Advances in Polymer Technology

WILEY

REVIEW ARTICLE OPEN ACCESS

Starve Feeding in Screw Extruders: A Review

Mohammad Pourhosseinian[1,2] | Bahram Haddadi[2]

[1]Institute of Chemical, Environmental and Biological Engineering, TU Wien, Vienna, Austria | [2]Competence Center CHASE GmbH, Linz, Austria

Correspondence: Mohammad Pourhosseinian (mohammad.pourhosseinian@tuwien.ac.at) | Bahram Haddadi (bahram.haddadi@chasecenter.at)

Received: 5 September 2025 | **Revised:** 9 March 2026 | **Accepted:** 12 March 2026

Academic Editor: Srijoni Sengupta

Keywords: extrusion | polymer processing | screw extruders | starve feeding

ABSTRACT

Starve-fed polymer extrusion has become an important strategy for improving process control, energy efficiency, and product quality, but it also introduces partially filled flow regimes that are not captured by classical flood-fed concepts. This review provides a critical assessment of starve-fed operation in single-screw and corotating twin-screw extruders, structured by extruder type and process region. Key experimental techniques, including screw pull-out/quench analysis, window-based and optical visualization, residence time distribution (RTD) measurements, mixing assessments, ultrasonic sensing, pressure profiling, and specific mechanical energy (SME) monitoring, are reviewed with emphasis on how starve feeding modifies melting mechanisms, fill level, RTD, and energy consumption. The experimental evidence base is particularly strong for starve-fed single-screw extrusion, where pull-out and RTD studies clearly demonstrate a transition from contiguous solid-bed melting to mixed conductive/dispersed melting; corresponding data for starve-fed twin-screw extruders remain comparatively scarce and are often limited to local visualization and RTD in selected elements. Modeling approaches are then summarized, from early analytical and empirical models to modern global feed-to-die descriptions utilized to partially filled operation. Their capabilities and limitations are discussed separately for single- and twin-screw machines, highlighting where starve-fed conditions can be treated by adapted flood-fed models and where new formulations are required. Finally, advanced numerical techniques, computational fluid dynamics (CFD), discrete element method (DEM), and smoothed particle hydrodynamics (SPH), are reviewed with respect to extruder type and phase: DEM for granular solids conveying in the feed region, CFD for free-surface melt flow in partially filled single screws and selected twin-screw sections, and SPH for resolving starved and intermeshing flows with explicit free surfaces. The achievements and current limitations of these methods are identified, along with future research needs in improved modeling of partially filled regions, tighter coupling between DEM and CFD/SPH, real-time process monitoring, and scale-up strategies for industrial starve-fed extrusion.

1 | Introduction

Screw extrusion is one of the most important and widely used manufacturing techniques for producing continuous products with specific shapes by forcing materials such as plastics, metals, or food through a die [1–3]. In the present review, the focus is on polymer extrusion, where this highly versatile process softens materials, usually by applying heat, to manufacture a wide variety of products [4–6]. One of the key advantages of extrusion lies in its ability to combine several operations, such as mixing, heating, and forming, into a single streamlined step, which reduces production time and energy consumption compared to traditional batch processes [4]. The continuous nature of extrusion ensures consistency in product quality and makes it ideal for industries requiring high precision and uniformity.

However, extrusion does have its limitations. One significant drawback is the high capital cost of extrusion equipment, especially for twin-screw systems, which are used for more complex applications [5]. Furthermore, extrusion requires precise control of operational parameters, such as temperature, pressure, and screw speed; improper control can lead to defective or inconsistent products [4]. The process also has material limitations, as some materials are prone to thermal degradation or undesirable reactions under the high-temperature and high-pressure conditions typical for extrusion [5]. While extrusion is more energy-efficient than conventional batch processes, such as traditional batch molding, it remains an energy-intensive method, particularly during prolonged operations [7].

Extruders, generally categorized into single- and twin-screw types, differ primarily in complexity and processing capabilities (Figure 1); while single-screw systems are simpler and cost-effective for basic applications, twin-screw extruders offer superior mixing and material control for complex processes [8]. Delvar et al. [9] provided a comprehensive overview of twin-screw extruders and their various subtypes. In this review, starve-fed plasticating screw extrusion is considered in a general way, covering both forming-oriented and compounding-oriented applications, with the focus placed on how starve feeding affects melting, pressure development, residence time, and mixing inside the machine rather than on the specific downstream product.

Flood feeding (also called flood-fed or full feeding) and starve feeding are two contrasting modes of supplying material to an extruder, and they fundamentally alter the filling pattern along the screw. Single-screw extruders have traditionally been run flood-fed (ensuring a stable solid bed conveyance), but they can be starve fed if equipped with precise feeders [10]. Figure 2 illustrates these distinct filling patterns for a single-screw extruder. Twin-screw extruders, on the other hand, are most often designed to be starve-fed [11]. Corotating twin-screw extruders almost always employ metered starve feeding at the main hopper and any side feeders, because this allows intentional control of fill in each zone and prevents overfilling of the intermeshing screws [12, 13].

In contrast to flood feeding where material is delivered in excess, starve feeding means that the material feed rate is deliberately set below the maximum conveying capacity of the screw, which will cause partially filled regions. The material is metered (usually by a feeder or dosing system) at a controlled rate, and the screw turns fast enough that it could convey more than is being fed. As a result, the screw is partially filled in the feed zone, there is an air gap above the fluid, and the hopper throat is not flooded with material [14]. In this case, the throughput is determined by the feeder's mass flow rate rather than the screw's theoretical capacity; at least until the screw speed becomes so high that its capacity can no longer keep up with the feed rate. In practical terms, starve feeding "uncouples" the feed rate from screw speed. The screw RPM can be increased without necessarily increasing output (as long as the feeder continues to limit the flow), or vice versa [15]. This decoupling is a major advantage for process control, allowing independent optimization of screw speed (which influences mixing and heat generation) and throughput [16].

This independent optimization capability provided by starve feeding directly contributes to its effectiveness in maintaining stable pressure and preventing pressure fluctuations. In extreme starve-fed cases (particularly in TSEs), almost the entire screw might be unpressurized until just before the die. One practical advantage of starve feeding is the significant reduction in pressure fluctuations at the die. In flood-fed single-screw extruders, even small variations in feeding or melting can cause sudden surges in die pressure and affect extrudate output. In contrast, starve feeding avoids overfilling the screw, allowing precise control of die pressure by adjusting the feed rate [17]. Twin-screw extruders are inherently designed to operate starved, with pressure buildup occurring predominantly in the last kneading or metering elements that seal flow and generate the required force for the die [5].

In classical flood-fed single-screw extrusion, the drag-flow conveying mechanism and the formation of a compact solid bed generally lead to a highly filled screw channel once solids compaction and melting are established. Under many operating conditions, the metering zone operates close to fully filled up to the die, except in deliberately vented zones, although the actual fill level depends on material properties, screw design, and processing conditions. In contrast, corotating twin-screw extruders are commonly operated in starve-fed mode, where individual screw elements frequently run partially filled and become fully filled only in specific sections designed for melting, intensive mixing, or pressure build-up. In deliberately starve-fed single-screw operation, the classical fully filled assumption is likewise relaxed, and extended partially filled regions may exist upstream of the fully filled section. Since this review focuses on starve-fed operation, the discussion emphasizes these intentionally partially filled zones and their roles in conveying, melting, mixing, and degassing.

The efficiency and performance of screw extruders are governed by their distinct functional zones, each designed to achieve specific material transformations. Figure 3 is a generic functional schematic; in the following, we explicitly distinguish between the fully filled operation of classical flood-fed single-screw extruders and the typically partially filled operation of starve-fed single-screw and corotating twin-screw extruders.

In a single-screw extruder, the screw is typically divided into three primary functional zones as shown in Figure 3. The feeding zone (A) is the initial section with a constant, deep channel

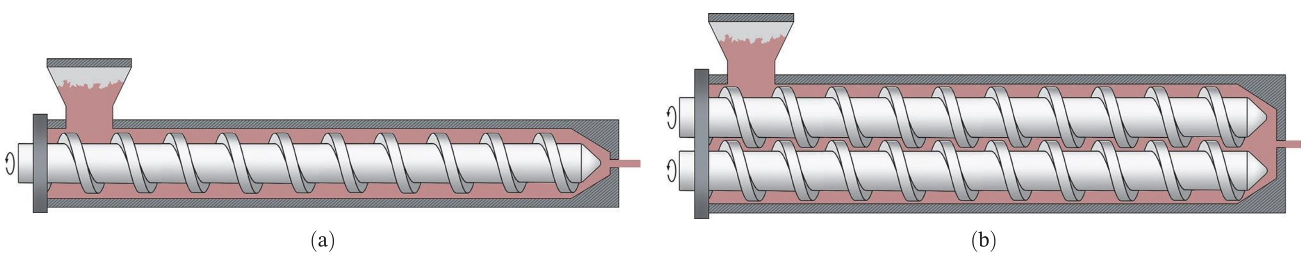

FIGURE 1 | (a) Single screw extruder vs. (b) corotating twin screw extruder schematic.

