Proceedings of the 11 th North American International Conference on Industrial Engineering and Operations Management, Milwaukee, Wisconsin, USA, June 9-11, 2026

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA11.20260359
Published: June 9, 2026

Mathematical Modeling and Sustainability Metrics for Recycled ABS Filament Produced via a Passive Vibratory Feeder Recycling System

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Abstract

Fused deposition modeling (FDM) generates substantial material waste in the form of disposable support structures, undermining the sustainability claims of additive manufacturing when petroleum-based polymers such as acrylonitrile butadiene styrene (ABS) are used without recovery strategies. This study addresses this challenge by proposing a closed-loop recycling approach for ABS support-structure waste using a low-energy Vertical Compounding Extrusion (VCE) system integrated with a passive vibratory feeder. The system leverages gravity-assisted feeding and synchronized passive vibration to ensure stable material flow and controlled short-glass-fiber reinforcement during reprocessing. A mathematical framework based on a modified rule of mixtures is developed to model the tensile performance of recycled and reinforced filament, explicitly accounting for fiber volume fraction, length efficiency, and orientation induced by extensional flow during extrusion. Numerical simulations demonstrate a non-linear increase in composite tensile strength with increasing fiber content, indicating that controlled reinforcement can not only offset polymer degradation from thermal recycling but also enable material upcycling beyond the properties of degraded ABS. Sustainability performance is evaluated using a Resource Recovery Efficiency (RRE) metric, with simulated scenarios yielding values exceeding 93%, indicating minimal material loss. The results demonstrate that targeted recycling of waste from homogeneous FDM support structures, combined with passive, low-energy feeding and reinforcement strategies, offers a viable pathway to improve material efficiency and integrate circular economy principles with decentralized additive manufacturing systems.

Keywords
Recycling, ABS filament, Additive manufacturing, Sustainability, Composite materials.

1. Introduction and Literature Review

Recent research pointed out that the sustainability benefits are highly context-dependent rather than inherent (Graziosi et al., 2024) even though additive manufacturing (AM) or 3D printing has increasingly been positioned as a key enabler of sustainable and distributed production systems due to its design flexibility and material efficiency. Among AM technologies, fused deposition modeling (FDM) is widely adopted because of its low cost and accessibility, particularly in prototyping, small-batch production, and decentralized manufacturing environments (Bănică et al., 2024). Acrylonitrile butadiene styrene (ABS) remains one of the most utilized FDM materials owing to its favorable mechanical strength, thermal resistance, and durability. Despite these advantages, the extensive use of ABS in FDM has raised environmental concerns related to plastic waste generation and end-of-life material management (Deshmukh et al., 2024).

A significant portion of material waste in FDM originates from support structures (Mishra et al., 2023) that are required to fabricate overhangs and complex geometries. These structures are intentionally sacrificial and are typically removed and discarded immediately after printing, leading to inefficient material utilization. Life-cycle-based assessments indicate that such waste streams meaningfully contribute to the environmental footprint of FDM, particularly when petroleum-based thermoplastics like ABS are used without recovery strategies (Sola et al., 2024). As additive manufacturing continues to scale across industries, unmanaged support-structure waste undermines claims of sustainability and conflicts with circular economy principles.

In response to these challenges, recycling and reuse of thermoplastic feedstocks have become central themes in recent additive manufacturing research (Singh et al., 2025). Mechanical recycling consisting of shredding, melting, and re-extruding polymer waste has emerged as the most feasible approach for FDM materials due to its relatively low energy demand and compatibility with existing infrastructure (Ranjan Madhu et al., 2022). Several post-2022 studies demonstrate that recycled ABS filament can be successfully produced and reused in standard FDM printers with minimal hardware modification, making it suitable for distributed and small-scale manufacturing environments (Sipahutar et al., 2023).

However, polymer degradation remains a critical limitation of mechanical recycling. Repeated thermal and mechanical processing can cause chain scission and oxidation in ABS, leading to reduced molecular weight, altered rheological behavior, and gradual declines in mechanical performance (Sipahutar et al., 2023). Recent experimental studies show that while tensile and flexural properties of recycled ABS decrease across successive recycling cycles, the reductions are often modest when the number of reprocessing iterations is controlled. Thermal properties such as glass transition temperature remain comparatively stable, indicating continued suitability for non-load-critical and functional applications (Rajendran et al., 2025).

