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Flow Analysis and Shear Rate Comparison of Counter-rotating and Co-rotating Intermeshing Twin-screw Extruders for Filament Extrusion of Polypropylene-based Biocomposites

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ABSTRACT

This study investigates and compares the performance of counter-rotating and co-rotating intermeshing twin-screw designs in filament extruder machines. The research sought to determine whether the counter-rotating intermeshing design with its opposite flow direction offers advantages over the co-rotating intermeshing design in terms of flow analysis and shear rates. Flow analysis was conducted to examine the velocity of the polypropylene-based biocomposite material inside the barrel. Shear rate data was obtained by evaluating the relationship between shear rate and screw speed to assess the stability and maximum shear rate of the twin-screw extruders. The results revealed that the counter-rotating intermeshing twin-screw extruders exhibited higher shear rates and more consistent pressure compared to the co-rotating intermeshing design. The superiority of the counter-rotating extruder was attributed to its opposite flow direction and distinct thread shapes, facilitating efficient material compression and improved dispersion of polymer-based biocomposite materials. The study suggested the potential for further exploration and refinement of

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the counter-rotating intermeshing twin-screw extruder design, particularly in producing polypropylene-based biocomposite filaments for Fused Deposition Modeling (FDM) machines.

Keywords: Counter-rotating intermeshing, filament extruder machines, flow analysis, twin-screw designs, shear rates

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INTRODUCTION

The use of natural fibers in producing biocomposite filaments has gained increasing popularity due to their environmental friendliness and potential for economic benefit. The integration of additive manufacturing (AM) technology has revolutionized the production of biocomposite filaments for Fused Deposition Modelling (FDM), which provides opportunities for developing sustainable, biodegradable products. To produce FDM filament, twin-screw extruders have played a significant role in the formulation and production of biocomposite filaments by providing excellent shear mixing to ensure uniform dispersion of natural fibers (Khalid & Billa, 2022; Yang et al., 2018).

Biocomposite filaments are made up of natural fibers combined with a polymer matrix. Natural fibers such as kenaf, coconut, corn, and hemp are renewable and biodegradable, making them an ideal choice for producing sustainable consumer products (Calì et al., 2020; Deb & Jafferson, 2021; Rett et al., 2021; Xiao et al., 2019). The polymer matrix is usually composed of synthetic materials such as polypropylene (PP), which are biodegradable, and some others are readily recyclable.

Manufacturing biocomposite filaments presents challenges due to the distinct properties of natural fibers and the polymer matrix (Balla et al., 2019). Achieving homogeneity in the mixture is crucial but can be difficult. Twin-screw extruder technology has emerged as an effective solution for addressing these issues (Liu et al., 2021; Ren et al., 2023). The versatility of twin-screw extruders makes them suitable for various industrial applications, including producing biocomposite filaments (Bauer et al., 2022; Senturk-Ozer et al., 2011; Zheng et al., 2022). Incorporating different natural fibers and polymer types can be easily achieved, ensuring a wide range of material combinations.

Moreover, twin-screw extruders offer high efficiency, enabling high throughput rates and ensuring repeatability, which is vital for industrial-scale production (Hejna et al., 2021). Twin-screw extruders find applications beyond compounding plastics; they are also used in food production (e.g., breakfast cereals and chocolates), pharmaceutical manufacturing, and chemical production. Continuous advancements in twin-screw extruder technology further enhance their efficiency and versatility, addressing the challenges of extruding biocomposite-reinforced polymer filaments.

On the other hand, AM, commonly known as 3D printing, has revolutionized the production of biocomposite filaments. 3D printing allows for developing sustainable products with intricate designs, making it ideal for customized and personalized product development. FDM works by melting a thermoplastic filament and depositing it layer-by-layer to create a 3D object. Natural fibers biocomposite filaments can be utilized in FDM to create sustainable products, such as consumer product designs, biomedical devices, and biodegradable packaging. These materials can reduce carbon footprint, minimize waste, and improve the environmental impact of the manufacturing process. As the technology continues to develop, more applications of these materials are expected in AM, particularly in FDM.

The increasing demand for sustainable materials drives the need for more environmentally friendly alternatives. Growing market demand for biodegradable polymer and natural fiber composites presents a significant opportunity for twin-screw extruders to play a key role in meeting these needs. Henceforth, twin-screw extruder technology is significant for producing sustainable and eco-friendly materials to meet the demand for more environmentally friendly products.

The study presents an investigation comparing the performance of co-rotating and counter-rotating twin-screw extruders in terms of their capability to effectively mix biocomposite-reinforced polypropylene (PP) for producing FDM filament. The study involved a comprehensive analysis that included designing the twin screws using SolidWorks software and evaluating them through simulation analysis using computational fluid dynamics (CFD) software. The primary objective of the investigation is to determine which type of screw extruder demonstrates superior performance in terms of mixing efficiency and the quality of the resulting filament. By utilizing advanced design and simulation techniques, the study aims to provide valuable insights into the selection and optimization of screw extruders to produce high-quality biocomposite-reinforced PP filaments for FDM-based AM applications.

Literature Review

FDM 3D printers use thermoplastic filament to make 3D printed parts by adding layers from materials such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polypropylene (PP), and polycarbonate (PC). In recent years, researchers have increased the effort to develop alternative biocomposite filaments available for FDM by mixing the thermoplastic material with natural fibers (Han et al., 2019; Kariz et al., 2018; Mastura et al., 2020; Mazzanti et al., 2019). In Malaysia, sources of natural fibers such as kenaf, sugar palm, wood dust, and oil palm fruit bunch are cheap and abundant; therefore, they are ready to be exploited (Aida et al., 2021). The utilization of natural fiber-reinforced polymer composite as a filament in FDM is a subject that has not been widely explored. Nonetheless, incorporating them in FDM presents advantages such as accelerated prototyping processes when dealing with these materials.

The production process for natural fiber-reinforced polymer composite filaments is similar to that of conventional filaments, typically made from a single material such as PP or ABS. However, adding natural fiber to the composite filaments introduces another step of mixing the fibers with the thermoplastic polymer. Generally, the production process for filaments involves several steps. The natural fibers, which can come from kenaf, sugar palm, wood, or coconut, are cleaned and dried to remove impurities. They are then mixed with the thermoplastic polymer pellets.

During filament extrusion, materials in pellet form are fed from a hopper to the barrel. Rod heaters melt the materials, and a screw moves them longitudinally along the barrel through three zones, which are: feed, melt, and metering (Pitayachaval & Watcharamaisakul, 2019). Compression, shearing, and heating will liquefy the granules. The melted plastic moves through the metering zone into the die, which will be pumped out in a 1.75 mm or 3 mm diameter filament. The hot filament is cooled down by water or a cooling fan system and wound onto a spool. The resulting filament is a biocomposite material with the strength and durability of natural fibers combined with the thermoplastic polymer's flexibility and ease of use. Figure 1 shows the schematic diagram of the filament extruder setting.