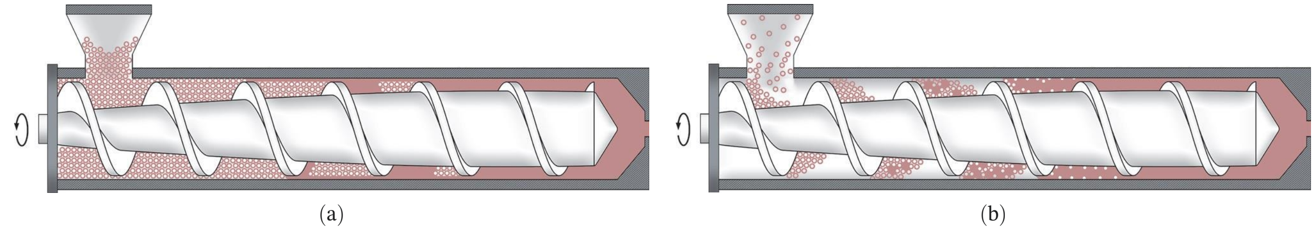

FIGURE 2 | (a) Flood fed vs. (b) starve fed single screw extruder schematic.

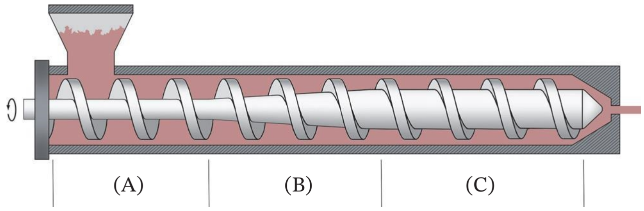

FIGURE 3 | Single screw extruder main zones schematic: A) feeding, B) compression, and C) metering zone.

designed to introduce raw material via a hopper and convey it forward as a solid bed. The compression zone (B) is where the channel depth gradually decreases; this reduction in volume compacts the material and facilitates the transition from a solid to a molten state. Finally, the metering zone (C) features a uniform and shallow channel that ensures a consistent melt flow and generates the pressure required for extrusion. Unlike twin-screw extruders which use modular intermeshing elements, this single-screw design mostly relies on fixed axial zones with varying channel depths to process the material.

At the feed inlet, materials enter as loose pellets or powder. In flood-fed single-screw extrusion, the solids quickly form a compact bed, and the screw channel becomes fully filled after an initial short distance. Under starve-feeding conditions, by contrast, the feed rate is kept below the conveying capacity, so the feed zone remains only partially filled, with material forming a shallow bed rather than a packed plug [18]. In compression zone, as the screw geometry transitions to shallower channels (in single-screw designs) or as conveying elements build pressure (in twin-screws), the material gradually goes from partially filled to fully filled. In flood-fed single-screw extrusion, a continuous fluid forms and fills the screw channel early, whereas in partially filled operation the "fill length" extends further down the screw [19]. Up to the point of fully filled section, the melting polymer exists in a two-phase form (solid and melt) with an air or vapor pocket, meaning this upstream melting section is only partially filled [16]. Once enough polymer has melted to occupy the channel space, the material becomes fully filled and pressure can then build rapidly.

In corotating twin-screw extruders operated under starve-fed conditions, the degree of fill varies along the screw. While conveying elements and some distributive mixing sections may operate under partially filled conditions, kneading blocks and other dispersive mixing elements are typically locally fully filled due to their higher flow resistance, which enables effective melting and dispersive mixing [20]. In contrast, while some starve-fed single-screw extruders may utilize mixing sections, these elements are typically designed to operate closer to a full state to ensure sufficient shear is applied to the melt.

Degassing sections explicitly require partially filled conditions. In vented extruders (single or twin-screw), upstream of the vent, a melt seal (a short fully filled zone) is often maintained to prevent backflow of gases; immediately under the vent opening, the screw channel depth is increased, or the screw elements are designed to reduce pumping, causing the melt to un-fill [21]. This creates a large free surface area of molten polymer exposed under the vent, enabling trapped air, moisture, or solvents to escape. Thus, partially filled regions are deliberately engineered in degassing zones to improve volatiles removal [22, 23].

Most analyses of the extrusion process have focused on classical flood-fed single screw extrusion, particularly on melt conveying and, later, solid conveying [24, 25]. This highlights the gap in research studies concerning the understanding of such complex dynamics that needs further investigation due to several challenges like irregular feed rates, pressure fluctuations, and material behavior. In this review, various methods used to study the effects of starve feeding on process performance and product quality, generally classified as experimental, computational, or analytical are examined. The primary focus is on starve-fed extrusion of polymeric materials; examples from food, pharmaceutical, or other extrusion fields are included only where they provide methodological insight that is directly applicable to polymer processing.

2 | Experimental Methods

Experimental investigations of starve-fed extrusion rely on a relatively consistent toolbox of methods, including screw pull-out/quench experiments to map melting profiles, in situ visualization (transparent barrels or optical sampling) to observe fill level and agglomerate dynamics, tracer-based residence time distribution (RTD) and mixing studies, and indirect monitoring via pressure, ultrasonic sensors, and specific mechanical energy (SME). In the following, each technique is first discussed in terms of starve-fed single-screw or screw-type-independent studies, and then corresponding developments for corotating and other twin-screw systems are highlighted.

Among these methods, screw pull-out experiments have been particularly influential for clarifying melting mechanisms under starve-fed conditions. In this method, the extruder is stopped at steady state, the barrel rapidly cooled, and the screw removed with solidified polymer attached. Analyzing cross sections reveals the melting profile along the screw. Originally developed to study flood-fed extrusion, it helped uncover the contiguous solid melting (CSM) mechanism, where a compact solid bed melts via a thin film at the barrel wall and an accumulating melt pool [26, 27]. However, when adapted to single screw starve-fed extrusion, the pull-out technique has revealed a completely different melting regime [28]. Instead of a long contiguous solid bed with a single melt pool at the downstream end, starved extruders exhibit a two-stage melting: conductive melting dominates in the upstream starved zones (solid particles heat up without forming a compacted bed) and further down where the screw eventually becomes fully filled, the remaining solids undergo a dispersed melting in the melt pool. In other words, the solid feed does not form one continuous plug, it breaks up early and forms agglomerates or chunks that melt individually once surrounded by melt [18, 19, 28].

Experimental screw pull-out evidence supports the researchers observation about the classical continuous solid bed which was largely absent in starve-fed single-screw extrusion [28]. For instance, in a starve-fed polyethylene extrusion study by Rathner et al. [29], screw pull-out samples were image-analyzed by adding a 2% carbon black masterbatch to the feed, which produced a color contrast between melted and unmelted polymer. The cross sections clearly distinguished white solid fragments from black-melted regions, allowing quantification of the fraction of material melted at each screw position. Those tests revealed a dispersed solid residue in the first half of the screw when operating at a 25% feed rate, confirming that solids were melting in a dispersed manner rather than as a continuous plug. Further experimental observations showed that pellets did not form a uniform bed in starved zones [24, 28]. Instead, they accumulated preferentially on the upstream side of the screw flights, the so-called active or driving side, rather than distributing evenly around the channel. This clustering behavior, revealed through physical screw pull-out inspections, provides key insight into where initial melting may begin. Since the pellets tend to hug the flight flanks on the active side, that is likely where the first melt films initiate due to better heat transfer from the barrel. To date, systematic screw pull-out studies under starve-fed conditions have been reported almost exclusively for single-screw extruders; analogous dead-stop studies in twin-screw machines generally focus on fully filled or flood-fed operation and are, therefore, not discussed in detail here. These screw pull-out studies therefore constitute the primary experimental evidence for the melting mechanisms in starve-fed single-screw extrusion that are discussed later in this review.

Such unusual single-screw setups, deliberately starving the feed and using color-coded polymers for pull-out analysis, have led to important conclusions. For starve-fed single-screw extrusion, starve-feeding significantly prolongs the melting process, but ultimately results in a more complete melt by the end of the screw. Dispersed solid fragments are more uniformly surrounded by molten polymer, which enhances heat transfer and reduces the risk of unmelted solid cores, especially in highly viscous or filled systems [18, 24, 28, 29]. Additionally, the melting mechanism shifts from the classical film-and-pool pattern to a mixed conductive/dispersed melting regime [30]. This illustrates how the screw pull-out method, combined with use of tracers and imaging, has been adapted to study partially filled single-screw extrusion scenarios that were historically hard to observe.

Because the screw pull-out technique, while insightful, is both destructive and time-intensive, researchers have developed alternative in situ visualization methods to study melting and mixing processes in real-time during starve-fed or partially filled extrusion. One prominent method involves incorporating transparent viewing windows directly into the extruder barrel. For single-screw extrusion under starve-fed conditions, one of the few direct windowed flow-visualization studies identified is the work of Bawiskar and White [31]. In that study, transparent barrel sections allowed direct observation of starve-fed solids conveying in a laboratory single-screw extruder. The authors reported forward Archimedean transport of pellets on the underside of the screw and visualized the gradual disappearance of starved regions as melting proceeded, providing rare direct evidence of solids transport and filling behavior in a starved single-screw. In the same work, the visualization concept was extended to a modular self-wiping corotating twin-screw extruder operated under starve-fed conditions, thus, bridging single- and twin-screw flow visualization under comparable operating modes.

