DESIGN OF A HEATED TWIN SCREW AUGER CONVEYOR FOR SOLVENT REMOVAL IN A SOLVENT-BASED PLASTIC RECYCLING SYSTEM

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Abstract:

The Solvent-Targeted Recovery and Precipitation (STRAP) process provides a scalable pathway for extracting high-purity resins from complex mixed plastic waste streams. Building on our previous development of a 25 kg h^{-1} pilot-scale STRAP system, this study advances the front-end operations that govern material feeding, fast dissolution, high-throughput filtration, and solvent recovery from undissolved solids. A fully integrated conveying–dissolution–centrifugal-sifting–vacuum-drying system was designed, fabricated, and tested to enable continuous-to-batch-to-continuous operation, resolving one of the major bottlenecks in solvent-based recycling. High-shear turbulent dissolution reduced characteristic dissolution times by two orders of magnitude compared with non-turbulent mixing, achieving complete dissolution within seconds for model systems. The centrifugal sifter demonstrated rapid and repeatable phase separation (<3 min), generating wet solids containing 10–30 wt% solvent. A newly developed inclined twin-screw vacuum dryer, equipped with air-locking feed bins, recovered solvent with an overall drying efficiency of 38% and consistently produced <0.5 wt% residual solvent in the dried solids. This work establishes the integrated front-end processing required for continuous STRAP operation at pilot scale, providing validated engineering data that support techno-economic modeling and future industrial deployment.

1. Introduction and Motivation:

Global plastic production continues to rise while recycling rates remain critically low [1], largely due to the increasing complexity of mixed plastic waste streams. Multilayer packaging, engineered films, and post-consumer residues present heterogeneous combinations of polymers, fillers, and additives that cannot be effectively processed using conventional mechanical recycling technologies [2-5]. Chemical recycling offers a pathway to convert plastics into monomers, oils, or waxes for downstream use such as fuels or chemical feedstocks. However, they are costly and energy intensive. Further, the presence of additives, pigments, fillers, chlorinated plastics, and modifiers [6, 7] further complicates the process, or contaminates the products [8]. Solvent-based strategies, particularly those enabling polymer-selective dissolution, offer a promising platform for addressing these compositionally complex feedstocks. STRAP (Solvent-Targeted Recovery and Precipitation) has demonstrated the ability to recover multiple high-purity resins from mixed wastes by coupling solvent selection, high-shear dissolution, staged filtration, and controlled precipitation [9].

A key technical barrier to industrial deployment is the lack of validated pilot-scale data describing the front-end operations—conveying, dissolution kinetics, solid–liquid separation, and solvent recovery from non-dissolved solids—under realistic continuous operation. Prior work established the fundamental dissolution and filtration principles in bench-scale systems [9-12]. In contrast to mechanical recycling, STRAP avoids resin degradation, and compared with chemical recycling, it is far less energy- and capital-intensive [13, 14]. however, engineering-scale implementation introduces additional challenges related to throughput, flowability, thermal and hydrodynamic control, and vapor-handling safety. The 25 kg h^{-1} STRAP Pilot-Scale Unit (PSU) was developed to address these challenges and to quantify the transient behavior of each step under integrated operation.

This paper reports on the continuation of our effort to develop a fully integrated front-end STRAP module [15], while focusing on: (i) continuous-to-batch-to-continuous material handling architecture; (ii) high-shear, turbulence-enhanced dissolution; (iii) high-throughput centrifugal sifting dynamics; and (iv) solvent recovery using an indirect, vacuum-assisted twin-screw dryer. Collectively, these results provide essential engineering correlations and operational guidelines for future scale-up and techno-economic modeling.

In the context of the STRAP process, the terms *front-end* and *back-end* are defined based on process function rather than polymer-manufacturing convention. Here, *front-end operations* include all unit operations upstream of polymer precipitation and melt re-extrusion, namely material conveying, dissolution, solid–liquid separation, and solvent removal from undissolved solids. The *back-end* comprises precipitation, polymer purification, melt finishing, and pelletization.

From a traditional polymer manufacturing perspective, solvent removal is typically considered a back-end operation prior to pelletization. However, in STRAP, solvent removal occurs at multiple points in the process and serves distinct roles depending on stream composition. Solvent removal from heterogeneous, non-molten undissolved solids is therefore treated as a front-end operation, whereas residual solvent removal from purified, precipitated polymers is a back-end finishing step.

