Thermal and Mechanical Design of Twin Screw Extruders for Food Processing - A Review

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Abstract
Twin-screw extrusion has emerged as a versatile and sustainable processing technology for developing nutrient-rich snack foods from cereal, legume, and composite blends. This study provides a comprehensive evaluation of the mechanical, thermal, and nutritional aspects of extrusion, with an emphasis on how process parameters influence product quality. Mechanical design considerations such as screw geometry, pitch, channel depth, and length-to-diameter ratio were examined to highlight their role in material flow, shear distribution, and residence time. Thermal profiling was analyzed with respect to multi-zone barrel heating, internal frictional heat, and high-temperature short-time (HTST) treatment, demonstrating their effects on starch gelatinization and nutrient retention. Data-centric review of quality indices showed that expansion index (EI), bulk density (BD), water absorption index (WAI), water solubility index (WSI), and specific mechanical energy (SME) are strongly dependent on moisture content, screw speed, and additive level. Nutritional interactions were critically assessed, revealing significant improvements in protein digestibility (15–25%) and mineral bioavailability (iron and zinc retention 85–95%), while sensitive compounds such as β-carotene suffered notable degradation at elevated temperatures. Collectively, the findings underscore extrusion as a multi-parameter system, where optimized mechanical and thermal design can enable production of texturally desirable, nutritionally enhanced snacks aligned with global health demands.

Keywords: Twin-screw extrusion, snack food processing, expansion index, bulk density, water absorption index, protein digestibility, nutrient retention.

1. Introduction

The global demand for convenient, affordable, and nutritionally balanced foods continues to grow, leading to rapid innovation in food processing technologies. Among these, extrusion cooking has emerged as one of the most transformative methods for producing ready-to-eat (RTE) products such as snack foods, breakfast cereals, protein supplements, and weaning foods. Extrusion integrates mixing, shearing, cooking, shaping, and drying into a continuous, energy-efficient process, producing shelf-stable products with improved microbial safety and desirable sensory qualities [1], [2].

Compared to conventional thermal processes, extrusion cooking offers high-temperature short-time (HTST) treatment that gelatinizes starch, denatures proteins, and inactivates anti-nutritional factors while limiting the destruction of sensitive nutrients. For example, studies on maize–chickpea and potato-based snacks have shown that extrusion enhances expansion and digestibility while maintaining microbial safety [3], [4]. Furthermore, extrusion has proven highly adaptable for incorporating functional ingredients such as legumes, soy proteins, dietary fibers, and phytochemical-rich plant pomace, supporting the market shift toward health-oriented snack foods [5], [6].

One of the key strengths of extrusion is its ability to control structural and functional product attributes—such as expansion index (EI), bulk density (BD), water absorption index (WAI), and water solubility index (WSI)—through fine adjustments of barrel temperature, screw speed, feed moisture, and screw configuration [2], [7]. For instance, extruded oat and rice products processed at moderate moisture (~14–16%) and barrel temperatures (~120–140 °C) have achieved EI values above 3.5, indicating highly expanded, porous structures desirable in snack applications [2], [7].

Within extrusion technologies, twin-screw extrusion (TSE) has gained prominence over single-screw systems due to its superior mixing, flexibility, and control. TSE systems allow modular arrangement of screw elements—such as forwarding, kneading, and mixing blocks—making it possible to adapt to diverse formulations ranging from starch-rich cereals to high-protein legume composites [8], [9]. This adaptability enables manufacturers to address the technical challenges posed by protein- and fiber-rich blends, where expansion tends to be lower and texture denser compared to starch-based snacks [10], [5].

As a result, TSE is increasingly viewed not only as a tool for shaping snack foods but also as a platform for functional food innovation. Recent studies highlight its ability to incorporate vitamins, minerals, phytochemicals, and encapsulated bioactives while preserving their stability under controlled processing [6], [7]. This positions extrusion as a critical technology in addressing modern consumer demands for nutritionally enriched, sustainable, and affordable food products.

1.1 Extrusion Cooking: A Modern Backbone of Snack Food Processing

The snack food industry has shifted significantly from products focused solely on taste and texture to those emphasizing health, wellness, and nutrition. Consumers increasingly prefer snacks fortified with **whole grains, dietary fiber, plant proteins, and bioactive compounds** [1], [2]. In this context, extrusion cooking has emerged as a versatile technology, enabling the development of functional and fortified products with tailored nutritional and sensory attributes.