Liu et al. [32] developed a specialized transparent corotating twin-screw extruder equipped with 13 toughened glass windows spaced along the barrel, allowing full visual access to the screw channel. Video recordings of LDPE and ABS extrusion under starved conditions revealed pellets forming agglomerates with molten outer layers, which gradually melted as they traveled downstream. These direct observations supported the creation of a melting model that accurately predicted the required screw length for complete melting, validating the model against experimental data across various operating conditions. Similarly, Yichong and Fuhua [33] utilized a windowed corotating twin-screw extruder designed to capture melting behavior under different filling levels. Their setup provided visual insights into intermeshing and conveying zones, enabling classification of distinct melting regimes, from rolling agglomerates at lower fill levels to continuous beds at higher fills. These observations led to a melting regime transition model, introducing the novel “variety conception,” where different melting patterns were recognized as distinct physical phenomena requiring separate analytical treatment.

Expanding on these techniques, Yu et al. [34] developed a visualization system used for a novel non-twin screw extruder featuring asymmetric screw speeds (2:1 ratio) intended to enhance mixing. A segmented transparent barrel coupled with a multiangle camera system enabled real-time capture of viscoelastic fluid flows, revealing complex interactions such as uneven fill degrees, the formation of material dams, and stretching flows between asymmetric screws. Their geometric modeling directly correlated captured images with fill level variations, explaining how screw asymmetry influenced distributive mixing and flow dynamics.

Bernardo et al. [35] complemented traditional visualization approaches with a hybrid in situ optical method specifically developed for studying mixing and flow behaviors under partially filled and starved conditions in corotating twin-screw extrusion. Rather than conventional transparent windows, their method involved extracting small melt streams through axial sampling ports placed along the kneading zone. Real-time analysis of turbidity and birefringence signals from these samples allowed the researchers to identify and map underfilled screw regions, providing detailed spatial profiles of fill levels. Additionally, Bernardo et al. [35] investigated mixing through RTD experiments. Injecting tracer pulses at the feed, they tracked optical signatures at multiple screw positions, deriving RTD curves. These experiments revealed shorter residence times at increased screw speeds, but demonstrated that mixing behavior varied significantly with screw geometry. In particular, the KB90-6 neutral kneading block was shown to yield prolonged residence times and enhanced dispersive mixing under starved conditions, with two mixing indices derived from RTD data: a dispersive index based on curve area and a distributive index based on variance (σ^2). This enabled comprehensive mapping of screw configurations under partially filled operations, clarifying the interplay of residence time, flow symmetry, and geometry in controlling mixing efficiency of corotating twin-screw extruders.

The critical role of RTD analysis in starve-fed single-screw extrusion is further illustrated by Rathner et al. [29], who performed fluorescent dye–based RTD measurements in a starve-fed single-screw extruder. Their study demonstrated that reducing feed rates significantly broadened RTD curves, more than doubling mean residence times at 25% feed compared to flood-fed conditions. This broader RTD profile improved melting and dispersion of additives, confirming enhanced mixing due to increased interfacial stretching in starve-fed extrusion.

For corotating twin-screw extruders, Lepschi et al. [36] applied fluorescence spectroscopy in a partially filled corotating twin-screw extruder, tracking axial RTD evolution by injecting tracers at low concentrations and monitoring intensity at multiple points. Their analysis showed limited impact of polymer viscosity under partially filled conditions, while screw geometry, specifically conveying element design, dominated RTD behavior. Left-conveying elements induced longer residence times with lower RTD polydispersity, while right-conveying elements promoted rapid material transitions, emphasizing screw design's crucial role in controlling fill behavior and mixing.

When direct optical access is impractical, ultrasonic sensing provides a screw-type-independent, noninvasive alternative for detecting filled vs. empty zones. Françla et al. [37] embedded piezoelectric sensors in the barrel wall of a single-screw extruder to monitor polymer presence and interface transitions during extrusion. Changes in ultrasonic signal amplitude and time-of-flight reliably indicated whether polymer was present in front of the probe and whether melt–air interfaces or phase boundaries were passing the sensing location. In principle, the same sensing concept can be applied to partially filled or starve-fed operation: when screw sections are starved, ultrasonic reflections from the polymer vanish or weaken, allowing detection of empty regions or fluctuating fill. Subsequent work has transferred similar ultrasonic probes to twin-screw extruders, especially for inline monitoring of blending quality and RTD. Although most published ultrasonic studies to date emphasize fully filled or melt-blending conditions, the technology is inherently suited to mapping the transition between starved and fully filled zones in both single- and twin-screw machines, particularly where optical access is impossible.

Pressure monitoring along the barrel provides another indirect method to assess fill levels and melting progression, particularly in starve-fed single-screw extruders. Lopez-Latorre and McKelvey [19] equipped a starve-fed single-screw extruder with multiple pressure transducers along the barrel. Their model predicted the axial location where pressure begins to rise as a function of screw fill, and they demonstrated practical benefits of controlled partial filling such as reduced energy consumption and improved process stability. In corotating twin-screw food extrusion, pressure profiles measured along the barrel have been used to interpret how feed rate, water content, and screw configuration affect filling behavior and energy dissipation [38]. Although many of these twin-screw studies consider highly filled or near-flood-fed conditions, their pressure data and modeling approaches are directly relevant when twin-screw extruders are deliberately run slightly starved to avoid excessive pressure, surging, or erratic flow. More generally, sudden local pressure increases in vented sections, whether in single- or twin-screw machines, can indicate undesirable vent flooding during devolatilization [22, 23], making pressure transducers a sensitive diagnostic for transitions between starved and fully filled regions.

Extrusion is energy-intensive, so energy efficiency is crucial in both single- and twin-screw systems. SME, defined as the work input from the extruder motor per unit mass processed, is widely used as a process metric, independent of screw type. Experimentally, SME is determined via motor power or torque combined with throughput measurement [39]. For starve-fed single-screw extrusion, Nastaj and Wilczyński [15] showed that specific power consumption in starve-fed mode is typically 10%–20% lower than in flood-fed operation, because reduced fill levels decrease material resistance and viscous drag in the upstream channel and help avoid unnecessary pressure build-up [14]. In starve-fed single-screw studies such as Rathner et al. [29], SME and residence time were analyzed together, revealing that even though starve feeding increases residence time and melt temperature, no significant degradation was observed, suggesting that improved melting and mixing can be achieved without sacrificing material integrity. In corotating twin-screw food extrusion and pharmaceutical hot-melt extrusion, SME is also a key control parameter [38–40]. However, most of these twin-screw SME studies are not explicitly framed as starve-fed, even though metered feeding and partially filled sections are common. The general trend remains that operating away from fully packed channels often reduces SME at equivalent throughput, provided that melting and mixing remain adequate.

Despite the significant insights gained from these experimental methods, each technique has practical limitations. Screw pull-out experiments are destructive and limited in time resolution; windowed visualization requires specialized hardware and often restricts operating pressures; optical RTD methods and ultrasonic sensing can be limited by signal interpretation and calibration; pressure/SME measurements, while robust, provide only indirect information about the local morphology of solids and melt. Moreover, systematic starve-fed studies exist only for a subset of screw geometries and operating conditions, particularly for twin-screw extruders. Therefore, complementary modeling approaches are essential: they enable detailed exploration of internal phenomena such as melting mechanisms, solid–melt coexistence, and transitions between partially and fully filled regions that are challenging to capture experimentally. Modeling, thus, enhances the analysis of starve-fed extrusion by providing predictive power, allowing the study of conditions beyond experimental reach, and facilitating optimization of both single- and twin-screw processes, as discussed in Section 3 (Modelling Techniques).

3 | Modeling Techniques

Modeling starve-fed extrusion presents unique challenges due to the presence of partially filled screw regions, especially near the feed zone. This significantly alters the thermal, flow, and pressure characteristics along the screw, needing specialized models that can capture the dynamics of partially filled regions and fill-length transitions.

Early single-screw extrusion models, developed by McKelvey, Tadmor, and Klein, laid the foundation for screw flow theory under simplified, fully filled assumptions [41–44]. However, starve-fed extrusion processes deviate from these idealized conditions. In starve-fed models, the extruder is conceptually divided into two distinct regions: a starved zone, where the channel is only partially filled and no pressure builds up, and a flooded zone, where material fills the channel completely and pressure begins to rise. In the starved section, melting is primarily driven by heat conduction into loosely packed granules. Once it gets fully filled, the system transitions into a pressurized state governed by classical melting mechanisms, such as those proposed by Tadmor [45]. Tadmor developed the first rigorous melting model, known as the Tadmor melting mechanism, which assumes a solid polymer bed persists along the screw's pushing side while a thin melt film forms at the interface with the heated barrel [44]. As the screw rotates, the melt film is sheared off and accumulates as a melt pool on the opposite side. The model divides the cross-section into three regions: solid bed, melt film, and melt pool, and uses an energy balance, accounting for barrel heat conduction and viscous dissipation, to predict the melting rate of the solid bed.