2. Review of Related Work

Solvent-based plastic recycling has progressed substantially over the past decade, with several industrial groups pursuing polymer-selective dissolution as a strategy for generating high-purity resins from heterogeneous waste streams. Currently, the only solvent-based commercial plant in the United States is operated by PureCycle [16], focusing solely on PP. PureCycle recently received a USFDA No Objection Letter confirming their PureFive™ Ultra-Pure Recycled resin is suitable for food-contact applications, underscoring the efficacy of solvent-based recycling. PureCycle relies on liquefied petroleum gas (LPG) solvents at high pressures and temperatures, leading to high capital and operational costs. In contrast, STRAP process employs relatively inexpensive solvents (e.g., heptane, xylene) at modest temperatures (90-110°C) and ambient pressure (<1bar). Through extensive lab-scale experiments and Techno-Economic Analysis (TEA), we have demonstrated that STRAP can extract multiple resins from a single feedstock in a cost-effective manner [13, 14]. Other solvent-based pilot initiatives are underway in Europe (Fraunhofer IVV, MultiCycle, Ineos Inovyn), though limited disclosures restrict meaningful comparisons. STRAP represents a unique opportunity to advance solvent-based recycling beyond the state of the art by addressing diverse feedstocks at lower cost and energy demand.

Previous bench-scale work has validated dissolution kinetics, precise solvent selection enabled by computational solubility modeling, and staged extraction of multiple resins from a single feedstock. Subsequent pilot-scale studies further established fast dissolution (<30 s for model systems), high-throughput centrifugal filtration (<3 min), and consistent separation of solvent-rich wet solids suitable for downstream drying.

This section contextualizes the present work within the broader field of solvent-based recycling and highlights the remaining knowledge gaps—particularly in continuous material handling, integrated dissolution–filtration dynamics, and safe, efficient solvent recovery—that motivate the advancements reported in this paper.

3. Technological Approach

The integrated front-end STRAP system was designed to enable continuous feeding of mixed plastic waste, batch dissolution under high-shear turbulent conditions, and continuous downstream separation and solvent recovery. The solvent-recovery system presented here addresses front-end solvent removal from undissolved, non-molten solids, and is distinct from conventional back-end melt devolatilization used for purified polymers. Figure 1 illustrates the 3D presentation of the overall architecture, which consists of four tightly coupled subsystems: (i) material conveying and dosing; (ii) the high-shear dissolution vessel; (iii) centrifugal sifting for rapid solid–liquid separation; and (iv) a vacuum-assisted indirect dryer that recovers solvent from the undissolved solids.

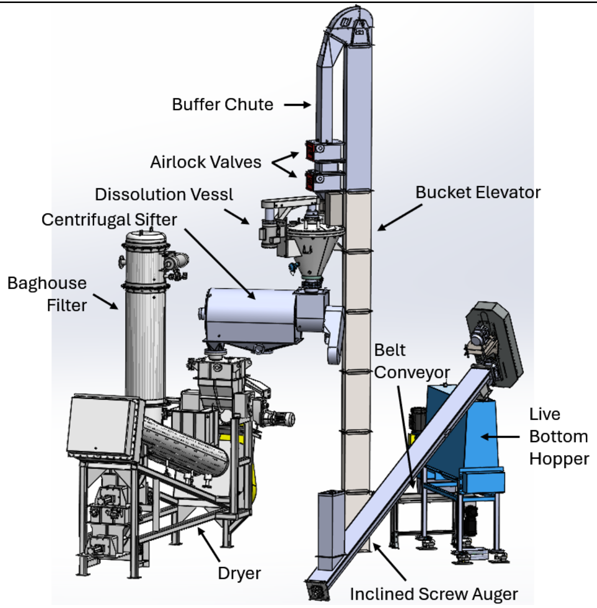

Figure 1. 3-D presentation of combined feeding-dissolution-filtration-dying system.

3.1 Material Conveying and Dosing

A live-bottom hopper equipped with dual augers meters shredded feedstock onto a belt conveyor, which continuously delivers material to a bucket elevator. The elevator charges a buffer chute positioned above a double-flap airlock valve, enabling controlled transfer into the dissolution vessel without introducing atmospheric oxygen or disturbing the downstream vacuum environment. The continuous conveying system feeds the airlock at a steady rate, while the dissolution vessel accepts material in discrete batches. This continuous-to-batch transition is regulated by level sensors in the buffer chute to prevent bridging or overflow and to maintain consistent mass flow into the reactor.