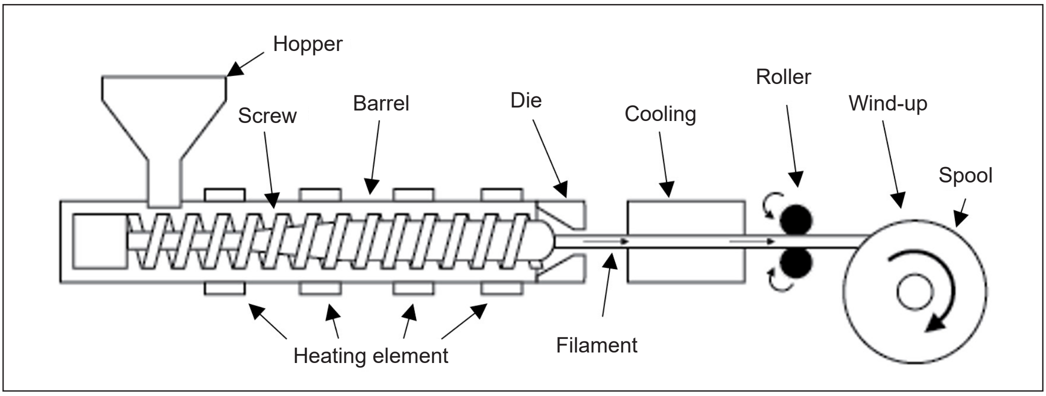


Figure 1. Schematic diagram of filament extruder setting

Natural fiber tends to be clumped, resulting in poor mechanical properties and inconsistencies. Another challenge in extruding natural fiber-reinforced polymer composites is achieving a uniform fiber orientation throughout the material. The orientation of the fibers can also greatly affect the mechanical properties of the filament, and achieving consistent orientation can be difficult due to the complex rheological behavior of the materials during extrusion. Several techniques have been developed to improve the dispersion of natural fibers in the polymer matrix, such as using a twin-screw extruder, which is able to provide better mixing capabilities to address this issue (Royan et al., 2021).

Generally, there are two types of filament extruder machines, which can be categorized based on the screw used in a barrel. They are single-screw and twin-screw extruders. Twin-screw extruders have two screws that rotate within a barrel. As the material moves through the barrel, it is heated and mixed using various heating and mixing elements. The pressure created by the rotation of the screw forces the material through the die, which shapes the material into desired form. The screws are designed to intermesh, creating a self-wiping action that mixes and shears the material as it moves through the barrel. The intermeshing action of the screws allows better mixing and processing of the material compared to a single-screw extruder (Netto et al., 2022). The twin-screw extruder has certain benefits over the single twin-screw extruder as it does not need to use drag force to move the material. This results in lower shear heat, more effective mixing, and reduced flexibility for slow-speed tasks (Pitayachaval & Watcharamaisakul, 2019). Therefore, the advantages of twin-screw extruders make them a popular choice in industries where precise control over the manufacturing process is essential.

The intermeshing system is a key feature of twin-screw extruders that enables them to process materials effectively. There are three types of intermeshing twin-screw extruders: (1) non-intermeshing twin-screw extruders, (2) partially intermeshing twin-screw extruders, and (3) fully-intermesh twin-screw extruders. Opposed to fully intermeshing twin-screw extruders, non- and partially intermeshing twin-screw extruders have a gap between the screws. In contrast to non-intermeshing twin-screw extruders, fully intermeshing twin-screw extruders typically have a more complex screw design with kneading and mixing elements that enhance the mixing and shearing of materials. Therefore, fully intermeshing twin-screw extruders are designed for high-shear and high-mixing applications, while non-intermeshing twin-screw extruders are typically used for low-shear applications.

In this system, the screws rotate in either co-rotating or counter-rotating directions in the barrel. According to Rauwendaal's classic literature (1981), intermeshing counter-rotating extruders are screw characters that are good at moving material through the barrel quickly and evenly, which is important when working with heat-sensitive materials like PVC. They are operated at low speeds, typically between 10 to 30 rpm. By using these screw designs, heat exposure can be minimized, and the risk of damage to the material can be reduced. Therefore, a fully intermeshing, counter-rotating twin-screw extruder can achieve the highest positive conveying. Figure 2 shows the cylindrical, fully-intermeshing, counter-rotating twin-screw extruder. In contrast, Figure 3 shows the cylindrical, fully-intermeshing, co-rotating twin-screw extruder, and Figure 4 shows the extrusion screw geometry parameter guideline (Pitayachaval & Watcharamaisakul, 2019).

Understanding critical factors is essential for guaranteeing filament quality. Three pivotal parameters stand out: screw design, temperature control, and material feed rate (Chen et al., 2017; Kittikunakorn et al., 2020; Yacu, 2020). Screw design influences mixing, shearing, and conveying through the barrel, encompassing parameters such as diameter, pitch, length-to-diameter ratio (L/D ratio), flight depth, and helix angle. Larger

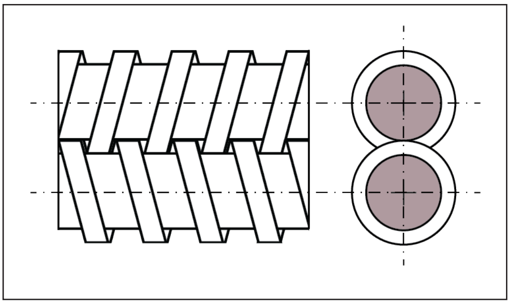


Figure 2. Cylindrical, fully intermeshing, counter-rotating twin-screw extruder

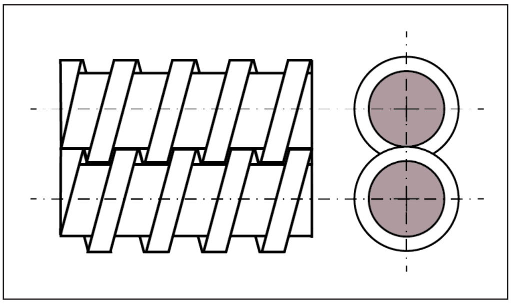


Figure 3. Cylindrical, fully-intermeshing, co-rotating twin-screw extruder

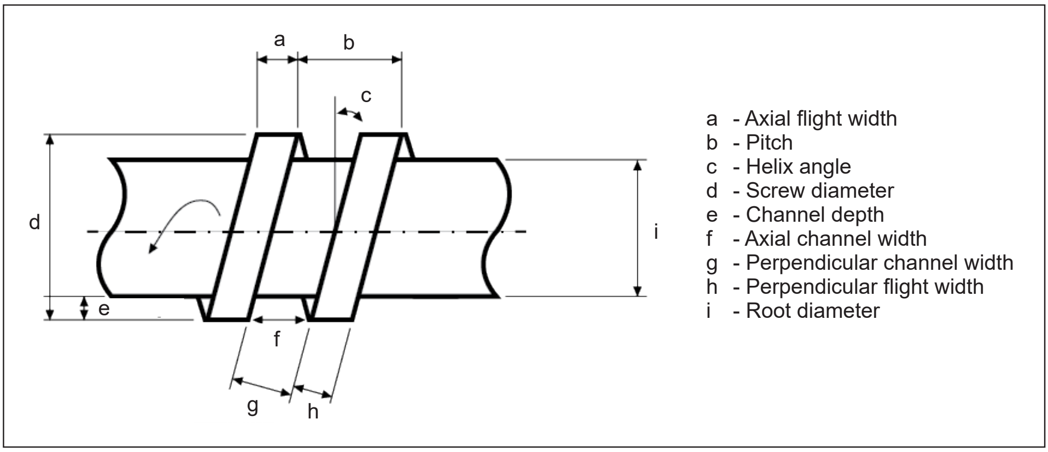


Figure 4. Extrusion screw geometry parameter guideline

screw diameters provide a greater surface area for heat transfer and mixing, which can be advantageous for materials that require extensive melting and mixing. The pitch of the screw, the distance between two flights along the axis, affects the residence time of the material in the barrel. A larger pitch produces faster material conveyance and a shorter residence time, which can be useful for heat-sensitive materials. The L/D ratio determines the residence time and the degree of mixing the material undergoes. Typically, a higher L/D ratio allows for more prolonged interaction between the material and the screws, leading to better mixing and homogenization (Irfan et al., 2021; Wang et al., 2023). Twin-screw extruders often have L/D ratios ranging from 20:1 to 40:1(Dhaval et al., 2022; Jacobs et al., 2022).

According to Nandi et al. (2021), the flight depth, which is the distance from the screw core to the top of the flight, can be varied. Shallow flights create high shear and intensive mixing, while deeper flights result in gentle conveying with less shear. The appropriate flight depth depends on the material properties and the desired characteristics of the end product. On the other hand, the helix angle, the angle between the screw flight and the axis of the screw, affects the forward conveying efficiency. A larger helix angle leads to better conveying efficiency, which is crucial for materials with poor flow properties.