Unlike in fully flooded models, the fill length (the axial location where the channel becomes fully occupied) is not known beforehand. Instead, it must be determined as part of the model solution, often through iterative methods. Analytical treatment of this transition is difficult, as the free surface in the starved zone depends on complex and coupled phenomena including material rheology, operating conditions, and screw geometry. Early efforts to describe this transition were made by researchers such as Lopez-Latorre, McKelvey, and Isherwood, who highlighted how low feed rates delay melting and shorten the pressurized region, affecting both output and thermal stability [14, 19].

Analytical models for starve-fed extrusion typically begin from a known feed rate, unlike flood-fed approaches that compute output from screw geometry and speed. In this inverse setup, the model calculates how far along the screw the material travels before the drag flow exceeds the imposed feed rate, this point marks the start of the flooded region. Some early analytical frameworks estimated this fill point by comparing the screw's theoretical drag capacity to the supplied throughput [46]. Beyond that point, pressure builds and conventional pressure-melting equations are applied.

However, purely analytical approaches often fall short in capturing real starve-fed behavior, due to uncertainties in fill level, free surface shape, and local melting dynamics. To address these gaps, empirical observations have been integrated into analytical models. For instance, Potente [47] introduced the concept of a "melting delay" zone, an empirical correction acknowledging that melting typically initiates some distance from the hopper. This helped refine melting models to better match experimental observations [47]. In this approach, the initial melting is delayed due to reduced thermal penetration into the loosely packed solids, and the melt film thickness evolved along the screw. Similarly, purely empirical models have been used in starve-fed extrusion process scale-up and optimization studies to identify how reduced filling influences output and quality. For example, Underwood [48] applied design-of-experiments to extrusion and used regression to find optimal conditions, an approach that could be extended to starved conditions by including feed rate as a factor.

The most significant developments in starve-fed modeling came with the emergence of global and zone-based models, which simulate the entire extrusion process by integrating submodels for solids conveying, melting, and melt pumping. Wilczyński et al. [16] played a key role here, developing comprehensive simulation tools like SSEM-Starve (an extension of their Single-Screw Extrusion Model for starved feeding) and later the Global Screw Extrusion Model (GSEM). These were among the first fully predictive models for starve-fed single screws, capable of handling partially filled conditions. Crucially, they implement a two-stage melting mechanism in line with Tadmor's framework: in the starved (partially filled) zone, polymer granules accumulate along the screw's pushing flight and melting is governed primarily by heat conduction from the barrel, forming a thin melt film; once the screw channel becomes fully filled, the process shifts into the classic Tadmor-type melting regime dominated by viscous shear dissipation and melt pool growth. This approach captured the distinctive melting behavior under starved conditions, a delayed melt onset followed by a rapid melting once flow becomes pressurized, which earlier one-stage models could not fully describe.

Building on these global frameworks, Nastaj and Wilczyński recently proposed a dedicated computational scale-up strategy for both flood-fed and starve-fed single-screw extrusion. In their approach, the global model (GSEM and related variants) is embedded in an optimization loop, where scale-up is formulated as a multiobjective problem: The target extruder (different diameter or length) is required to reproduce selected process descriptors of a reference machine, such as melt temperature at the die, pressure and fill-factor profiles, plasticating length, and SME. A genetic-algorithm-based procedure automatically adjusts screw geometry and operating conditions to minimize deviations between simulated reference and target profiles, yielding scale-up solutions that respect both thermal and mechanical similarity under metered (starved) as well as fully flooded conditions [49]. This work follows a long line of optimization-oriented contributions by Covas and Gaspar-Cunha [50], who pioneered the use of evolutionary algorithms and other metaheuristics for extrusion. For plasticating single-screw extruders, they developed optimization procedures to select screw design and operating conditions under multiple, often conflicting criteria such as throughput, melt quality, and energy consumption, by coupling global extrusion models with genetic algorithms. For corotating twin-screw extruders, they extended these ideas to optimize not only the operating conditions but also the detailed screw configuration, using multiobjective evolutionary algorithms to balance mixing performance, residence time, and SME. They further proposed optimization-based methodologies for extrusion scale-up, in which the geometry and operating conditions of a larger line are chosen so that key process variables of a laboratory extruder (temperature, pressure, SME, and plasticating length) are reproduced as closely as possible [50, 51].

A key feature of these global models is their inverse (backward) computation scheme for determining the fill point. In starve-fed operation the throughput is fixed by the feeder, but the axial position where the screw transitions from partially filled to fully filled is initially unknown. To resolve this, global simulators start calculations from the die end backward: given the known output flow, they compute the pressure profile upstream along the screw until it drops to zero, marking the onset of starvation (the fill length) [15]. Once this fill point is found, the simulation of the upstream starved region proceeds forward from the hopper to ensure that melting and mass continuity conditions are satisfied at the transition. This backward-forward iterative algorithm (often called an "inverse" approach) is necessary because the usual one-to-one relationship between pressure and flow breaks down in partially filled sections. By integrating all zones, solids conveying, a possible melting delay zone near the feed, the melting section, melt conveying, and the die, into a single model, the GSEM and similar frameworks can predict pressure, temperature, solid bed fraction, and screw fill profiles with much higher fidelity than separate analytical equations. For example, GSEM simulations clearly show the pressure dropping to zero at the fill point in starved operation and reveal the two distinct melting stages with a conduction-driven region followed by a viscous dissipation region. These outcomes align with experimental observations and confirm that starve feeding shifts the melting mechanism toward barrel-conduction in the early screw length (with delayed pressurization). The ability to compute the fill length as part of the solution, rather than assume it, is a major advantage of global models and has proven essential for accurately modeling starved extrusion.

Importantly, twin-screw extruders, which by design are usually starve-fed, have also benefited from global modeling advancements. Wilczyński et al. [52] applied similar zone-based modeling to closely intermeshing counter-rotating twin-screw extruders, using an inverse computation approach analogous to the single-screw case. (Others did the same for corotating twin-screws around the same time [53–55].) These early twin-screw models were somewhat simplified, they typically assumed a single melting stage and often required the user to predefine where along the screws the material fully filled the intermeshing channels. Nevertheless, they demonstrated the feasibility of predicting partial fill behavior in twin-screw machines. Building on that foundation, researchers have since developed more sophisticated twin-screw starve-fed models that incorporate two-stage melting and automatically solve for the fill length, much like the single-screw global models. For corotating twin-screw extruders, Covas and Gaspar-Cunha [50] proposed a dedicated scaling-up methodology that couples a global plasticating model with multiobjective evolutionary optimization. In their approach, the target (scaled) extruder geometry and operating conditions are chosen such that key process quantities of a reference machine, such as melt temperature, residence time, SME, and pressure profile, are matched as closely as possible. This model-based scale-up framework allows systematic evaluation of trade-offs between throughput, energy input and mixing performance when transferring formulations from lab-scale corotating twin-screw lines to industrial scale [56, 57]. More recently, Nastaj and Wilczyński [58] used their validated counter-rotating twin-screw model (TSEM) as the core of a computer-based scaling-up system. In this system, each scale-up criterion (for example, melt temperature at the die, relative plasticating length, or full axial distributions of temperature, pressure, solid bed fraction, and fill factor) is treated as an objective function in a genetic-algorithm-based procedure (GASES_TWIN). By simulating both a reference and a target machine under metered (starved) feeding, the algorithm searches screw configurations and operating conditions that minimize the differences between their profiles, providing a systematic methodology for scaling up counter-rotating twin-screw extrusion [58]. This underscores how global modeling of starved extrusion isn't just of academic interest, it has direct practical implications, allowing engineers to fine tune feeding rates and screw designs to achieve optimal performance. A comprehensive overview of optimization methodologies for polymer extrusion, including these and many other contributions to single- and twin-screw systems, can be found in the by Gaspar-Cunha et al. [59].

In summary, modeling starve-fed extrusion requires specialized frameworks that capture nonpressurized flow, conduction-driven melting, and the axial transition to full filling. While early analytical models offered useful insights, it is the integration of empirical findings and global zone-based simulations that has enabled accurate, predictive modeling of starved operation. These models are now essential tools for screw design, process optimization, and have already been embedded in computer-aided scale-up methodologies for single-screw, corotating and counter-rotating twin-screw extruders, without resorting to full 3D simulation. However, they do depend on the quality of the underlying submodels and often require some calibration. With the advent of more powerful computation, some aspects of global models are now being augmented or replaced by numerical simulation (computational fluid dynamic/discrete element method [CFD/DEM]) as discussed next; still, global models remain invaluable for quick analysis and optimization studies (including screw design via trialing different zone lengths virtually).