3.2 High-Shear Dissolution Vessel

The dissolution reactor is a 60 L, hot-solvent-compatible vessel fitted with four baffles and a vertical shaft operating up to 1700 rpm. The combination of baffle-induced turbulence, high impeller tip velocity, and optimized solvent-to-plastic ratios enables dissolution times that are orders of magnitude faster than traditional laminar-mixing systems. Upon completion of the preset mixing interval, a pneumatic butterfly valve rapidly discharges the slurry into the centrifugal sifter, minimizing premature precipitation and temperature losses.

3.3 Centrifugal Sifter for Solid–Liquid Separation

The slurry is conveyed by an auger into a cylindrical sifting section containing a reinforced stainless-steel mesh. Rotating paddles propel the non-dissolved solids axially while the dissolved polymer–solvent solution is expelled centrifugally through the screen. Typical separation times are <3 min, with wet solids containing 10–30 wt% solvent depending on material properties and screen size. The sifter operates continuously and serves as the batch-to-continuous transition into the drying system.

3.4 Vacuum-Assisted Indirect Dryer

Solvent entrained in the wet solids is recovered using an inclined twin-screw auger encased in an oil-jacketed heating chamber. Three nitrogen-purged feed bins upstream and downstream of the heating zone maintain an air-locking sequence that prevents oxygen ingress, allowing the system to operate safely at sub-atmospheric pressures. The oil-heated screws provide controlled residence times of 30–90 min, depending on rotational speed, enabling reduction of residual solvent to <0.5 wt%. Vapor-phase solvent is extracted through a baghouse filter and condensed for reuse. The overall drying efficiency is approximately 38%, consistent with performance metrics of industrial indirect dryers.

This technological approach establishes an integrated, pilot-scale front-end module capable of processing 25 kg h^{-1} of mixed plastic waste under realistic operational conditions, providing critical engineering data for scale-up and system optimization.

Commercial solvent removal and devolatilization technologies are widely used in polymer manufacturing and recycling, including vented single- and twin-screw extruders, thin-film evaporators, and wiped-film dryers. [17-20] These systems are predominantly designed for homogeneous polymer melts, where residual solvents, monomers, or moisture are removed by exposing the molten polymer to vacuum under high surface renewal conditions. As a result, these technologies inherently rely on melt formation, which promotes blending of polymer phases and loss of compositional distinction in mixed-polymer feeds.

In contrast, the stream addressed in this work is the undissolved solids fraction exiting STRAP front-end filtration, which may comprise mixed plastics, fillers, additives, and other non-dissolved residues that can retain value for further downstream separation or upgrading. Processing this material through melt-based devolatilization would irreversibly blend heterogeneous polymers and complicate subsequent processing steps. Therefore, STRAP requires a low-temperature, non-melting solvent-removal approach capable of operating under vacuum while preserving material identity. This gap motivates the development of the indirect, vacuum-assisted twin-screw dryer presented here. The dryer was specifically designed for non-molten, solvent-rich undissolved solids, where maintaining polymer phase separation and avoiding thermal blending are essential for downstream STRAP processing.

4. Results and Discussion

The integrated STRAP front-end module described in this study is currently in the development and validation stage; therefore, each subsystem was initially evaluated using non-hazardous model systems prior to operation with organic solvents and plastic–solvent mixtures. This staged testing approach enables isolation of hydrodynamic, thermal, and transport phenomena while mitigating safety risks associated with solvent handling during early pilot-scale operation.

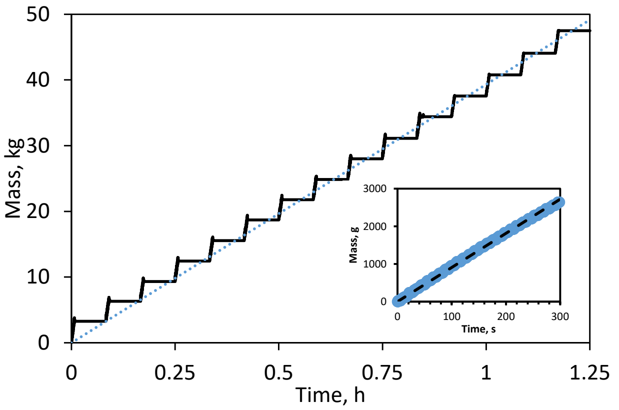

Figure 2. Flow of the material coming out of the double-flap airlock. The inset is material coming out of the live bottom hopper.