To mitigate performance degradation, contemporary research has explored design-based and hybrid material strategies. For instance, studies on multi-material and core–shell printing approaches demonstrate that recycled ABS can be effectively used in infill regions while virgin material is retained for outer shells, preserving mechanical integrity while significantly reducing virgin polymer consumption (Chawla et al., 2023). Such approaches are particularly relevant for recycling support-structure waste, where aesthetic quality and peak strength are often secondary considerations.

From a sustainability perspective, integrating ABS recycling into closed-loop and circular manufacturing frameworks has received increasing attention since 2022. Reviews focusing on sustainable additive manufacturing emphasize that targeted recycling of process-generated waste streams can substantially reduce carbon emissions, energy consumption, and reliance on virgin feedstock when compared with conventional filament production (Prasad et al., 2024; Sola et al., 2023). Life cycle assessments further indicate that recycled thermoplastics offer meaningful environmental advantages when recycling is performed near the point of use, minimizing transportation and preprocessing impacts (Sola et al., 2024).

Despite these advances, systematic reviews consistently identify a gap in research addressing support-structure waste as a distinct and homogeneous recycling stream. Most existing studies focus on failed prints or post-consumer plastics, with limited differentiation of support materials from other forms of FDM waste (Prasad et al., 2024). Given that support structures experience comparatively fewer thermal cycles and predictable geometries, they represent an underutilized opportunity for closed-loop recycling in FDM systems. Moreover, literatures addressing material handling and feeding mechanisms for recycled polymer reprocessing remains limited, particularly in relation to passive, low-energy systems that align with sustainability objectives (Radu et al., 2025).

Fused deposition modeling using ABS filament generates a substantial volume of material waste in the form of disposable support structures, which are routinely removed and discarded following printing. This practice leads to inefficient material utilization, increased polymer consumption, and heightened environmental impact, contradicting the principles of sustainable manufacturing and circular economy frameworks (Kazakova & Lee, 2022). Although ABS is mechanically recyclable, the absence of systematic, low-energy approaches for recovering and reprocessing support-structure waste combined with concerns regarding material degradation and filament quality has limited its practical adoption. Addressing this gap by developing an efficient recycling system and evaluating the recyclability and reusability of recycled ABS filament through modeling and simulation is essential for improving resource efficiency and advancing FDM as a truly sustainable manufacturing technology.

1.1 Objectives

The objectives of this study are to design and develop a recycling system for ABS filament support structures using a passive vibratory feeder mechanism, and to evaluate the recyclability and reusability of the resulting recycled filament through mathematical modeling and simulation.

2. Methods

This study adopts a design-science research methodology to address the mechanical degradation of recycled Acrylonitrile Butadiene Styrene (ABS) or Polylactic Acid (PLA). The approach centers on a custom-engineered **Vertical Compounding Extrusion (VCE)** system, designed to facilitate in-situ fiber reinforcement of 3D printing waste through a gravity-assisted, low-energy architecture.

The process begins with the systematic harvesting of sacrificial support structures from FDM prints. Unlike failed prints or post-consumer waste, support material is a relatively homogeneous feedstock, having typically undergone only one thermal cycle. These structures are harvested and sorted to ensure no foreign contaminants or adhesives are present. Once collected, the bulky lattice structures are processed through a mechanical granulator. This shredding stage reduces the waste into irregular flakes with a controlled particle size distribution between **2mm and 5mm** (Zhang et al., 2019). This specific size range is critical to the vertical system; particles smaller than 2mm risk premature melting and "bridging" in the hopper throat, while particles larger than 5mm can cause mechanical jams in the feeding screw according to Zhang et al. (2019).