4 | Numerical Simulation Techniques

As extrusion processes have grown more complex (especially with the adoption of starve feeding, novel materials, and advanced screw geometries), traditional analytical models alone have become insufficient for capturing the full range of physical phenomena involved. Numerical simulation techniques have, therefore, emerged as essential tools, offering detailed, physics-based insight into flow, heat transfer, phase transitions, and particle behavior in extrusion systems. These simulations, including CFD, DEM, and smoothed particle hydrodynamics (SPH) approaches, allow researchers to investigate regions that are analytically difficult. For starve-fed single-screw extruders, current numerical tools can describe solids conveying and partially filled melt flow with considerable detail on laboratory and pilot scales, although fully resolved simulations of industrial screws including melting and devolatilization remain rare. For corotating twin-screw extruders, high-fidelity simulations are typically limited to individual elements or short sections (e.g., feed, conveying, or kneading blocks), and often treat either the solid phase (DEM) or the melt phase (CFD/SPH) in isolation. Fully 3D, transient simulations of entire starve-fed twin-screw lines, including solids conveying, melting, and multiphase flow, are still beyond routine practice. In the following, the main numerical techniques are discussed explicitly with respect to the type of extruder and process region they can currently address.

4.1 | CFD Simulations

CFD provides deep insight into the fluid dynamics of partially filled regions, where melt coexists with air, and the fill level evolves along the screw. Unlike flood-fed cases that often assume axial periodicity, starve-fed simulations require modeling the entire screw length to capture the dynamic fill length and transitions from partially to fully filled zones.

A fundamental challenge in CFD of screw extruders is handling the moving screw and its relative motion against the barrel. One common strategy is to use a rotating reference frame: The screw is kept stationary in the model while a tangential velocity is imposed on the barrel, mimicking screw rotation. This avoids deforming the mesh and allows a steady-state solution in the screw frame. Alternatively, sliding mesh or arbitrary Lagrangian–Eulerian (ALE) techniques explicitly move or remesh the domain as the screw turns. These approaches allow the screw surface to physically move relative to the fluid, avoiding geometric approximation of the helix [9, 60, 61]. Such techniques are now routinely applied to single-screw geometries and, with greater meshing effort, to localized regions of corotating twin-screw extruders (e.g., one or a few elements), but full-machine twin-screw simulations remain very demanding. While periodic boundary conditions can be applied to simulate a single screw channel repeating infinitely (useful for fully filled metering sections), this is not valid under starve-fed conditions [62]. In starve feeding the flow is not axially periodic, there is a finite filled length after which the channel runs partially empty. Therefore, CFD models of starve-fed extruders typically must simulate the entire screw (or a long enough section from feed to die) to capture where the flow transitions from partially filled to fully filled.

In starve-fed simulations, representing the free surface between the polymer melt and air in the partially filled region is crucial. Most studies employ a volume-of-fluid (VOF) or similar multiphase method to track this moving interface [63–65]. Using VOF, researchers have simulated partially filled single-screw extruders by initializing the flow so that the fluid occupies only part of the channel and then allowing the material to advance downstream. Such simulations are inherently transient, as the screw turns and material is conveyed, the free-surface interface moves until a steady fill length is established. These CFD models can predict the fill length (the point along the screw where the channel transitions from starved to fully filled) and the shape of the melt pool in the starved region. Lübke and Wünsch [66], for example, demonstrated a 3D VOF–based CFD model of a partially filled single-screw extruder, solving only the liquid melt phase with appropriate boundary conditions at the free surface. By comparing a simplified 2D "unwrapped" screw channel and a full 3D screw, they showed how the degree of filling and material properties influence the free-surface position and fill length. These early simulations laid the groundwork for understanding starved flow behavior in single-screw extruders.

Recent CFD studies have explicitly examined the differences between assuming a flood-fed (fully filled) vs. starve-fed screw. Olofsson et al. [67] introduced a comprehensive 3D CFD model with free-surface tracking for a starve-fed single-screw extruder, using a pulse-tracer method to determine the RTD. Their results quantified the impact of accounting for partial filling instead of assuming a flooded screw, showing that neglecting the free surface can lead to significant errors in predicting the mean residence time. This underscores that including the entire partially filled flow in simulations is important, and that simplifying a starved single-screw extruder as if it were fully filled can misestimate performance. In a lab-scale starved extruder, the CFD model was able to pinpoint the fill length and showed how RTD broadens under starved conditions compared to the flooded assumption. Olofsson et al. [68] found, for instance, that a lower feed rate (more severe starvation) led to a wider RTD and higher overall shear experienced by the material, whereas a higher fill level yielded a narrower RTD and less shear. This indicates that partial filling fundamentally changes the flow: At lower fill levels, the material experiences more exposure to air and more intermittent flow patterns, resulting in greater shear and mixing intensity in the screw channel. Indeed, starve-fed CFD visualizations often reveal enhanced distributive mixing due to the presence of a free surface and secondary flows, the material can circulate in the partially filled space in ways not possible when the channel is completely full. These chaotic advection patterns help explain why processors sometimes observe improved mixing uniformity under starve-fed operation.

To manage computational cost, some authors have explored data driven approaches such as reduced-order models informed by CFD. In a follow-up study, Olofsson et al. [68] validated their full 3D starve-fed CFD model against an industrial extruder with sensors, achieving good agreement (within ~6%–11% error in RTD predictions after accounting for slight screw wear). They then developed a simplified 2D convection-diffusion model as a reduced-order representation of the flow, using the velocity field from the 3D CFD and calibrating a diffusion term to match the RTD curve. The 2D model reproduced the key features of the RTD with only minor discrepancies, demonstrating that it is possible to bridge detailed CFD and fast prediction in starve-fed systems. Such approaches are promising for real-time process optimization: the high-fidelity CFD captures where and how the screw fills, and the reduced model makes rapid predictions based on that information.

Overall, CFD simulations give unique insight into partially filled screw extrusion that traditional analytical models cannot easily provide. They can predict how the fill level varies along the screw for given throughput and screw speed and how that fill level in turn affects pressure generation, mixing, and thermal history. Notably, most earlier simulation work focused on fully filled extruders. Dedicated CFD studies of starve-fed single screws have been relatively limited until recently, due in part to the complexity of free-surface and moving-boundary simulation. With modern software and hardware, however, these challenges are being overcome. The primary limitations of CFD in this area remain the high computational cost and complexity of setting up multiphase, moving boundary flows. Solving the full 3D, transient free-surface problem for a long screw is time-consuming and resource-intensive. For single-screw extruders, such starve-fed CFD models are now well established at research scale, whereas for corotating twin-screw extruders comparable starve-fed CFD studies are still short and are typically restricted to short sections or simplified geometries rather than entire machines. Nonetheless, ongoing improvements in numerical algorithms (e.g., more efficient mesh handling and advanced VOF techniques) and ever-increasing computational power continue to extend the reach of CFD.

4.2 | DEM

The DEM has emerged as a key tool for studying solid conveying behavior in extrusion systems, especially in the partially filled (starve-fed) regions where pellets or powder are loosely packed and the assumptions of a continuum breakdown. In practice, DEM has been applied most extensively to the feed and solids-conveying sections of starve-fed single-screw extruders, and to a lesser extent to the solids supply and prefeeding devices of corotating twin-screw extruders. DEM treats each pellet as an individual entity and tracks contact forces, collisions, and heat transfer as they move through the screw channel. Unlike continuum models, DEM naturally captures the granular nature of the solids and offers direct insights into fill level, bed formation, and particle transport in starve-fed screws.

Early DEM studies by Moysey and Thompson [69, 70] applied full 3D simulations to the feed section of a starve-fed single-screw extruder, explicitly showing that pellets did not form a continuous bed but instead accumulated preferentially along the pushing side of the screw flight. Their work revealed recirculatory particle motion, stagnation zones, and the influence of wall friction on conveying, all key features of starved flow that are inaccessible to continuum-based models. They also showed how screw speed and particle shape affected axial motion, leading to fill fractions below 50% in some starve-fed cases.

DEM has provided a much better understanding of how solid pellets enter the screw and begin to move forward. It has verified the classic assumption from Darnell and Mol that wall friction vs. particle friction governs whether the solids stick to the screw or barrel. By assigning realistic friction coefficients to pellet–pellet and pellet–wall interactions, DEM simulations have shown whether the solid bed tends to adhere to the screw (as assumed in analytical models) or slip. Studies using DEM have explored how changes in screw speed or barrel roughness affect the mass flow of solids into the machine. These simulations help address issues like feeding inconsistencies and starvation onset. For instance, DEM can simulate a starved feed by simply reducing the number of particles supplied per unit time and then observing how far into the screw the particles spread. If the feed rate is low, DEM will show pellets filling only a portion of each channel before falling behind the flight, directly visualizing the starved condition [71].