Temperature control affects material viscosity, flow behavior, and final product properties, while precise control in heating and cooling zones is vital (Pitayachaval & Watcharamaisakul, 2019). The extruder barrel is divided into different heating and cooling zones; precise temperature control in each zone is essential. Material feed rate directly impacts output rate, residence time, and process stability (Rao et al., 2022; Zhuang et al., 2023). A consistent and uniform feed rate ensures steady conditions in the barrel. Fluctuations in feed rate can lead to variations in product dimensions, mechanical properties, and surface finish. The feed rate also influences the barrel's shear forces and mixing efficiency. A higher feed rate resulted in increased shear forces that benefit materials that require intense mixing. However, this can also cause overheating and material degradation if not properly managed (Thyashan et al., 2024; Wang et al., 2022). It is important to balance the material feed rate with the screw speed to ensure optimal processing conditions. A mismatch can lead to poor mixing, surging, or even blockages in the barrel.

Common extruder issues include screw wear, damage, and fouling, each affecting performance and output (Corleto et al., 2021; Demirci et al., 2021; Liu et al., 2021). Screw wear occurs over time due to the abrasion of the material being processed caused by exposure to certain chemicals or moisture, resulting in reduced performance and output. Screw damage can occur if foreign objects, such as hard plastics, enter the extruder. The damage can cause misalignment, leading to reduced performance, inconsistent output, or even failure of the extruder. Screw fouling, on the other hand, results from the accumulation of material on the screws and other surface within the extruder. It leads to reduced efficiency and output as well as increased wear and tear on the machine.

Co-rotating extruders excel in efficiency and material handling but require higher maintenance due to increased wear. In contrast, counter-rotating extruders offer lower initial investment and maintenance costs but with limited throughput and mixing capabilities. Table 1 provides a comparative table of co-rotating and counter-rotating fully intermeshing twin-screw extruders, focusing on various operational and performance aspects.

Recent studies have focused on twin-screw extruders to understand the material flow, mixing, and melting dynamics for both common polymers and polymer-based biocomposites (Dong et al., 2020; Irfan et al., 2021; Mysiukiewicz et al., 2020; Schall et al., 2023; Vergnes et al., 2022). Investigations delve into various performance aspects, including melting efficiency, pressure and temperature profiles, viscosity considerations, and the influence of processing conditions and screw design. Researchers explore how parameters like screw speed, feed rate, profile, pellet size, and extruder size affect melting efficiency and effectiveness (Lewandowski & Wilczyński, 2022; Stritzinger et al., 2021).

Table 1
Comparative table of co-rotating and counter-rotating fully intermeshing twin-screw extruders

Aspect	Co-rotating twin-screw extruder	Counter-rotating twin-screw extruder
Efficiency	High (excellent for complex and high output).	Moderate (better for low-shear, simple mixing)
Material Handling	Versatile (handles diverse and difficult materials).	Limited (best for less complex materials).
Maintenance	Higher cost (due to high-shear wear).	Lower cost (due to simpler design and lower wear).
Ease of operation	Complex (requires specialized knowledge).	Simpler (easier to operate and maintain).
Initial investment	Higher (reflected by advanced capabilities).	Lower (more cost-effective).
Throughput	High (suitable for high-volume production).	Lower (less suitable for high-volume production).
Mixing ability	Excellent (high shear and intensive kneading).	Less effective (due to lower shear force).
Degassing	Adequate.	Efficient.
Suitability	High-end applications (e.g., specialty plastic).	Straightforward tasks (e.g., PVC compounding).

Additionally, different screw configurations are examined to understand their role in shaping melting behavior and overall extruder performance. Computational Fluid Dynamics (CFD) analysis provides a comprehensive approach to evaluating extruder performance, allowing visualization of flow patterns, pressure gradients, and heat transfer characteristics (Prashanth et al., 2019). Through CFD simulations, researchers can identify areas for optimization and explore various design configurations and operational parameters to enhance filament fabrication technology.

MATERIALS AND METHODS

This study investigated two types of twin-screw filament extruders: counter-rotating intermeshing and co-rotating intermeshing. The dimensions of the twin-screw designs, including barrel diameter, screw tip diameter, screw root diameter, centerline distance, and screw pitch, are presented in Table 2. The schematic of the screw design is shown in Figure 5.

In the counter-rotating intermeshing design, one screw has a left-sided thread while the other screw has right-handed threads, enabling them to rotate in opposing

Table 2
Dimensions of twin-screw filament extruder

Item	Dimension
Barrel diameter (mm)	25
Screw tip diameter (mm)	25
Screw root diameter (mm)	15
Centerline distance (mm)	20
Screw pitch (mm)	6
Nozzle diameter (mm)	2

directions. Contrariwise, the co-rotating twin-screw design features identical right-handed threads, causing them to rotate in the same direction and speed. However, both designs have the same configuration in terms of the thread position, with the threads overlapping each other. The cross-sectional views of both twin-screw designs are depicted in Figure 6. Figures 7 and 8 show the twin-screw counter-rotating and co-rotating intermeshing orientation.

SolidWorks CFD software was utilized to analyze the material's behavior as it flowed inside the barrel. PP was chosen as the polymer for the analysis, representing a copolymerized type that exhibits favorable characteristics for extrusion applications. Furthermore, PP serves as the polymer matrix in the natural fiber filament used in this study. The specific PP grade employed in the study possesses a melt flow rate of 1.8 g/10 min at 230°C and 2.16 kg, conforming to the ISO 1133 standard (Vincent et al., 2020).

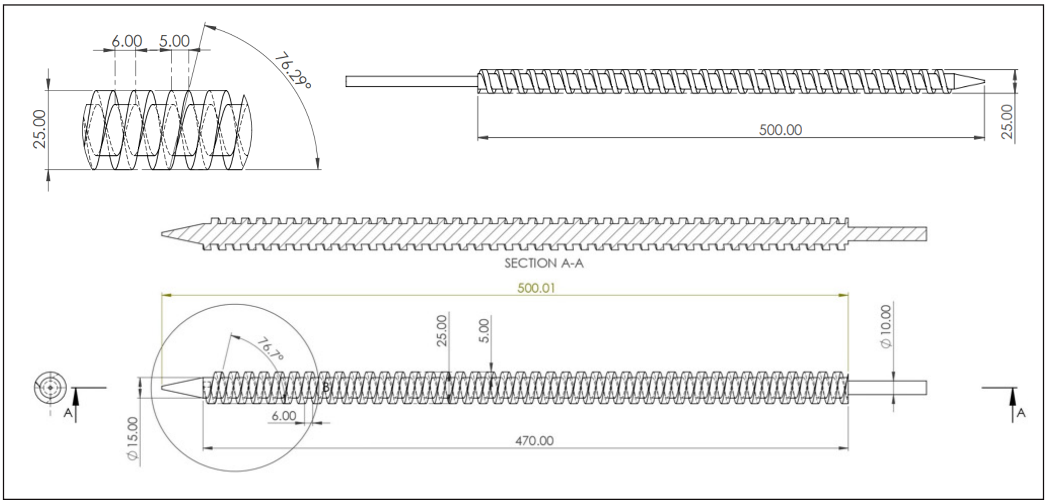
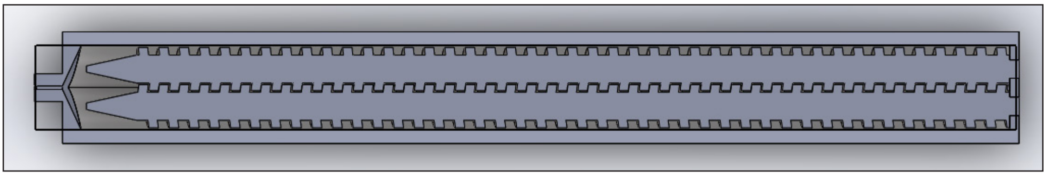
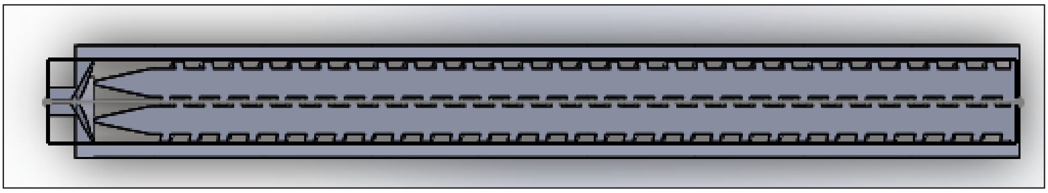