2.1 Integrated Vertical Compounding (VCE) Overview

The core of the system shown in Figure 1 utilizes vertical orientation to leverage gravitational forces. Unlike traditional horizontal extruders, the VCE uses gravity to maintain a constant pressure head, ensuring that the shredded flakes naturally descend into the compression zone (Hicks & Freese, 2022). This design minimizes the footprint and energy requirements while preventing the "starve-feeding" issues common when processing recycled materials with inconsistent bulk densities.

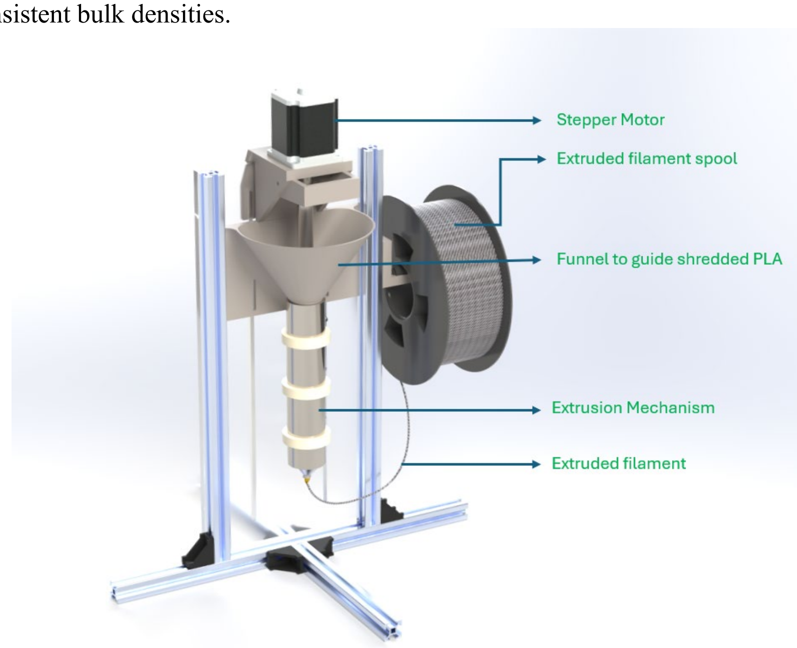


Figure 1. Isometric View of the Integrated Vertical Compounding Extruder (VCE)

2.2 Dual-Phase Synchronized Feeding and Passive Vibration

The shredded polymer flakes are introduced into the primary hopper while a secondary feeder is loaded with short-strand glass fibers. A critical challenge in composite extrusion is the tendency of glass fibers to bridge or clog the intake. The VCE addresses this through the **Dual-Phase Synchronized Feeding Module** shown in Figure 2.

As the high-torque NEMA stepper motor rotates the lead screw, its natural resonant frequency generates micro-vibrations across the chassis. The secondary feeder is positioned at a **10° inclination** relative to the horizontal plane, a value calculated based on the **Angle of Repose** for short-strand glass fibers. These vibrations act as a passive conveyor, fluidizing the fiber bed and ensuring a consistent, bridge-free volumetric flow into the molten matrix. This synchronization ensures that the fiber-to-matrix ratio remains constant, which is vital for the mechanical predictability of the final filament.