One particular strength of DEM is in geometrically complex screws or feeding devices. Grooved feed sections (often used to increase solids conveying capacity) have been studied with DEM, confirming how grooves affects the solids and prevent them from slipping [72–75]. Moreover, DEM can capture the effect of very high screw speeds where centrifugal forces might fling particles and reduce conveying efficiency, which can cause starve feeding, a regime difficult for continuum models. Leßmann et al. [76] simulated solids feeding in a smooth-barrel extruder across various feed-section (hopper/pocket) geometries at screw speeds up to 900 rpm. They showed that only feed-section designs that rapidly fill (fully charge) the screw channel can sustain a roughly linear increase in throughput with speed even at these high rpms. From these simulation results, Leßmann et al. [76] used dimensional analysis to derive a predictive model of solids throughput as a function of feed-zone geometry and process parameters. Similarly, Trippe and Schöppner [77] addressed the challenges of high screw speeds and back pressure in starve-fed extruders through DEM simulations. They extended their simulations to screw speeds up to approximately 2000 rpm and included an adjustable back pressure at the die to investigate its influence on the feeding zone. Their DEM results showed that at very high screw speeds the screw channel can remain only partially filled even when back pressure is present, deviating from the traditional expectation of a completely filled (plug) solid bed under hopper-backup conditions. In other words, beyond a certain screw speed, pellets could not be captured fast enough by the rotating flight, leading to persistent starved regions despite the tendency of back pressure to push material backward. They quantified these effects and incorporated them into an improved solids-conveying model. They developed a mathematical model that accounts for the reduced filling degree at high speeds and the associated pressure build-up in the feed zone, expanding the Darnell–Mol theory to these extreme conditions.

In summary, DEM simulations provide a microscopic- and particle-level view of starve-fed extrusion. It excels in capturing the feed and solids transport processes, predicting phenomena like starvation (by visualizing how incomplete filling occurs) and providing inputs (like solid residence time and fill fraction along the screw) to other models. The trade-off is computational intensity. Simulating millions of particles (which a full-scale extruder hopper might contain) is very expensive, so DEM studies often use a scaled-down model or only simulate a portion of the flow. However, despite the valuable work done in recent years, the models are partly dependent on empirical model parameters. In both single- and twin-screw systems, DEM is, therefore, typically restricted to the upstream solids-conveying region, while downstream melting and melt conveying must be described by continuum methods. However, a key limitation of DEM is that its application is typically restricted to the feed section, as it cannot model the phase transition that occurs during melting. This limitation can be addressed by coupling DEM with CFD, allowing accurate simulation of both granular flow in the feed zone and fluid dynamics in the melting and melt conveying regions.

4.3 | SPH

SPH is a Lagrangian and mesh-free CFD technique that has proven especially suitable for simulating partially filled or starve-fed screw extruders. Unlike grid-based CFD, SPH does not require mesh deformation to handle moving boundaries. It naturally represents free surfaces, a critical advantage when modeling the gas-melt interface in starve-fed flow. So far, SPH has been used predominantly for corotating twin-screw elements operated under starve-fed or partially filled conditions, with fewer but conceptually similar applications to single-screw geometries.

SPH simulations represent the polymer melt as a set of discrete fluid particles. In starve-fed systems, this allows fluid particles to occupy only a portion of the screw channel, while empty space inherently represents the air or void region. This enables the direct capture of fill level, melt pool evolution, and pressure behavior under starvation, without imposing artificial boundaries or assumptions about flow continuity. Recent work by Eitzlmayr, Khinast, and Matic applied SPH to starve-fed twin-screw extruder elements, demonstrating that SPH accurately resolved flow fields even when the channel was only partially filled [78, 79]. Their simulations showed how chaotic mixing patterns and RTDs differed significantly between flooded and starved conditions-driven largely by the presence of the free surface and low pressure.

In more advanced simulations, Dong et al. [80] used SPH to model non-Newtonian melt behavior in starved screw flows. Their results showed how screw-barrel clearance and fluid rheology interact under partial fill, revealing that shear-thinning fluids experience greater asymmetry and shift in flow patterns when the channel is not fully occupied [80]. SPH particles allowed the researchers to track residence time, mixing, and interface deformation dynamically, confirming that fill level is a dominant variable in shaping flow behavior. These studies illustrate that SPH can capture starve-fed flow features in both single- and twin-screw configurations once the corresponding 3D geometry is resolved.

In addition, SPH's particle-based nature makes it ideal for visualizing mixing and distributive flow in starved extruders. By tagging SPH particles with scalar tracers, researchers can directly observe stretching, folding, and dispersion under chaotic advection in the partially filled domain, providing a useful tool for analyzing mixing in pharmaceutical or reactive extrusion.

In summary, SPH offers a robust and intuitive approach for simulating starved extrusion, capturing complex flow regimes with free surfaces, incomplete filling, and strong shear gradients, conditions where traditional CFD often struggles. It is especially effective in modeling conveying and mixing behavior in screws with low fill levels or complex features, without the need for remeshing or artificial constraints. For single-screw extruders, SPH is attractive where strong three-dimensional effects arise (e.g., mixing sections or special geometries), while for corotating twin-screw extruders it currently provides one of the most practical ways to resolve partially filled and starve-fed flow in intermeshing regions with an explicit free surface.

Taken together, these numerical techniques now allow starve-fed single-screw extruders to be analyzed by combining DEM for solids conveying with CFD or SPH for the partially filled melt, at least over significant portions of the machine. For corotating twin-screw extruders, state-of-the-art simulations typically focus on individual elements or zones, DEM for solids intake and preconditioning, and CFD or SPH for local melt flow and mixing, while fully coupled, end-to-end simulations of industrial starve-fed twin-screw lines remain a longer-term research goal.

5 | Conclusion

Starve feeding represents a significant advancement in screw extrusion technology, fundamentally altering the process dynamics, product quality, and energy efficiency compared to traditional flood-fed operations. This review has summarized the current state of knowledge on starve-fed extrusion with explicit distinction between single-screw and corotating twin-screw extruders and between solids-conveying, melting, and fully filled melt-conveying regions.

On the experimental side, screw pull-out and quench studies, limited but powerful window visualization, RTD measurements, mixing assessments, ultrasonic sensing, and pressure/SME monitoring collectively show how starve feeding changes melting, mixing, and pressurization. For single-screw extruders, screw pull-out and RTD experiments provide the clearest physical picture. Starve feeding extends the melting length and replaces the classical contiguous solid bed with a mixed conductive/dispersed melting regime, which can improve melt homogeneity and mixing uniformity when properly controlled. For corotating twin-screw extruders, experimental insights into starve-fed behavior come mainly from local visualization, RTD and mixing studies in selected elements, and pressure/SME data; systematic pull-out or whole-machine studies under starved conditions are still rare.

Analytical and empirical models developed for flood-fed extrusion have been adapted to account for partially filled regions, particularly in starve-fed single-screw extrusion. Global models and composite melting descriptions can now predict fill lengths and melting profiles with reasonable accuracy, but often require iterative or hybrid formulations and calibration against experimental data. For twin-screw systems, modeling has focused predominantly on fully filled or near-flood-fed conditions, and only a limited number of approaches explicitly treat starve-fed operation or axially varying fill levels.

Advanced numerical simulation techniques have opened new avenues for studying starve-fed extrusion. CFD with free-surface tracking can describe partially filled melt flow in single-screw extruders and, to a growing extent, in localized twin-screw geometries, providing detailed information on fill length, RTD, mixing, and thermal history. DEM has proven particularly valuable for solids conveying and the onset of starvation in feed zones, especially in single-screw machines and complex feed geometries, while SPH offers a mesh-free alternative well suited to partially filled, intermeshing twin-screw elements with strong free-surface effects. In practice, however, these tools are still used in a segmented fashion: DEM for upstream solids, CFD or SPH for downstream melt, and typically only over limited sections rather than entire industrial lines.

Despite these advances, several key research needs remain. Comprehensive experimental datasets under well-characterized starve-fed conditions, especially for corotating twin-screw extruders, are required to validate and refine models and simulations. Coupled DEM–CFD/SPH frameworks should be further developed to seamlessly describe the transition from granular solids to melt without prescribing the melting pattern a priori. Improved global models that embed starve-fed behavior into design tools, together with real-time monitoring and control strategies based on pressure, SME, and inline sensing, are needed to make starve feeding more predictable and robust at industrial scale. Addressing these topics will significantly enhance the industrial applicability and economic viability of starve-fed extrusion across polymers, foods, pharmaceuticals, and other complex formulations.

Author Contributions

Mohammad Pourhosseinian: conceptualization, methodology, writing – original draft. **Bahram Haddadi:** conceptualization, methodology, supervision, writing – review and editing.

Acknowledgments

The authors acknowledge financial support through the COMET Centre CHASE, funded within the COMET – Competence Centers for Excellent

Technologies programme by the BMK, the BMDW and the Federal Provinces of Upper Austria and Vienna. The COMET programme is managed by the Austrian Research Promotion Agency (FFG). Special thanks are extended to Christian Marschik for his valuable support and contributions. His insights and encouragement were greatly appreciated throughout this work. The authors acknowledge TU Wien Bibliothek for financial support through its OpenAccess Funding Programme. The authors used artificial intelligence (AI) tools only for grammar correction and language improvement. No scientific content, data analysis, interpretation, or conclusions were generated by AI.