For the dissolution subsystem, polyethylene glycol (PEG-20,000) in water was selected as a representative model polymer–solvent system. At comparable concentrations, PEG-20,000 aqueous solutions exhibit viscosities on the same order of magnitude as polyolefin solutions (e.g., polyethylene in xylene) under STRAP-relevant temperature and shear conditions. As a result, PEG provides a physically meaningful analogue for assessing turbulence-enhanced mass transfer, shear-driven boundary-layer disruption, and characteristic dissolution times, independent of solvent chemistry. The dissolution trends reported here therefore reflect transport-limited behavior that is directly transferable to organic solvent systems used in STRAP.

For the solvent-recovery subsystem, moisture-removal experiments were conducted to validate residence-time control, vacuum stability, thermal equilibration, and energy efficiency of the indirect twin-screw dryer under conservative operating conditions. Water was selected as a bounding case due to its high latent heat of vaporization. Because the latent heat of evaporation of typical STRAP solvents (e.g., xylene) is approximately seven times lower than that of water, the demonstrated ability to reduce moisture content from ~5 wt% to <0.5 wt% indicates sufficient thermal capacity to remove substantially higher solvent loads. Based on this scaling, the dryer is capable of reducing solvent contents from ~35 wt%—typical of undissolved solids exiting STRAP filtration—to <0.5 wt% under the operating conditions demonstrated in this study. Solvent- and plastic-specific validation experiments are ongoing and will be reported in future publications as part of the continued scale-up and integration of the STRAP pilot-scale unit.

Following the model-system validation approach described above, the performance of the front-end STRAP module was evaluated through a series of integrated experiments focusing on material feeding, dissolution kinetics, centrifugal sifting dynamics, and solvent recovery in the indirect vacuum dryer.

4.1 Material Conveying and Dosing

The continuous-to-batch feeding configuration was assessed by operating the live-bottom hopper, belt conveyor, and bucket elevator continuously while intermittently actuating the double-flap airlock to deliver discrete batches into the dissolution vessel. Mass flow measurements showed that the steady feeding from the hopper matched the periodic discharge through the airlock, resulting in stable material accumulation in the buffer chute prior to each batch cycle, as shown in Figure 2. The airlock released 2–3 kg of material within 10–15 s during each batch transfer, after which the chute refilled over the subsequent ~300 s dissolution period. Level sensors effectively prevented overfilling or starvation, demonstrating robust control of the continuous-to-batch transition.

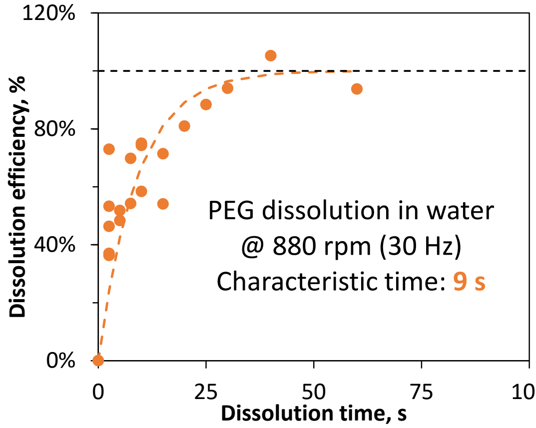

Figure 3. Dissolution efficiency in the intense turbulent flow in the dissolution vessel.

Visual inspections and recorded mass profiles confirmed unobstructed flow through all conveying components. No bridging or compaction effects were observed across tested feedstocks, indicating that the downsized particle geometry achieved through prior shredding was sufficient for reliable flowability.

4.2 High-Shear Dissolution Vessel

Dissolution tests were conducted using polyethylene glycol (PEG-20,000) as a model polymer system to quantify the influence of high-shear mixing, as shown in Figure 3. With 2–3 kg PEG dissolved into 20–30 L of water, complete dissolution was achieved within ~30 s under 1700 rpm operation, corresponding to a characteristic time nearly two orders of magnitude shorter than non-turbulent laboratory mixing. The rapid response is attributed to the combined effects of baffle-induced turbulence, enhanced shear rates, and minimized boundary layer resistance.

Transient mass measurements before and after sifter separation confirmed a first-order dissolution behavior. These dissolution times provide a validated basis for coupling the vessel's operational cycle with the upstream conveyor timing and downstream filtration capacity.

