiring structural integrity, albeit at the cost of higher energy consumption during processing and the need for more robust extrusion or injection molding equipment.

Conversely, the walnut shell composites, characterized by lower viscosity, higher MFI, and reduced die swell, demonstrate a fundamentally different behavior. The lubricating effect and weaker polymer–filler interface that facilitate processability are likely to result in a different mechanical property profile. While these composites might exhibit lower stiffness and tensile strength compared to their $CaCO_3$-filled counterparts, they are anticipated to offer advantages in applications requiring complex flow paths, thin walls, or reduced energy consumption during manufacturing (Fu *et al.*, 2008).The reduced die swell is particularly beneficial for profile extrusion, ensuring better shape fidelity and minimizing post-extrusion distortions.

In summary, the choice between fillers presents a clear trade-off between $CaCO_3$ for superior mechanical rigidity and walnut shell for enhanced processability and formability. These findings provide a rheologically grounded framework for the informed selection of fillers in PS/PP blends based on target applications, bridging the gap between process-induced structures and final product performance.

4. Conclusions

This comprehensive comparative study unequivocally demonstrates that the nature of the filler—rigid inorganic $CaCO_3$ versus soft organic walnut shell powder—fundamentally dictates the processing–structure–property relationships in PS/PP blends. The $CaCO_3$ composites are characterized as reinforcing systems, as evidenced by significantly elevated melt viscosity, shear stress, and flow activation energy, and by more pronounced shear-thinning behavior. These traits enhance rigidity and dimensional stability but at the expense of processability, making them suitable for structural applications. Conversely, walnut shell powder acts as an efficient processing aid. The unique chemical composition of its lignocellulosic components imparts a pronounced lubricating effect, resulting in lower viscosity, a higher melt flow index, reduced die swell, and a lower thermal sensitivity to flow. This combination significantly improves the blend's processability, reducing energy consumption for operations such as extrusion and injection molding.

Consequently, this research provides clear, rheologically grounded guidelines for material selection:

- For applications demanding superior flow characteristics and energy efficiency (e.g., complex molds, thin-walled products), the PS/PP blend with 8% walnut shell filler processed at 220°C is highly recommended.
- For end-uses where mechanical stiffness and dimensional stability are paramount, the 12% $CaCO_3$ composite is the preferable choice, despite its higher flow resistance.

These findings not only bridge the gap between rheology and potential mechanical performance but also strongly advocate for the successful utilization of walnut shell, an abundant agricultural waste product, as a sustainable and functional filler. Future work will focus on correlating these rheological findings with direct mechanical performance tests and exploring surface modifications to further optimize interfacial adhesion and composite properties.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request**.**

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Conflict of Interest

The authors declare no conflict of interest.

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