Funding

This study was funded by TU Wien Bibliothek. Open Access funding provided by Technische Universitat Wien/KEMÖ.

Disclosure

The authors take full responsibility for the content of this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data are available upon request.

References

1. J. L. White, *Twin Screw Extrusion: Technology and Principles* (Hanser, 1990).

2. D. R. Gray and R. V. Chinnaswamy, "Role of Extrusion in Food Processing," in *Food Processing*, (Elsevier, 1995): 241–268.

3. G. Kvam-Langelandsvik, K. G. Skorpen, J. C. Werenskiold, and H. J. Roven, "Review of Metal Screw Extrusion: State of the Art and Beyond," *Metals* 14, no. 10 (2024): 1117.

4. J. M. Harper, *Extrusion of Foods* (CRC Press, 2019).

5. C. Rauwendaal, *Polymer Extrusion* (Hanser Publishers, 2014).

6. N. Yadav, D. Suvedi, A. Sharma, et al., "Extrusion Technology in Food Processing: Principles, Innovations and Applications in Sustainable Product Development," *Food and Humanity* 5 (2025): 100672.

7. C. Abeykoon, A. L. Kelly, J. Vera-Sorroche, E. C. Brown, and P. D. Coates, "Monitoring and Modelling of the Energy Consumption in Polymer Extrusion," in *2014 European Control Conference (ECC)*, (IEEE, 2014): 1030–1035.

8. T. Goto, S. Ashihara, M. Kato, I. Okajima, and T. Sako, "Use of Single-Screw Extruder for Continuous Silane Cross-Linked Polyethylene Recycling Process Using Supercritical Alcohol," *Industrial & Engineering Chemistry Research* 51, no. 19 (2012): 6967–6971.

9. E. Delvar, I. Oliveira, M. S. C. A. Brito, et al., "Literature Review on Single and Twin-Screw Extruders Design for Polymerization Using CFD Simulation," *Fluids* 10, no. 1 (2025): 9.

10. M. M. Crowley, F. Zhang, M. A. Repka, et al., "Pharmaceutical Applications of Hot-Melt Extrusion: Part I," *Drug Development and Industrial Pharmacy* 33, no. 9 (2008): 909–926.

11. D. Bigio, K. Cassidy, M. Dellapa, and W. Baim, "Starve-Fed Flow in Co-Rotating Twin Screw Extruders," *International Polymer Processing* 7, no. 2 (1992): 111–115.

12. B. Padmanabhan, C. Chincholi, S. Jayanth, and S. Steer, "Special Intake Elements to Overcome Feed Limitation in Corotating Twin-Screw Extruders -Design Features and Experimental Results," (2009).

13. A. C.-Y. Wong, T. Liu, and F. Zhu, "Solid Transportation in the Feeding Zone of Intermeshing Co-Rotating Twin-Screw Extruders," *Journal of Polymer Research* 7, no. 3 (2000): 135–147.

14. D. P. Isherwood, R. N. Pieris, and J. Kassatly, "The Effect of Metered Starve Feeding on the Performance of a Small Extruder," *Journal of Engineering for Industry* 106, no. 2 (1984): 132–136.

15. A. Nastaj and K. Wilczyński, "Optimization for Starve Fed/Flood Fed Single Screw Extrusion of Polymeric Materials," *Polymers* 12, no. 1 (2020): 149.

16. K. Wilczyński, A. Nastaj, A. Lewandowski, K. J. Wilczyński, and K. Buziak, "Fundamentals of Global Modeling for Polymer Extrusion," *Polymers* 11, no. 12 (2019): 2106.

17. K. J. Wilczyński, "Experimental and Theoretical Study on Screw Filling in Starve Fed Single Screw Extruders," *International Polymer Processing* 33, no. 2 (2018): 171–179.

18. M. R. Thompson, G. Donoian, and J. P. Christiano, "Melting Mechanism of a Starved-Fed Single-Screw Extruder for Calcium Carbonate Filled Polyethylene," *Polymer Engineering & Science* 40, no. 9 (2000): 2014–2026.

19. L. Lopez-Latorre and J. M. McKelvey, "Melting and Pressurization in Starve Feed Extrusion," *Advances in Polymer Technology* 3, no. 4 (1984): 355–364.

20. J. White, *Screw Extrusion: Science and Technology* (Hanser Verlag, 2002).

21. K. Kohlgrüber and M. Bierdel, *Co-Rotating Twin-Screw Extruder: Fundamentals, Technology, and Applications* (Hanser, 2008).

22. M. Ohara, Y. Sasai, S. Umemoto, et al., "Experimental and Numerical Simulation Study of Devolatilization in a Self-Wiping Corotating Parallel Twin-Screw Extruder," *Polymers* 12, no. 11 (2020): 2728.

23. N. H. Wang, T. Sakai, and N. Hashimoto, "Modeling of Polymer Devolatilization in a Multi-Vent Screw Extruder," *International Polymer Processing* 10, no. 4 (1995): 296–304.

24. K. Wilczyński, A. Nastaj, and K. J. Wilczyński, "Melting Model for Starve Fed Single Screw Extrusion of Thermoplastics," *International Polymer Processing* 28, no. 1 (2013): 34–42.

25. C. Marschik, W. Roland, and T. A. Osswald, "Melt Conveying in Single-Screw Extruders: Modeling and Simulation," *Polymers* 14, no. 5 (2022): 875.

26. A. La Gala, R. Fiorio, D. V. A. Ceretti, M. Erkoç, L. Cardon, and D. R. D'hooge, "A Combined Experimental and Modeling Study for Pellet-Fed Extrusion-Based Additive Manufacturing to Evaluate the Impact of the Melting Efficiency," *Materials* 14, no. 19 (2021): 5566.

27. M. Dörner, C. Marschik, V. Schöppner, and G. Steinbichler, "Development of an Analytical Model to Describe the Disperse Melting in Wave-Dispersion Screws," *Polymers* 12, no. 4 (2020): 946.

28. K. J. Wilczyński, A. Lewandowski, and K. Wilczyński, "Experimental Study of Melting of Polymer Blends in a Starve Fed Single Screw Extruder," *Polymer Engineering & Science* 56, no. 12 (2016): 1349–1356.

29. R. Rathner, D. Tranchida, W. Roland, et al., "Properties of Starve-Fed Extrusion on a Material Containing a VHMWPE Fraction," *Polymers* 13, no. 6 (2021): 944.

30. F. Knaup, F. Brüning, and V. Schöppner, "Improvement in an Analytical Approach for Modeling the Melting Process in Single-Screw Extruders," *Polymers* 16, no. 22 (2024): 3130.

31. S. Bawiskar and J. L. White, "Solids Conveying and Melting in a Starve Fed Self-Wiping Co-Rotating Twin Screw Extruder," *International Polymer Processing* 10, no. 2 (1995): 105–110.

32. T. Liu, A. C.-Y. Wong, and F. Zhu, "Prediction of Screw Length Required for Polymer Melting and Melting Characteristics," *International Polymer Processing* 16, no. 2 (2001): 113–123.

33. G. Yichong and Z. Fuhua, "Study of the Different Flow Patterns in the Melting Section of a Co-Rotating Twin-Screw Extruder," *Polymer Engineering & Science* 43, no. 2 (2003): 306–316.

34. H. Yu, B. Xu, H. Wu, L. Turng, and M. Wang, "A Visualization of Flow Patterns of Viscoelastic Fluid Partially Filled in a Co-Rotating Nontwin Screw Extruder," *Polymer Engineering and Science* 59, no. S1 (2019): E24–E32.

35. F. Bernardo, J. A. Covas, and S. V. Canevarolo, "On-Line Optical Monitoring of the Mixing Performance in Co-Rotating Twin-Screw Extruders," *Polymers* 14, no. 6 (2022): 1152.

36. A. Lepschi, G. Gerstorfer, and J. Miethlinger, "Determining the Residence Time Distribution of Various Screw Elements in a Co-Rotating Twin-Screw Extruder by Means of Fluorescence Spectroscopy," *AIP Conference Proceedings* 1664 (2015): 020005.

37. D. R. Françla, C.-K. Jen, K. T. Nguyen, and R. Gendron, "Ultrasonic in-Line Monitoring of Polymer Extrusion," *Polymer Engineering & Science* 40, no. 1 (2000): 82–94.

38. P. Lewko, A. Wójtowicz, and M. Różańska-Boczula, "Effect of Extruder Configuration and Extrusion Cooking Processing Parameters on Selected Characteristics of Non-Starch Polysaccharide-Rich Wheat Flour as Hybrid Treatment With Xylanase Addition," *Processes* 12, no. 6 (2024): 1159.

39. H. Kantrong, C. Charunuch, N. Limsangouan, and W. Pengpinit, "Influence of Process Parameters on Physical Properties and Specific Mechanical Energy of Healthy Mushroom-Rice Snacks and Optimization of Extrusion Process Parameters Using Response Surface Methodology," *Journal of Food Science and Technology* 55, no. 9 (2018): 3462–3472.