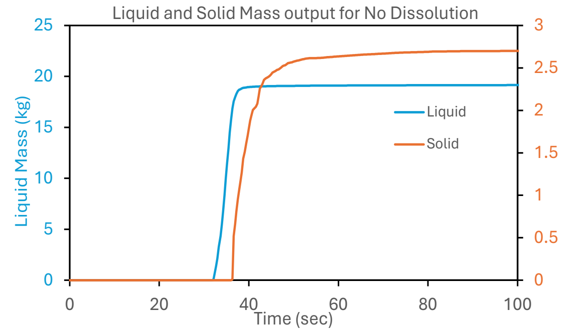

Figure 4. The out from the centrifugal sifter: liquid and solid.

4.3 Centrifugal Sifter for Solid–Liquid Separation

The centrifugal sifter's liquid–solid separation dynamics were evaluated using multi-layer plastic films and water. The components were mixed in the dissolution vessel for ~30s before being drained into the centrifugal sifter in ~2s. A representative experiment is shown in Figure 4, yielded total separation times <180 s, satisfying the required throughput for the 25 kg h^{-1} operation window. Across repeated trials, the sifter exhibited highly consistent mass-flow profiles for both filtrate and solids, with negligible variability in residence time or final wet-solid mass. Wet solids consistently retained 10–30 wt% solvent, depending on the feedstock and screen configuration. These metrics align with design targets for the subsequent drying step.

4.4 Vacuum-Assisted Indirect Dryer

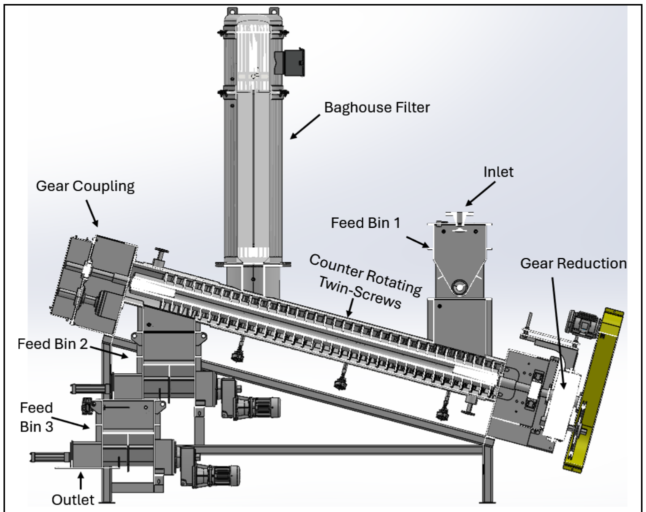

Figure 5: CAD representation of the Dryer System and components: feed bin 1; inclined twin screw auger heating chamber; feed bin 2; feed bin 3; baghouse filter; gear coupling system housing; and gear reduction system.

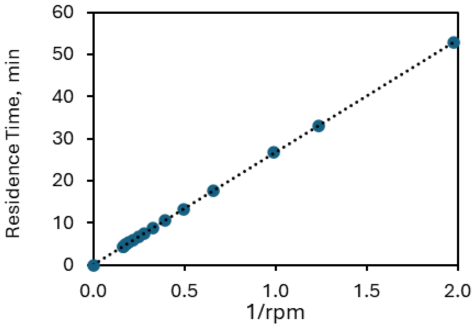

Figure 6. Residence time vs inverse rotational speed of the heating chamber augers.

The dryer is 10' long and has twin 6 ½" diameter hollow shafts with helical auger spirals ~ 12 ¾" in diameter as shown in Figure 5. The section responsible for the drying is the inclined heating chamber. The non-dissolved solids that are wet with solvent will be fed into the Feed Bin 1 inlet from the centrifugal sifter. The feed bin has a single screw auger and pneumatic cylinder with a plug to cover the outlet. Following the batch operation from the dissolution vessel, the sifter will deposit the non-dissolved solids into feed bin 1 every 5 minutes. The feeding process will take ~150 seconds to complete but the feed bin will only remain unactive for the first 60s. At the 60s point, the plug valve of feed bin 1 will open and the auger motor will power on to discharge the material. This process will run for 90s, after which the motor will shut down, the plug valve will close and remain dormant for the remainder of the 300s timer (150s). The output material from Feed Bin 1 will fall into the counter rotating twin screws, which are encased in an oil jacketed wall. This oil jacket will heat the material as it pushed along the length of the twin augers. As the material dries, the solvent vapor will be pulled through the baghouse filter via a vacuum pump which contains screens to remove any fine particles entrained with the flow of the vapor. The baghouse is equipped with a nitrogen purge system to reverse the flow through the filters and drop the built-up particles back into the solid stream. At the end of the augers the material is then dropped into feed bin 2. feed bins 2 and 3 operate on an independent 200s timer. The material will be fed into feed bin 2 for 90s, in parallel feed bin 3 will open its plug valve and operate its motor. After the 90s, 10s is allocated for Feed Bin 3 to shut down its operation and seal, and feed bin 2 to active its components. In this time there is also a nitrogen purge and vacuum pulling sequence that will remove any air from feed bin 3 before feed bin 2 opens its plug valve. Feed Bin 2 will have 90s to deposit the material into feed bin 3. After this sequence another 10s is allowed for feed bin 2 to shut down and feed bin 3 to become active. The operation of feed bin 3 will discharge the dried non-dissolved solids out of the system such that it can be collected with a Z-conveyor.