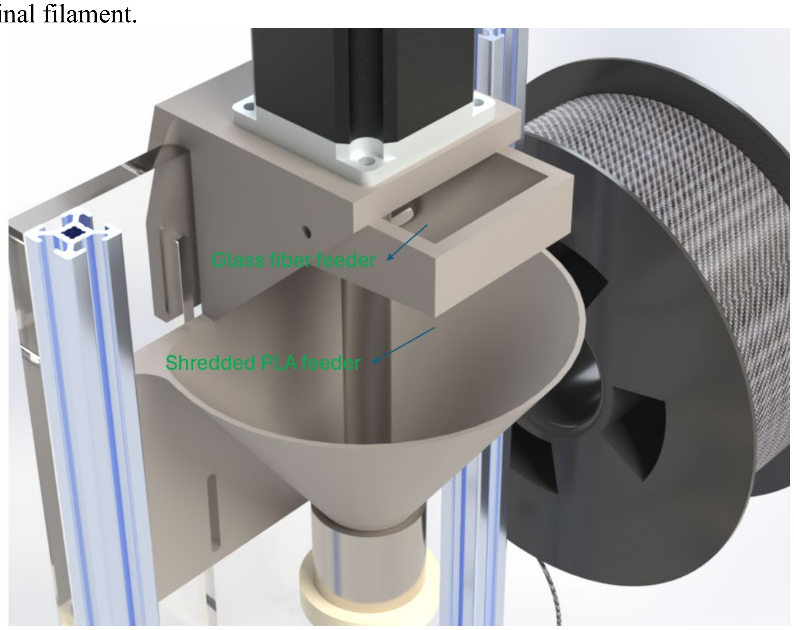


Figure 2. Detail View of the 10° Passive Vibratory Feeder Mechanism for Glass fibers

2.3 Thermal-Kinetic Processing and Fiber Wetting

Inside the barrel shown in Figure 3, the material undergoes a triple-zone thermal treatment designed to preserve polymer integrity while ensuring the wetting of the fibers. Three ceramic heater bands maintain a specific gradient.
According to Thakur et al. (2024) and as shown in Table 1, the thermal profile is carefully structured across three heating zones to optimize both the melting behavior of the ABS and its interaction with the glass fibers. In Zone 1 (Upper), maintained at 210°C ± 5°C, the primary objective is to gradually soften and transition the solid ABS shreds into a viscoelastic state without causing premature degradation; this controlled heating ensures consistent feed and prevents thermal shock. The material then progresses into Zone 2 (Mid) at 230°C ± 2°C, which serves as the critical processing region where the polymer reaches its lowest viscosity. At this stage, the molten ABS is sufficiently fluid to fully wet and encapsulate the individual fiber strands, promoting strong interfacial adhesion that is essential for mechanical performance. Simultaneously, the rotation of the lead screw introduces mechanical shear forces that drive dispersive and distributive mixing, ensuring uniform fiber distribution throughout the matrix and minimizing agglomeration. Finally, in Zone 3 (Lower) at 220°C ± 3°C, the temperature is slightly reduced to create a stabilization zone where melt strength is increased. This adjustment enhances the cohesiveness of the composite melt, allowing it to maintain structural integrity as it is pressurized and forced through the die, thereby preventing tearing, irregular flow, or defects in the final extrudate (Thakur et al., 2024).

2.4 Extensional Flow Alignment and Filament Formation

In the proposed design the molten composite is forced through a **1.75 mm interchangeable nozzle**. The conical interior geometry of the nozzle induces **extensional flow**. As the melt accelerates toward the exit, the polymer chains and the glass fibers are physically stretched and aligned along the longitudinal axis of the filament.