Figure 5. Dimension of the screw design



(a)



(b)

Figure 6. Cross-sectional view of (a) counter-rotating and (b) co-rotating, intermeshing twin-screws

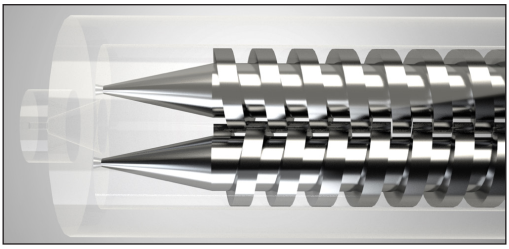


Figure 7. Twin-screw counter-rotating intermeshing orientation

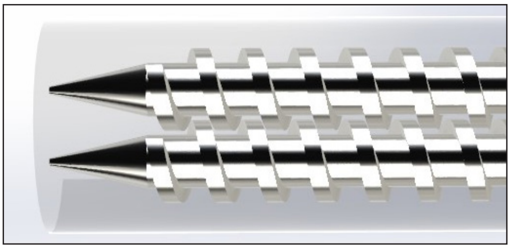


Figure 8. Twin-screw co-rotating intermeshing orientation

The extrusion screw's length-to-diameter (L/D) ratio needs to be considered to run the CFD analysis. The L/D ratio is a parameter used to describe the geometry of screws, especially in plastic-based extrusion screw machines. It represents the ratio of the flighted length of the screw to its outside diameter (Bauer et al., 2022). The L/D ratio was specified to be 20:1, which is the most standard ratio used in the industry. Both the counter-rotating and co-rotating extruder designs shared common specific parameters, including a screw diameter of 25 mm and a screw length of 500 mm. In conjunction with the L/D ratio calculation of 500/25=20:1, these values were chosen to ensure accurate analysis of the material behavior within the barrel using SolidWorks CFD software. Additionally, a temperature setting of 190°C and a revolution-per-minute (rpm) speed of 26 rpm were applied to both the counter-rotating and co-rotating extruders. During the analysis, these operating conditions were maintained consistently for both extruder designs, facilitating a direct comparison of their performance.

RESULTS AND DISCUSSION

Velocity Flow Analysis on Counter-rotating Twin-screw Extruder

Figure 9 depicts the cross-sectional cut plot pressure flow inside the counter-rotating twin-screw chamber. In pressure analysis, the color scale visually represents pressure distribution and magnitude within a system, ranging from cooler colors for lower pressures to warmer colors for higher pressures. Researchers use this scale to identify pressure variations and pinpoint potential issues. The visualization facilitates quick interpretation of pressure data and enables comparative analysis under different conditions.

Observation from the simulation has shown that the pressure build-upbuild-up was consistent as the molten polymer spread across every corner of the screw threads. The counter-rotating design, along with the different shapes of screw threads, caused the pressure build-up at the intermesh section to overlap. Consequently, this increased drag on the material, especially when mixing composite materials.

Figure 10 shows the velocity analysis of the counter-rotating twin-screw extruder. Based on the analysis of velocity flow, the PP exhibited a flow through the barrel chamber

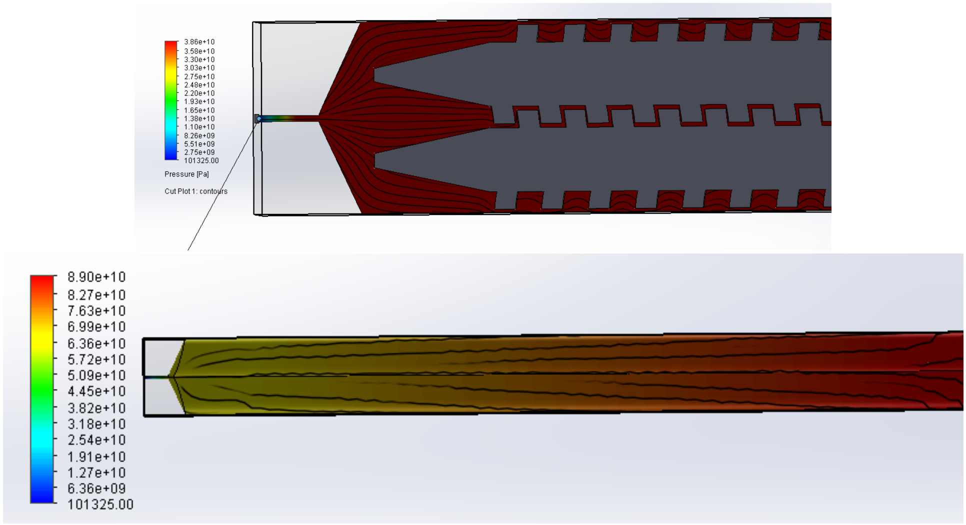


Figure 9. Cross-sectional cut plot pressure flow of counter-rotating twin-screw

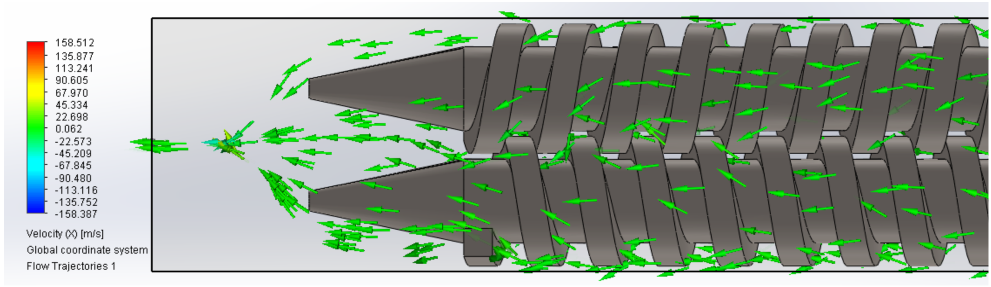


Figure 10. Velocity flow trajectory

at a temperature of 190°C. The counter-rotating twin screw compressed the material towards the nozzle exit, resulting in the resistance caused by the screw threads. This resistance led to a more complex flow pattern with multiple directions. The collision of the flow at the intermeshing section significantly increased the shear rate of the PP. Consequently, this enhanced the mixing of the material, allowing for better binding.

Figure 11 illustrates the relationship between velocity (m/s) and screw length (m), showcasing notable initial flow instability within the melting and mixing zones. The findings indicated that the molten PP attained stability at 0.0237 m or 23.78 mm from the melting initiation point, exhibiting a velocity of 0.0542 m/s or 54.2 mm/s. However, as the material progressed towards the nozzle exit, the flow was stabilized further.

Figure 12 presents the pressure variation with respect to the screw length. The findings demonstrated initial flow instability during the melting initiation and mixing zones.