Drying tests were performed to characterize residence time behavior, solvent removal efficiency, and thermal equilibrium of the indirect twin-screw dryer. Residence time experiments—conducted by tracking tracer particles through the heating chamber at screw speeds from 0.5 to 6 rpm—revealed a near-linear correlation between 1/frequency and residence time, as shown in figure 6, confirming predictable plug-flow-like behavior governed by auger pitch and rotational speed.

Operational drying tests were performed with solid waste adjusted to 5 wt% initial moisture. The oil heater was turned on and set to 180°C three hours prior to the loading of the material to allow the heating chamber to reach 90°C.

A vacuum pump was used to bring the chamber to a pressure of -24 in Hg, gauge. The system reached steady-state performance after ~4 h of continuous operation. The outlet material consistently exhibited <0.5 wt% residual moisture. Figure 7 shows data for the outlet moisture content (MC) and material temperature (T). The results follows:

$$(1)\ MC = Ae^{-\frac{t}{\tau}}$$

$$(2)\ T = A(1 - e^{\frac{t}{\tau}})$$

The characteristic time (τ) for both curves is 1.1 hours, and after ~ 4 hours the system reached thermal equilibrium.

The drying system was designed to utilize indirect heating methods via oil jacket heating rather than direct heating methods due to safety considerations. The design of the heating chamber and oil jacket and operation of the feed bins allows for a volume swap of air with nitrogen using the nitrogen generator and vacuum pumping system. This eliminates the potential for air to come into contact the solvent vapor. Energy-balance analysis showed a drying efficiency of approximately 38%, consistent with industrially deployed indirect drying technologies.

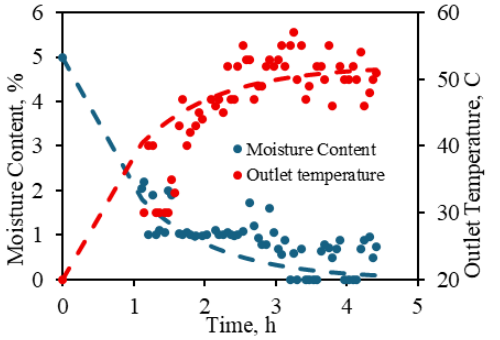

Figure 7. Outlet waste moisture content and temperature characteristics from startup of the system to steady-state.

5. Conclusions

This work advances the development of a fully integrated front-end module for the STRAP process, addressing key engineering challenges associated with feeding, fast dissolution, solid–liquid separation, and solvent recovery at pilot scale. Through continuous-to-batch-to-continuous operation, the system demonstrated stable and predictable performance across several critical subsystems. High-shear turbulent mixing enabled dissolution times on the order of seconds, meeting the throughput requirements of downstream filtration. The centrifugal sifter provided rapid and reproducible separation of dissolved and undissolved fractions, generating wet solids with solvent contents compatible with indirect drying. The newly developed inclined twin-screw vacuum dryer effectively removed entrained solvent to <0.5 wt%, achieving a drying efficiency consistent with established indirect thermal drying technologies. It is noted that commercial devolatilization systems remain appropriate for purified, precipitated polymer streams in STRAP; the present work addresses the unmet need for solvent removal from heterogeneous, non-molten solids in the front-end of the process.

These results collectively validate the operability and robustness of the 25 kg h^{-1} STRAP Pilot-Scale Unit and provide essential engineering correlations—residence times, transition dynamics, characteristic dissolution constants, and solvent-removal efficiencies—required for scale-up and techno-economic assessment. The work establishes a critical foundation for integrating the front-end system with downstream precipitation, purification, and extrusion modules. Future efforts will focus on full-system coupling, solvent and additive management strategies, long-duration reliability testing, and comprehensive TEA/LCA evaluations to support industrial deployment of solvent-based plastic recycling technologies.

6. Acknowledgements

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