40. S. A. Thompson and R. O. Williams III, "Specific Mechanical Energy—An Essential Parameter in the Processing of Amorphous Solid Dispersions," *Advanced Drug Delivery Reviews* 173 (2021): 374–393.

41. J. M. McKelvey, *Polymer Processing* (No Title, 1962).

42. I. Klein and D. I. Marshall, *Computer Programs for Plastics Engineers* (No Title, 1968).

43. Z. Tadmor and I. Klein, *Engineering Principles of Plasticating Extrusion* (Van Nostrand Reinhold Company, 1970).

44. Z. Tadmor and C. G. Gogos, *Principles of Polymer Processing* (John Wiley & Sons, 2013).

45. M. Hyvärinen, R. Jabeen, and T. Kärki, "The Modelling of Extrusion Processes for Polymers—A Review," *Polymers* 12, no. 6 (2020): 1306.

46. D. B. Todd, "Drag and Pressure Flow in Twin Screw Extruders," *International Polymer Processing* 6, no. 2 (1991): 143–147.

47. H. Potente, *Rechnergestützte Extruderauslegung* (Univ.-GH, Technologie der Kunststoffe, 1992).

48. W. M. Underwood, "Experimental Method for Designing Extrusion Screws," *Chemical Engineering Progress* 58 (1962): 59.

49. A. Nastaj and K. Wilczyński, "Computational Scale-Up for Flood Fed/Starve Fed Single Screw Extrusion of Polymers," *Polymers* 14, no. 2 (2022): 240.

50. J. A. Covas and A. Gaspar-Cunha, "Extrusion Scale-Up: An Optimization-Based Methodology," *International Polymer Processing* 24, no. 1 (2009): 67–82.

51. A. Gaspar-Cunha, A. Poulesquen, B. Vergnes, and J. A. Covas, "Optimization of Processing Conditions for Polymer Twin-Screw Extrusion," *International Polymer Processing* 17, no. 3 (2002): 201–213.

52. K. Wilczynski, Q. Jiang, and J. L. White, "A Composite Model for Melting, Pressure and Fill Factor Profiles in a Metered Fed Closely Intermeshing Counter-Rotating Twin Screw Extruder," *International Polymer Processing* 22, no. 2 (2022): 198–203.

53. S. Bawiskar and J. L. White, "Melting Model for Modular Self Wiping Co-Rotating Twin Screw Extruders," *Polymer Engineering & Science* 38, no. 5 (1998): 727–740.

54. J. L. White, B.-J. Kim, S. Bawiskar, and J. M. Keum, "Development of a Global Computer Software for Modular Self-Wiping Corotating Twin Screw Extruders," *Polymer-Plastics Technology and Engineering* 40, no. 4 (2001): 385–405.

55. B. Vergnes, G. D. Valle, and L. Delamare, "A Global Computer Software for Polymer Flows in Corotating Twin Screw Extruders," *Polymer Engineering & Science* 38, no. 11 (1998): 1781–1792.

56. A. Gaspar-Cunha and J. A. Covas, "A Scaling-up Methodology for Co-Rotating Twin-Extruders," in *27th World Congress of the Polymer Processing Society PPS-27*, (Marrakesh, Morocco, 2011), 1–6.

57. F. Berzin, C. David, and B. Vergnes, "Optimization and Scale-Up of Twin-Screw Reactive Extrusion: The Case of EVA Transesterification," *International Polymer Processing* 35, no. 5 (2020): 422–428.

58. A. Nastaj and K. Wilczyński, "Scaling-Up for the Counter-Rotating Twin Screw Extrusion of Polymers," *Polymers* 16, no. 19 (2024): 2720.

59. A. Gaspar-Cunha, J. A. Covas, and J. Sikora, "Optimization of Polymer Processing: A Review (Part I—Extrusion)," *Materials* 15, no. 1 (2022): 384.

60. B. Erzincanli and M. Sahin, "An Arbitrary Lagrangian–Eulerian Formulation for Solving Moving Boundary Problems With Large Displacements and Rotations," *Journal of Computational Physics* 255 (2013): 660–679.

61. M. H. Kim, W. Szydlowski, J. L. White, and K. Min, "A New Model of Flow in a Tangential Counter-Rotating Twin Screw Extruder," *Advances in Polymer Technology* 9, no. 1 (1989): 87–95.

62. G. A. Campbell, P. A. Sweeney, N. Dontula, and C. Wang, "Frame Indifference: Fluid Flow in Single Screw Pumps and Extruders," *International Polymer Processing* 11, no. 3 (1996): 199–207.

63. M. Lübke and O. Wünsch, "Two-Phase Flow in Single-Screw Extruders," *PAMM* 12, no. 1 (2012): 509-510.

64. H. Ding and Y. Jiang, "CFD Simulation of a Screw Compressor With Oil Injection," *IOP Conference Series: Materials Science and Engineering* 232 (2017): 012020.

65. A. Lehr, G. Janiga, A. Seidel-Morgenstern, and D. Thévenin, "CFD Simulation of a Solid-Liquid Counter-Current Screw Extractor," in *Computer Aided Chemical Engineering*, 48, (Elsevier, 2020): 223–228.

66. M. Lübke and O. Wünsch, "Investigation of the Free-Surface Flow in Partially Filled Extruders," *PAMM* 13, no. 1 (2013): 293-294.

67. E. H. Olofsson, M. Roland, J. Spangenberg, N. H. Jokil, and J. H. Hattel, "A CFD Model With Free Surface Tracking: Predicting Fill Level and Residence Time in a Starve-Fed Single-Screw Extruder," *The International Journal of Advanced Manufacturing Technology* 126, no. 7-8 (2023): 3579–3591.

68. E. H. Olofsson, A. Dan, M. Roland, N. H. Jokil, R. Ramachandran, and J. H. Hattel, "Numerical Modeling of Fill-Level and Residence Time in Starve-Fed Single-Screw Extrusion: A Dimensionality Reduction Study From a 3D CFD Model to a 2D Convection-Diffusion Model," *The International Journal of Advanced Manufacturing Technology* 132, no. 3-4 (2024): 1111–1125.

69. P. A. Moysey and M. R. Thompson, "Investigation of Solids Transport in a Single-Screw Extruder Using a 3-D Discrete Particle Simulation," *Polymer Engineering & Science* 44, no. 12 (2004): 2203–2215.

70. P. A. Moysey and M. R. Thompson, "Discrete Particle Simulations of Solids Compaction and Conveying in a Single-Screw Extruder," *Polymer Engineering and Science* 48, no. 1 (2008): 62–73.

71. J. Trippe and V. Schöppner, "Investigation of the Influence of Material and Pellet Shape on the Dissipation in the Solids Conveying Zone of Single-Screw Extruders Based on the Discrete Element Method (DEM)," *AIP Conference Proceedings* 1914 (2017): 080002.

72. O. Celik and C. Bonten, "Three-Dimensional Simulation of a Single-Screw Extruder's Grooved Feed Section," *AIP Conference Proccedings* 1779 (2016): 050004.

73. K. S. Johann, S. Mehlich, M. Laichinger, and C. Bonten, “Experimental Investigation of the Solid Conveying Behavior of Smooth and Grooved Single-Screw Extruders at High Screw Speeds,” *Polymers* 14, no. 5 (2022): 898.

74. F. Brüning and V. Schöppner, “Numerical Simulation of Solids Conveying in Grooved Feed Sections of Single Screw Extruders,” *Polymers* 14, no. 2 (2022): 256.

75. F. Brüning and V. Schöppner, “Calibration of a Contact Model for DEM Simulations of Grooved Feed Sections of Single Screw Extruders,” *AIP Conference Proceeding* 2607 (2023): 020006.

76. J.-S. Leßmann, R. Weddige, V. Schöppner, and A. Porsch, “Modelling the Solids Throughput of Single Screw Smooth Barrel Extruders as a Function of the Feed Section Parameters,” *International Polymer Processing* 27, no. 4 (2012): 469–477.

77. J. Trippe and V. Schöppner, “Modeling of Solid Conveying Pressure Throughput Behavior of Single Screw Smooth Barrel Extruders Under Consideration of Backpressure and High Screw Speeds,” *International Polymer Processing* 33, no. 4 (2018): 486–496.

78. A. Eitzlmayr, J. Matić, and J. Khinast, “Analysis of Flow and Mixing in Screw Elements of Corotating Twin-Screw Extruders via SPH,” *AIChE Journal* 63, no. 6 (2017): 2451–2463.

79. J. Matic, A. Eitzlmayr, I. Kondor, G. Koscher, and J. Khinast, “Particle-Based Modelling of Free-Surface Flow and Distributive Mixing in Modular Co-Rotating Twin-Screw Extruders,” (2016).

80. T. Dong, J. Wu, Y. Ruan, J. Huang, and S. Jiang, “Simulation of Multiphase Flow and Mixing in a Conveying Element of a Co-Rotating Twin-Screw Extruder by Using SPH,” *International Journal of Chemical Engineering* 2023 (2023): 8383763.