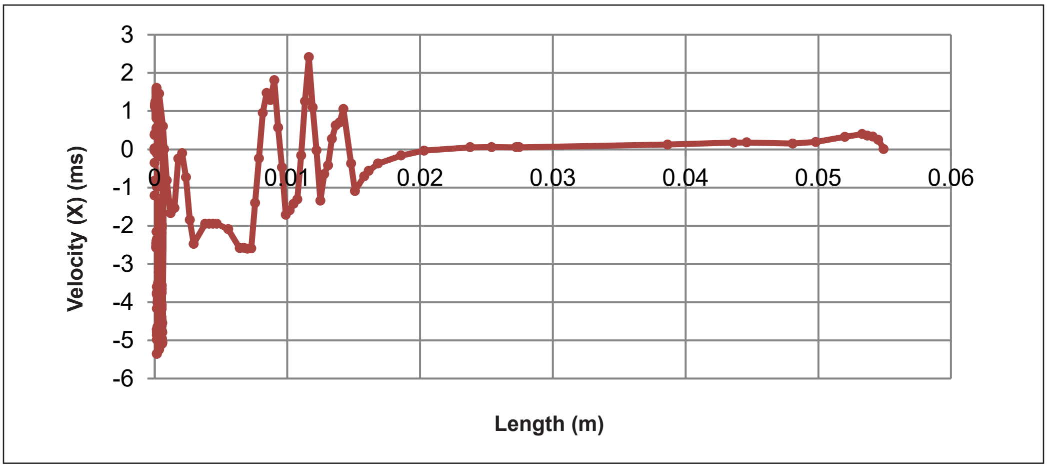


Figure 11. Velocity vs. screw length

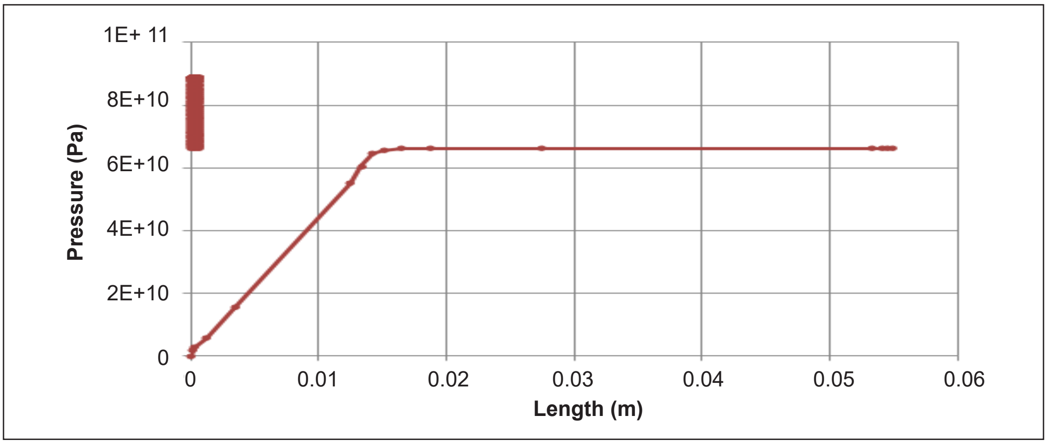


Figure 12. Pressure vs. screw length

However, as the flow advanced toward the nozzle exit, it exhibited enhanced stability. Examination of the accompanying chart revealed that the pressure within the extrusion melting zone initiated at 0.0164 m or 16.40 mm from the melting inlet, with a pressure reading of 6.6×10^{10} Pa.

Velocity Flow Analysis on Co-rotating Twin-screw Extruder

Figure 13 presents the cross-sectional view of the co-rotating twin screw, providing insight into the pressure build-up within the compression chamber. The color variations observed in the figures indicated increased pressure as the material approached the exit or nozzle. The nozzle itself was designed with 2.00 mm diameter holes. Notably, despite setting the initial pressure at 90 Pa from the starting point of the melting zone, there was a continuous increase in pressure.

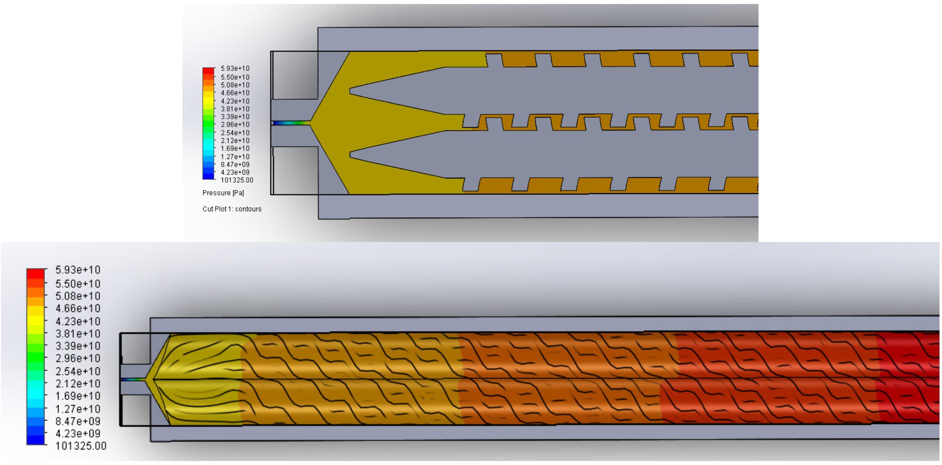


Figure 13. Cross-sectional cut plot pressure flow of co-rotating twin-screw

A further test was performed to determine the trajectory or flow of the molten PP when it was compressed by using the co-rotating and intermeshing twin-screw type. The results in Figure 14 showed that the flow was much more towards one direction, which means the flow was somehow much identical to the single screw extruder, as it did not flow against each other. Thus, the mixing capability did not reach the maximum potential in this case.

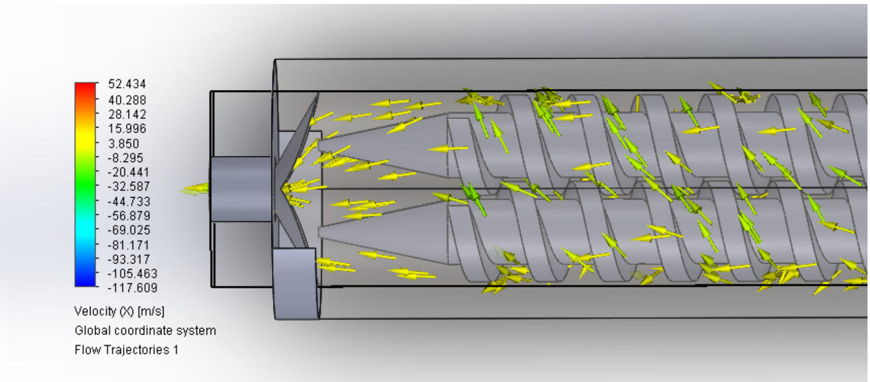


Figure 14. Flow trajectory of co-rotating twin-screw

Figure 15 depicts the relationship between velocity (m/s) and screw length (m), revealing the presence of initial flow instability within the melting and mixing zones. However, as the material progressed toward the nozzle, the flow stabilized. The results indicated that the material attained stability at 0.0297 m or 29.74 mm from the melting point, with a velocity of 0.0597 m/s or 59.72 mm/s.