A major advantage of extrusion cooking is its **high-temperature short-time (HTST)** operation, which allows starch gelatinization and protein denaturation without extensive nutrient loss [3]. Studies on maize–chickpea and potato-based extrudates have demonstrated that extrusion not only improves product expansion but also enhances digestibility while maintaining microbial safety [4], [5]. Similarly, extrusion of oat, rice, and wheat blends has shown that process optimization (temperature ~120–140 °C, feed moisture ~14–16%) leads to improved expansion index (EI > 3.5), reduced bulk density, and desirable crispness [6], [7].

The process variables—**barrel temperature, screw speed, feed moisture, and screw configuration**—play a critical role in controlling product attributes such as **expansion index (EI), bulk density (BD), water absorption index (WAI), and water solubility index (WSI)** [8], [9].

1.2 Rise of Nutrient-Dense Composites: Legumes, Soy, and Protein Blends

Traditional snack products are often rich in starch and fat but lack **protein, vitamins, and minerals**. To address these nutritional gaps, researchers have increasingly incorporated legumes (chickpea, pea, lentil), soy derivatives, pulses, and composite cereal blends into extrusion formulations [2], [5], [10]. These ingredients significantly improve the **protein content, mineral availability, and dietary fiber** in snacks, aligning with consumer demand for functional and fortified foods.

However, the inclusion of high-protein and fiber-rich ingredients poses **technical challenges**. Proteins tend to interfere with starch expansion, leading to products with **lower puffing, denser texture, and altered mouthfeel** [11].

Twin-screw extrusion has proven especially useful in overcoming these formulation challenges. By adjusting **screw geometry, barrel temperature, and moisture content**, it is possible to balance texturization with nutrient retention [6], [14]. Studies on maize–soy, wheat–chickpea, and rice–pea blends show that although expansion is reduced compared to starch-rich matrices, extrusion significantly improves **protein digestibility (by 15–20%), inactivates anti-nutritional factors, and enhances mineral bioavailability** [5], [13].

Consequently, the rise of **nutrient-dense composites** represents a major technological and nutritional advance in extrusion processing, paving the way for snacks that are not only palatable but also aligned with **global health and sustainability goals**.

2. Thermal Design Considerations in Twin-Screw Extruders

Thermal management plays a decisive role in the performance of twin-screw extruders (TSE), particularly when processing nutrient-rich formulations composed of cereals, legumes, and plant-based composites. The thermal input governs the extent of starch gelatinization, protein denaturation, and inactivation of anti-nutritional factors, while also affecting product texture, expansion, and nutrient retention [1], [2]. Unlike single-screw systems, TSEs offer **multi-zone barrel heating** and **independent temperature control**, which enable precise thermal profiling tailored to the formulation. Improper thermal design can result in undercooked matrices, nutrient degradation, or poor expansion characteristics, highlighting the need for optimized heating strategies [3].

2.1 Barrel Temperature Zones in Twin-Screw Extrusion

A typical TSE barrel is divided into sequential zones: feeding, mixing, cooking, and die-head. Each section is equipped with independent heating elements and thermocouples, allowing localized temperature regulation [4]. In food extrusion, barrel temperatures generally range between **90 °C and 190 °C**, depending on the formulation and desired end-product characteristics. Moderate heating in the feeding and mixing zones prevents premature gelatinization, while higher temperatures in the cooking and die zones ensure starch transformation, microbial inactivation, and product expansion [5]. Multi-zone heating also supports the inclusion of **sensitive additives** such as vitamins and bioactives by limiting their exposure to elevated temperatures [6].

2.2 Heat Generation: External Heating vs. Internal Friction

The total thermal load in extrusion results from two sources: **external heating** (via cartridge or band heaters) and **internal heat** generated through viscous dissipation and shear within the material [7]. The balance between these mechanisms depends on screw speed, screw element geometry, and feed moisture. At higher screw speeds, internal friction can provide up to 70% of the total heat input, reducing the reliance on external heating systems [8]. However, excessive shear may increase localized overheating and nutrient degradation, especially in protein- and fiber-rich formulations [9]. Advanced extruders now integrate **feedback-controlled thermal systems** that continuously adjust external heating to complement internally generated shear heat, ensuring thermal stability along the barrel [10].