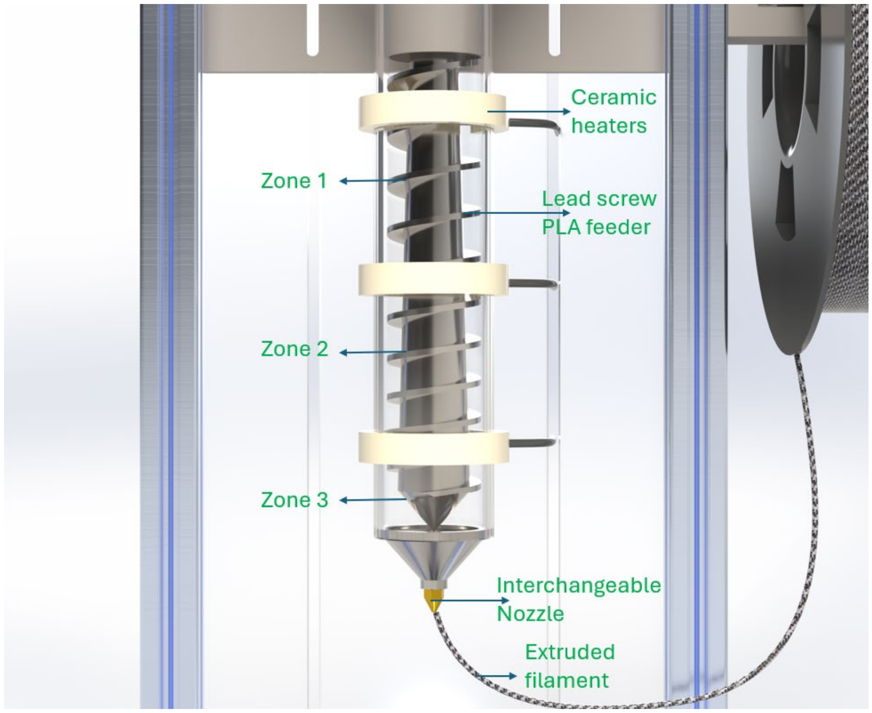


Figure 3. Cross-sectional View of the Extrusion Barrel and Nozzle Assembly

This alignment is the physical basis for the "Orientation Efficiency Factor" used in mathematical modeling. By ensuring the fibers are parallel to the direction of future tensile loads in 3D printed parts, the system achieves upcycling, where the added glass fibers more than compensate for the mechanical degradation of the recycled matrix, resulting in a filament that can exceed the strength of virgin material.

Table 1. Temperature Profile and Functional Description of Extrusion Processing Zones for ABS–Glass Fiber Composite

Zone	Temperature	Description
Zone 1 (upper)	210°C ± 5°C	Initiates the transition of solid ABS shreds into a viscoelastic state.
Zone 2 (middle)	230°C ± 2°C	Peak temperature zone where polymer viscosity is lowest, enabling full encapsulation of glass fibers and uniform mixing via mechanical shear.
Zone 3 (lower)	220°C ± 3°C	Stabilization zone that increases melt strength, ensuring structural integrity for extrusion through the die.

2.5 Mathematical Modeling and Material Logic

The theoretical performance of the developed upcycled filament is governed by the Modified Rule of Mixtures. This mathematical framework justifies the integration of glass fibers to compensate for the thermal degradation of the recycled ABS matrix. The composite tensile strength, σ_c, is defined as Equation 01:

$$\sigma_c = \eta_L \, \eta_O \, \sigma_f \, V_f + \sigma_m \left(1 - V_f\right) \tag{01}$$

where the model parameters are defined as follows:

- σ_c— theoretical tensile strength of the reinforced composite filament
- $V_f \in [0,1]$— fiber volume fraction, controlled by the synchronized stepper-motor feed rate
- σ_f— intrinsic tensile strength of the glass fiber reinforcement
- σ_m— tensile strength of the recycled polymer matrix (ABS or PLA)
- $\eta_L \in (0,1]$— fiber length efficiency factor accounting for sub-critical fiber length
- $\eta_O \in (0,1]$— fiber orientation efficiency factor representing alignment relative to the loading direction

η_L and η_O: Efficiency factors representing the fiber length and orientation, respectively.

To simulate this mathematical model, the following PyCharm code shown in Figure 4 was executed:

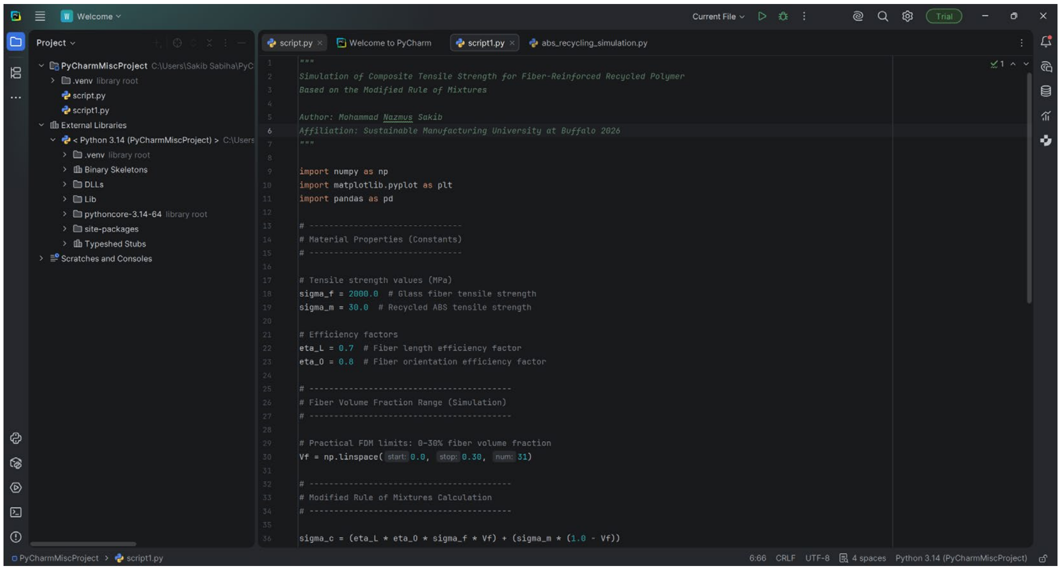


Figure 4. Simulation Code for Composite Tensile Strength

2.6 Sustainability Impact and Circular Economy Framework

The proposed design addresses the environmental burden of additive manufacturing through three distinct sustainability dimensions:

In FDM processes, support structures represent a predictable and homogeneous waste stream, often comprising up to 30% of total material usage. The VCE system enables a Closed-Loop Life Cycle by converting these discarded structures into high-value assets. The effectiveness of material recovery within the proposed closed-loop recycling system is quantified using the Resource Recovery Efficiency (RRE). This metric evaluates the proportion of input waste material that is successfully converted into usable composite filament. The model is defined as Equation 02:

$$\text{RRE} = \frac{W_{\text{filament}}}{W_{\text{ABS}} + W_{\text{fiber}}} \times 100 \tag{02}$$

where:

RRE— Resource Recovery Efficiency (%)

W_{filament}— total mass of the produced composite filament

W_{ABS}— initial mass of collected ABS support-structure waste

W_{fiber}— mass of glass fiber reinforcement introduced during compounding

In order to simulate possible outcomes, Table 2 represents the following parameters for the simulation of the above mathematical model:

Table 2. Scenario Chart

Scenario	ABS Waste W_{ABS}(kg)	Fiber W_{fiber}(kg)	Filament W_{filament}(kg)
A	5.0	0.5	5.2
B	10.0	1.0	10.3
C	8.0	0.8	8.4
D	12.0	1.5	12.6

The ABS waste ranges from 5-12 kg, whereas fiber weight ranges from 0.5-1.5 kg.

3. Results and Discussion

A numerical simulation was conducted based on the modified rule of mixtures to evaluate the effect of glass fiber reinforcement on the tensile strength of recycled polymer filament. The simulation examined the relationship between composite tensile strength (σ_c) and fiber volume fraction (V_f) within a practical processing range relevant to fused deposition modeling.

The baseline tensile strength of the recycled polymer matrix was set at 30 MPa, representing degraded ABS resulting from multiple thermal recycling cycles. Glass fiber tensile strength was assumed to be 2000 MPa. Fiber length efficiency (η_L) and orientation efficiency (η_O) were assigned values of 0.7 and 0.8, respectively, reflecting short fiber reinforcement and partial alignment induced by extensional flow during extrusion.
Simulation results demonstrate a near-linear increase in composite tensile strength with increasing fiber volume fraction across the evaluated range ($V_f = 0$–0.30). At zero fiber content, tensile strength corresponds to that of the recycled polymer matrix. Introduction of reinforcement substantially increases tensile strength even at low volume fractions.

The Figure 5 below illustrates the simulated relationship between fiber volume fraction and composite tensile strength generated from PyCharm code:

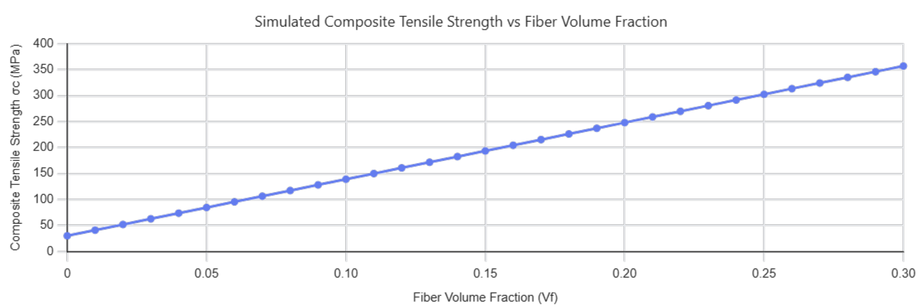


Figure 5. Composite Tensile Strength vs Fiber Volume Fraction Simulation Result

Key simulated results include:
$V_f = 0.00$: $\sigma_c \approx 30$MPa
$V_f = 0.10$: $\sigma_c \approx 140$MPa
$V_f = 0.20$: $\sigma_c \approx 248$MPa
$V_f = 0.30$: $\sigma_c \approx 357$MPa