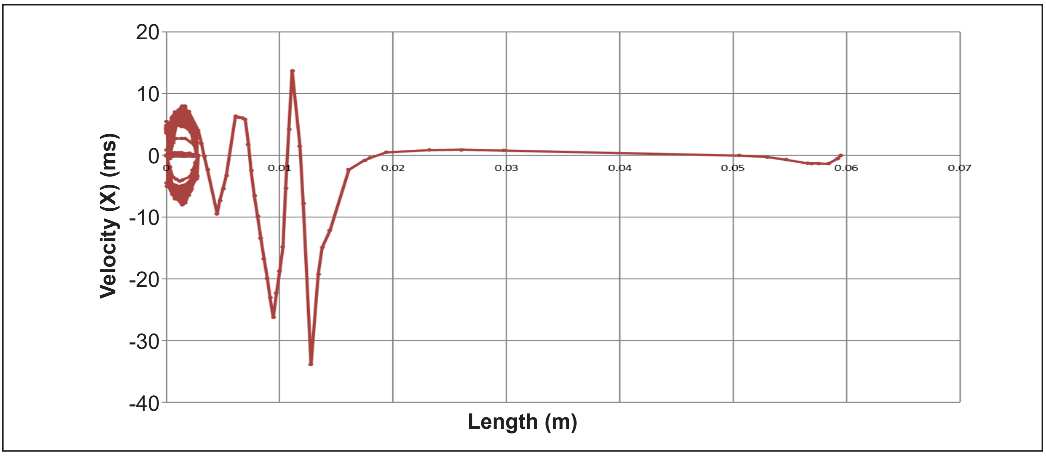


Figure 15. Co-rotating intermeshing screw fluid velocity vs screw length

Figure 16 illustrates the pressure variation along the screw length in the co-rotating intermeshing twin-screw design. The findings demonstrated enhanced flow stability as the material advanced toward the nozzle. The pressure inside the extrusion melting zone initiated at 0.0148 m or 14.80 mm from the melting inlet, with a recorded pressure value of 4.7 × 10^{10} Pa.

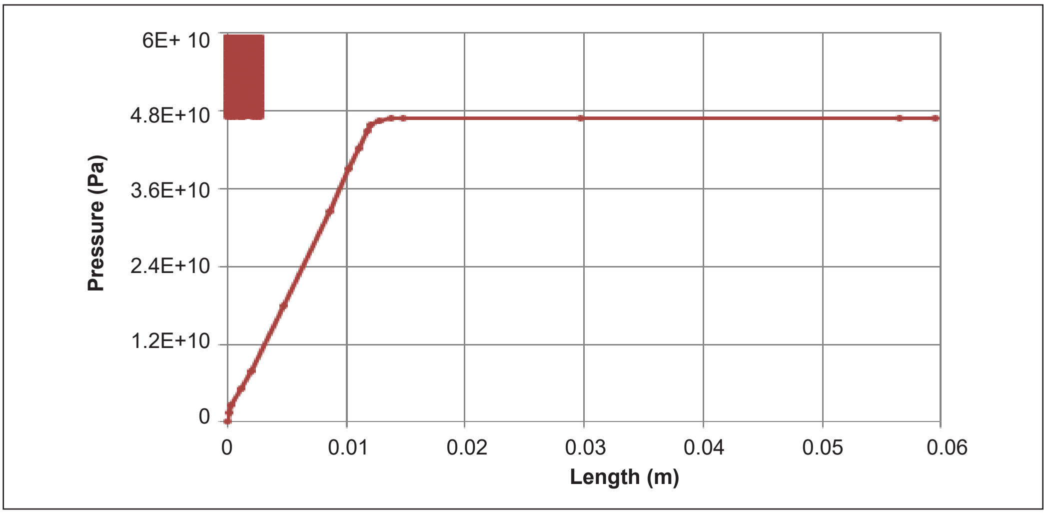


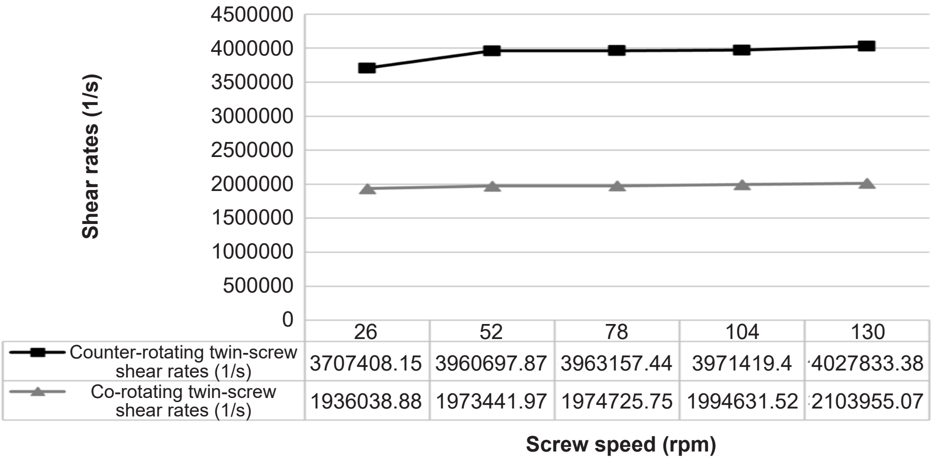
Figure 16. Co-rotating intermeshing screw pressure vs screw length

Based on the results above, comparing the counter-rotating and co-rotating intermeshing twin-screw designs revealed distinctive characteristics. The counter-rotating intermeshing configuration exhibited elevated shear stress and pressure build-up in the intermesh section. It can be attributed to the polymer's opposite-direction flow, which facilitated improved material compression and dispersion, resulting in superior mixing capabilities. Conversely, the co-rotating intermeshing screw design demonstrated controlled shear stress and high-pressure build-up in the screw tip section. Compared to the counter-rotating design, the PP's flow in the same direction within this configuration limited the extent of mixing. These findings underscored the advantages of the counter-rotating intermeshing design in terms of shear stress, pressure build-up, flow direction, and mixing performance, establishing it as a desirable choice for applications requiring effective material processing and blending.

Shear Rates Analysis on Counter-rotating and Co-rotating Twin-screw Extruders

The shear rate vs. screw speed relationship was examined to assess the stability and identify the extruder with the highest mixing capability. The design that exhibited the maximum shear rate value indicated superior mixing performance. Throughout the tests, a fixed pressure of 90 Pa and a temperature of 190°C were maintained, while the screw speeds were varied between the range of 26 to 130 rpm. Figure 17 presents a comparative analysis of shear rates between the counter-rotating and co-rotating twin-screw designs at various screw speeds.

Based on Figure 16, the results demonstrated that the counter-rotating screw consistently exhibited higher shear rates compared to the co-rotating screw at each tested speed. At a screw speed of 26 rpm, the counter-rotating screw achieved a shear rate of 3 707, 408.15 1/s, while the co-rotating screw demonstrated a significantly lower shear rate of 1 936, 038.88 1/s. This initial comparison highlighted the substantial disparity in shear rates between the two designs, favoring the counter-rotating screw. As the screw speed increased to 52 rpm, the counter-rotating screw continued to outperform the co-rotating screw in terms of shear rate. The counter-rotating screw attained a shear rate of 3 960, 697.87 1/s, whereas the co-rotating screw recorded a shear rate of 1 973, 441.97 1/s.



	26	52	78	104	130
Counter-rotating twin-screw shear rates (1/s)	3707408.15	3960697.87	3963157.44	3971419.4	4027833.38
Co-rotating twin-screw shear rates (1/s)	1936038.88	1973441.97	1974725.75	1994631.52	2103955.07

Figure 17. Comparative results of shear rates

Similar trends were observed at higher screw speeds. At 78 rpm, the counter-rotating screw achieved a shear rate of 3 963, 157.44 1/s, while the co-rotating screw lagged at 1 974, 725.75 1/s. At 104 rpm, the counter-rotating screw yielded a shear rate of 3 971, 419.4 1/s, while the co-rotating screw attained a shear rate of 1 994, 631.52 1/s. Lastly, at a screw speed of 130 rpm, the counter-rotating screw displayed a significantly higher shear rate of 4, 027, 833.38 1/s compared to the co-rotating screw's shear rate of 2, 013, 955.07 1/s.

The comparison of shear rates between the counter-rotating and co-rotating twin-screw designs has consistently demonstrated the superior performance of the counter-rotating screw in generating higher shear rates across all tested screw speeds. This clear disparity in shear rates emphasized the advantageous characteristics of the counter-rotating design, enabling enhanced material processing, dispersion, and mixing capabilities.