The simulation shows that glass-fiber reinforcement rapidly dominates load transfer beyond a low critical fiber volume fraction, with no nonlinear degradation or diminishing returns within the studied range. This indicates stable and effective reinforcement under controlled fiber dosing.

The results confirm that short glass fibers can restore and significantly enhance the tensile strength of recycled ABS or PLA, directly counteracting degradation from repeated thermal recycling and enabling material upcycling rather than downcycling. The near-linear dependence of tensile strength on fiber volume fraction demonstrates that the synchronized feeding mechanism provides predictable and tunable mechanical control, supporting filament consistency and process reliability.

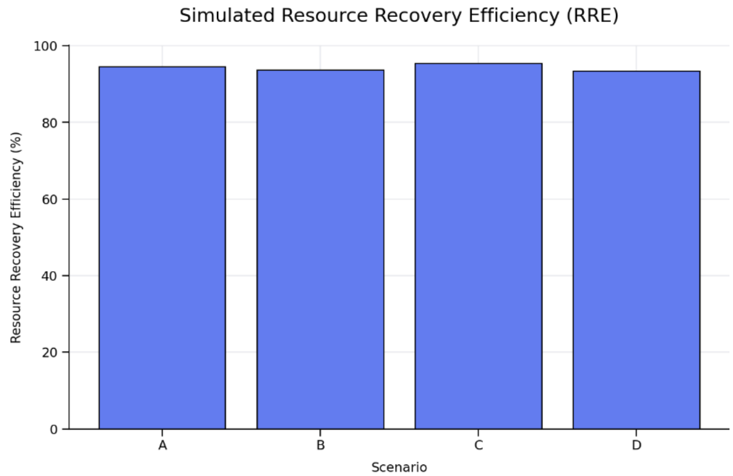
Efficiency factors for fiber length and orientation highlight the role of process-induced alignment, where extensional flow in the extrusion nozzle improves longitudinal strength. Overall, the findings support the Vertical Compounding Extrusion system as a viable and scalable approach for sustainable, value-added filament production, while motivating further experimental validation.

Simulation results for the RRE mathematical model are shown in Table 3 and Table 4 below:

Table 3. Scenario Chart

Scenario	**RRE (%)**
A	94.55
B	93.64
C	95.45
D	93.33

Table 4. RRE Scenario Simulation Bar Chart



RRE values consistently exceed 93%, indicating minimal material loss during shredding, compounding, and extrusion and it is assumed just for simulation purposes.

Slight reductions in RRE at higher mass throughput (Scenarios B and D) are attributable to processing losses and melt purge residuals, which are typical of extrusion-based systems.
The results demonstrate that the proposed VCE system effectively converts ABS support-structure waste into usable composite filament with high material utilization.

High RRE values validate the system's suitability for closed-loop and decentralized recycling, directly supporting circular economy objectives.

4. Conclusion

This study demonstrates that targeted recycling of FDM support-structure waste can meaningfully advance the sustainability of additive manufacturing. By integrating a passive vibratory feeder within a Vertical Compounding Extrusion system, recycled ABS support material is efficiently transformed into high-value, glass-fiber-reinforced filament. Mathematical modeling and simulation confirm that controlled fiber incorporation can not only offset polymer degradation but substantially enhance tensile performance, enabling material upcycling rather than downcycling. High resource recovery efficiencies further validate the system's suitability for closed-loop, decentralized recycling. Collectively, the findings highlight a scalable, low-energy pathway for reducing virgin material dependence and embedding circular economy principles within FDM workflows.

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