CONCLUSION

This study has investigated and compared the performance of counter-rotating intermeshing and co-rotating intermeshing twin-screw extruders in terms of velocity flow and shear rates for filament extruder machines. The analysis utilized SolidWorks CFD software to examine the behavior of polypropylene material inside the barrel, focusing on velocity and shear rates.

Based on the discussions and data presented above, the study concluded that the counter-rotating intermeshing twin-screw design outperformed the co-rotating intermeshing design in terms of shear rates and mixing capabilities for filament extruder machines. The shear rate data indicated that the counter-rotating screw consistently generated significantly higher shear rates compared to the co-rotating screw at various tested screw speeds. For instance, at a screw speed of 26 rpm, the counter-rotating screw exhibited a shear rate of 3 707, 408.15 1/s, while the co-rotating screw achieved a shear rate of 1 936, 038.88 1/s. This trend continued at higher screw speeds as well, further highlighting the superior performance of the counter-rotating screw. Nevertheless, the velocity flow analysis showed that as the material approached the nozzle exit, the flow became more stable for both twin-screw extruder configurations.

The results suggested that the counter-rotating intermeshing twin-screw design is more effective in material processing, compression, and dispersion, improving mixing capabilities. The opposite flow direction of the polymer in the counter-rotating design enables better material compression and dispersion, contributing to the enhanced shear rates observed. The incorporation of dual screw configurations and the screw designs of the counter-rotating and co-rotating intermeshing twin-screw extruders for biocomposite filament extrusion represents a significant advancement in this study. These elements contribute to enhanced mixing efficiency, a better understanding of material behavior, improved extruder performance, and the utilization of innovative technologies for producing high-quality polypropylene-based biocomposite filaments.

Further studies can explore and refine the counter-rotating intermeshing design to optimize its performance and expand its application in producing biocomposite filaments. Investigations could focus on studying the influence of other operational parameters, such as temperature and pressure settings, on the performance of the twin-screw designs. The impact of different polymer materials and fillers on the shear rates and mixing capabilities could be explored to broaden the understanding of the counter-rotating intermeshing twin-screw design in various material extrusion processes. These findings contribute to optimizing twin-screw designs in AM and suggest avenues for further research and development in enhancing the counter-rotating intermeshing design to produce biocomposite filaments.

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REFERENCES

Aida, H. J., Nadlene, R., Mastura, M. T., Yusriah, L., Sivakumar, D., & Ilyas, R. A. (2021). Natural fibre filament for Fused Deposition Modelling (FDM): A review. *International Journal of Sustainable Engineering*, *14*(6), 1988–2008. https://doi.org/10.1080/19397038.2021.1962426

Balla, V. K., Kate, K. H., Satyavolu, J., Singh, P., & Tadimeti, J. G. D. (2019). Additive manufacturing of natural fiber reinforced polymer composites: Processing and prospects. *Composites Part B: Engineering*, *174*, Article 106956. https://doi.org/10.1016/j.compositesb.2019.106956

Bauer, H., Matić, J., Evans, R. C., Gryczke, A., Ketterhagen, W., Sinha, K., & Khinast, J. (2022). Determining local residence time distributions in twin-screw extruder elements via smoothed particle hydrodynamics. *Chemical Engineering Science*, *247*, Article 117029. https://doi.org/10.1016/j.ces.2021.117029

Calì, M., Pascoletti, G., Gaeta, M., Milazzo, G., & Ambu, R. (2020). A new generation of bio-composite thermoplastic filaments for a more sustainable design of parts manufactured by FDM. *Applied Sciences (Switzerland)*, *10*(17), Article 5852. https://doi.org/10.3390/app10175852

Chen, B., Zhu, L., Zhang, F., & Qiu, Y. (2017). Process development and scale-up: Twin-screw extrusion. In Y. Qiu, Y. Chen, G. Z. Zhang, L. Yu & R. V. Mantri (Eds.), *Developing Solid Oral Dosage Forms: Pharmaceutical Theory and Practice.* (2nd ed.: pp. 821-868). Academic Press. https://doi.org/10.1016/B978-0-12-802447-8.00031-5

Corleto, C. R., Briscoe, M., & Knight, C. T. (2021). Failure analysis of twin screw extruder shaft. *Journal of Failure Analysis and Prevention*, *21*(5), 1622–1629. https://doi.org/10.1007/s11668-021-01208-5

Deb, D., & Jafferson, J. M. (2021). Natural fibers reinforced FDM 3D printing filaments. *Materials Today: Proceedings*, *46*, 1308–1318. https://doi.org/10.1016/j.matpr.2021.02.397

Demirci, A., Teke, I., Polychronopoulos, N. D., & Vlachopoulos, J. (2021). The role of calender gap in barrel and screw wear in counterrotating twin screw extruders. *Polymers*, *13*(7), Article 990. https://doi.org/10.3390/polym13070990

Dhaval, M., Sharma, S., Dudhat, K., & Chavda, J. (2022). Twin-screw extruder in pharmaceutical industry: History, working principle, applications, and marketed products: An in-depth review. *Journal of Pharmaceutical Innovation*, *17*(2), 294–318. https://doi.org/10.1007/s12247-020-09520-7

Dong, T., Jiang, S., Wu, J., Liu, H., & He, Y. (2020). Simulation of flow and mixing for highly viscous fluid in a twin screw extruder with a conveying element using parallelized smoothed particle hydrodynamics. *Chemical Engineering Science*, *212*, Article 115311. https://doi.org/10.1016/j.ces.2019.115311

Han, S. N. M. F., Mastura, M. T., & Mansor, M. R. (2019). Thermal and melt flow behaviour of kenaf fibre reinforced acrylonitrile butadiene styrene composites for fused filament fabrication. *Defence S&T Technical Bulletin*, *12*(2), 238–246.

Hejna, A., Barczewski, M., Skórczewska, K., Szulc, J., Chmielnicki, B., Korol, J., & Formela, K. (2021). Sustainable upcycling of brewers' spent grain by thermo-mechanical treatment in twin-screw extruder. *Journal of Cleaner Production*, *285*, Article 124839. https://doi.org/10.1016/j.jclepro.2020.124839

Irfan, M. S., Umer, R., & Rao, S. (2021). Optimization of compounding parameters for extrusion to enhance mechanical performance of kenaf-polypropylene composites. *Fibers and Polymers*, *22*(5), 1378–1387. https://doi.org/10.1007/s12221-021-0676-8

Jacobs, E., Qian, K., Pietsch, V. L., Richter, M., Jones, D. S., Andrews, G. P., & Tian, Y. (2022). Design and scale-up of amorphous drug nanoparticles production via a one-step anhydrous continuous process. *International Journal of Pharmaceutics*, *628*, Article 122304. https://doi.org/10.1016/j.ijpharm.2022.122304

Kariz, M., Sernek, M., & Kuzman, M. K. (2018). Effect of wood content in FDM filament on properties of 3D printed parts. *Materials Today Communication*, *14*, 135–140. https://doi.org/10.1016/j.mtcomm.2017.12.016

Khalid, G. M., & Billa, N. (2022). Solid dispersion formulations by FDM 3D printing—A review. *Pharmaceutics*, *14*(4), Article 690. https://doi.org/10.3390/pharmaceutics14040690

Kittikunakorn, N., Liu, T., & Zhang, F. (2020). Twin-screw melt granulation: Current progress and challenges. *International Journal of Pharmaceutics*, *588*, Article 119670. https://doi.org/10.1016/j.ijpharm.2020.119670

Lewandowski, A., & Wilczyński, K. (2022). Modeling of twin screw extrusion of polymeric materials. *Polymers*, *14*(2), Article 274. https://doi.org/10.3390/polym14020274

Liu, T., Kittikunakorn, N., Zhang, Y., & Zhang, F. (2021). Mechanisms of twin screw melt granulation. *Journal of Drug Delivery Science and Technology*, *61*, Article 102150. https://doi.org/10.1016/j.jddst.2020.102150

Mastura, M. T., Jumaidin, R., M. Razali, N., & Kudus, S. I. A. (2020). Green material for fused filament fabrication: A review. In M. T. Mastura & S. M. Sapuan (Eds.), *Implementation and Evaluation of Green Materials in Technology Development: Emerging Research and Opportunities* (pp. 1–27). IGI Global. https://doi.org/10.4018/978-1-7998-1374-3.ch001

Mazzanti, V., Malagutti, L., & Mollica, F. (2019). FDM 3D printing of polymers containing natural fillers: A review of their mechanical properties. *Polymers, 11*(7), Article 1094. https://doi.org/10.3390/polym11071094

Mysiukiewicz, O., Barczewski, M., Skórczewska, K., & Matykiewicz, D. (2020). Correlation between processing parameters and degradation of different polylactide grades during twin-screw extrusion. *Polymers*, *12*(6), Article 1333. https://doi.org/10.3390/POLYM12061333

Nandi, U., Trivedi, V., Ross, S. A., & Douroumis, D. (2021). Advances in twin-screw granulation processing. *Pharmaceutics*, *13*(5), Article 624. https://doi.org/10.3390/pharmaceutics13050624

Netto, J. M. J., Sarout, A. I., Santos, A. L. G., Lucas, A. de A., Chinelatto, M. A., Alves, J. L., Gaspar-Cunha, A., Covas, J. A., & Silveira, Z. de C. (2022). Design and validation of an innovative 3D printer containing a co-rotating twin screw extrusion unit. *Additive Manufacturing*, *59*, Article 103192. https://doi.org/10.1016/j.addma.2022.103192

Pitayachaval, P., & Watcharamaisakul, P. (2019). A review of a machine design of chocolate extrusion based co-rotating twin screw extruder. *IOP Conference Series: Materials Science and Engineering*, *703*(1), Article 012012. https://doi.org/10.1088/1757-899X/703/1/012012

Prashanth, S. R., Arumugam, S. K., Gangradey, R., Mukherjee, S., Kasthurirengan, S., Behera, U., Pabbineedi, G., & Mugilan, M. (2019). CFD modelling and performance analysis of a twin screw hydrogen extruder. *Fusion Engineering and Design*, *138*, 151–158. https://doi.org/10.1016/j.fusengdes.2018.11.014

Royan, N. R. R., Leong, J. S., Chan, W. N., Tan, J. R., & Shamsuddin, Z. S. B. (2021). Current state and challenges of natural fibre-reinforced polymer composites as feeder in FDM-based 3D printing. *Polymers*, *13*(14), Article 2289. https://doi.org/10.3390/polym13142289

Rao, R. R., Pandey, A., Hegde, A. R., Kulkarni, V. I., Chincholi, C., Rao, V., Bhushan, I., & Mutalik, S. (2022). Metamorphosis of twin screw extruder-based granulation technology: Applications focusing on its impact on conventional granulation technology. *AAPS PharmSciTech*, *23*(1), 1–23. https://doi.org/10.1208/s12249-021-02173-w

Rauwendaal, C. J. (1981). Analysis and experimental evaluation of twin screw extruders. *Polymer Engineering and Science*, *21*(16), 1092–1100. https://doi.org/10.1002/pen.760211608

Ren, A., Koleng, J. J., Costello, M., Spahn, J. E., Smyth, H. D. C., & Zhang, F. (2023). Twin-screw continuous mixing can produce dry powder inhalation mixtures for pulmonary delivery. *Journal of Pharmaceutical Sciences*, *112*(1), 272–281. https://doi.org/10.1016/j.xphs.2022.10.007

Rett, J. P., Traore, Y. L., & Ho, E. A. (2021). Sustainable materials for fused deposition modeling 3D printing applications. *Advanced Engineering Materials*, *23*(7), Article 2001472. https://doi.org/10.1002/adem.202001472

Schall, C., Altepeter, M., Schöppner, V., Wanke, S., & Kley, M. (2023). Material-preserving extrusion of polyamide on a twin-screw extruder. *Polymers*, *15*(4), Article 1033. https://doi.org/10.3390/polym15041033

Senturk-Ozer, S., Gevgilili, H., & Kalyon, D. M. (2011). Biomass pretreatment strategies via control of rheological behavior of biomass suspensions and reactive twin screw extrusion processing. *Bioresource Technology*, *102*(19), 9068–9075. https://doi.org/10.1016/j.biortech.2011.07.018

Stritzinger, U., Roland, W., Albrecht, H., & Steinbichler, G. (2021, May 10-21). *Modeling fully intermeshing co-rotating twin-screw extruder kneading-blocks: Part A. conveying characteristics*. [Paper presentation]. Annual Technical Conference - ANTEC, Conference Proceedings, Online.

Thyashan, N., Perera, Y. S., Xiao, R., & Abeykoon, C. (2024). Investigation of the effect of materials and processing conditions in twin-screw extrusion. *International Journal of Lightweight Materials and Manufacture* , *7*(3), 353-361. https://doi.org/10.1016/j.ijlmm.2023.09.003

Vergnes, B., Souveton, G., Delacour, M. L., & Ainser, A. (2022). Experimental and theoretical study of polymer melting in a co-rotating twin screw extruder. *International Polymer Processing*, *16*(4), 351–362. https://doi.org/10.1515/ipp-2001-0006

Vincent, R., Langlotz, M., & Düngen, M. (2020). Viscosity measurement of polypropylene loaded with blowing agents (propane and carbon dioxide) by a novel inline method. *Journal of Cellular Plastics*, *56*(1), 73–88. https://doi.org/10.1177/0021955X19864400

Wang, J., Hu, X., Liu, F., Long, Z., & Shao, M. (2022). Gel-spinning of ultra-high molecular weight polyethylene by a twin-screw extruder with an ultra-large length-to-diameter ratio. *Polymer Engineering and Science*, *62*(11), 3773–3785. https://doi.org/10.1002/pen.26143

Wang, J., Zheng, K., Hu, X., Long, Z., & Chen, K. (2023). Application of a twin-screw extruder with an ultra-high length-to-diameter ratio in the dry-jet wet spinning process of polyacrylonitrile nascent fibers. *Industrial & Engineering Chemistry Research*, *62*(21), 8477–8488. https://doi.org/10.1021/acs.iecr.3c00509

Xiao, X., Chevali, V. S., Song, P., He, D., & Wang, H. (2019). Polylactide/hemp hurd biocomposites as sustainable 3D printing feedstock. *Composites Science and Technology*, *184*, Article 107887. https://doi.org/10.1016/j.compscitech.2019.107887

Yacu, W. (2020). Extruder screw, barrel, and die assembly: General design principles and operation. In G. M. Ganjyal (Ed.), *Extrusion Cooking: Cereal Grains Processing* (pp. 73-117). Woodhead Publishing. https://doi.org/10.1016/b978-0-12-815360-4.00003-1

Yang, X., Wang, G., Miao, M., Yue, J., Hao, J., & Wang, W. (2018). The dispersion of Pulp-Fiber in high-density polyethylene via different fabrication processes. *Polymers*, *10*(2), Article 122. https://doi.org/10.3390/polym10020122

Zheng, C., Govender, N., Zhang, L., & Wu, C. Y. (2022). GPU-enhanced DEM analysis of flow behaviour of irregularly shaped particles in a full-scale twin screw granulator. *Particuology*, *61*, 30–40. https://doi.org/10.1016/j.partic.2021.03.007

Zhuang, Y., Saadatkhah, N., Morgani, M. S., Xu, T., Martin, C., Patience, G. S., & Ajji, A. (2023). Experimental methods in chemical engineering: Reactive extrusion. *The Canadian Journal of Chemical Engineering*, *101*(1), 59–77. https://doi.org/10.1002/cjce.24538