2.3 Short-Time High-Temperature Cooking: Benefits and Challenges

Extrusion is characterized by **high-temperature short-time (HTST) processing**, with residence times ranging from 15 to 60 seconds [11]. This rapid transformation improves digestibility by denaturing proteins, gelatinizing starch, and deactivating enzyme inhibitors, while also ensuring microbial safety [12]. Compared to conventional cooking, HTST processing retains more heat-sensitive nutrients such as certain amino acids and B-vitamins [13]. However, challenges arise at temperatures above 170–180 °C, where degradation of sensitive compounds like β-carotene, thiamine, and vitamin C accelerates [14]. Balancing thermal input with moisture and screw configuration is therefore critical to maximize nutrient preservation while achieving desirable product texture.

2.4 Effect of Barrel Temperature on Expansion Index (EI)

The **Expansion Index (EI)** is a key quality parameter in snack food extrusion, reflecting the degree of puffing and product porosity. Moderate barrel temperatures (110–140 °C) with low feed moisture (~14%) have been associated with high EI values (>3.5), particularly in rice and maize formulations

[2], [15]. In contrast, operating at elevated temperatures (160–190 °C) often results in reduced expansion (EI < 1.0) due to excessive starch degradation and lower melt viscosity [16]. Experimental studies on cereal–pomace blends confirm that higher thermal loads weaken the structural integrity of the matrix, reducing gas retention and foam stability [12]. Optimizing zone-specific heating is thus essential for maintaining expansion while minimizing thermal damage.

2.5 Influence of Temperature on Bulk Density

Bulk Density (BD) is inversely correlated with EI and serves as another critical indicator of product quality. Lower BD values (0.2–0.3 g/cm³) are desirable for light, crispy snacks, whereas higher BD (>0.8 g/cm³) indicates dense and less palatable products [17]. Barrel temperature strongly affects BD: moderate heating (130–140 °C) promotes expansion and reduces density, while higher temperatures (>160 °C) increase BD due to starch breakdown and poor bubble stability [18]. For example, fiber-enriched formulations extruded at 150–160 °C demonstrated BD values exceeding 1.0 g/cm³, highlighting the negative effect of high thermal stress on structural development [12]. Effective temperature management, combined with optimal screw speed and feed moisture, ensures products with low BD and desirable texture.

3. Mechanical Design Aspects of Twin-Screw Extruders

The mechanical design of twin-screw extruders (TSE) is central to their performance, efficiency, and versatility in processing diverse food formulations. Unlike single-screw extruders, where design is relatively constrained, TSEs provide modularity in screw element arrangement, torque distribution, and barrel zoning. These design choices directly affect material conveyance, mixing efficiency, shear application, residence time distribution (RTD), and ultimately, product characteristics such as expansion index (EI), bulk density (BD), and nutrient retention. To achieve both processing stability and product quality, engineers must balance geometry, speed, torque, and material wear considerations in the mechanical configuration of the extruder [1], [2].

3.1 Overview of Screw Geometry in Twin-Screw Extruders

Screw geometry forms the foundation of extrusion mechanics. A twin-screw extruder typically consists of intermeshing screws housed within modular barrel sections. The screws can be co-rotating or counter-rotating, with co-rotating designs favored in food processing due to superior mixing, self-wiping action, and higher throughput [3].

Screw elements are modular and can be broadly categorized as:

- **Conveying elements**, which transport material forward with minimal mixing.
- **Kneading blocks**, which apply intensive shear for mixing and dispersing.
- **Reverse elements**, which create localized backpressure, enhancing thermal and mechanical treatment.

The configuration of these elements dictates how energy is imparted into the food matrix. For example, protein-rich formulations often require additional kneading zones to ensure proper texturization, whereas starch-based snacks may rely more on forward conveying with moderate shear [4]. The modularity of screw geometry thus provides a flexible design space to customize processing for cereals, legumes, or composite blends.

3.2 Screw Speed: Ranges, Torque, and Shear Effects

Screw speed (N, in rpm) is one of the most sensitive parameters in extrusion. Typical TSEs for food applications operate in the range of **100–600 rpm**. At lower speeds, residence time is extended, enabling better thermal equilibrium but limiting expansion potential. Higher speeds, by contrast, shorten residence time but generate substantial **viscous shear heating** [5].

The mechanical torque demand increases with both speed and the resistance of the processed material. High-protein formulations or fiber-enriched blends exhibit higher torque loads due to increased viscosity. Torque is critical not only for predicting energy consumption but also for assessing mechanical durability of screws and gearboxes. Excessive torque can lead to premature screw wear or even shaft deformation if not adequately designed [6].

Shear rate, directly tied to screw speed, has a dual effect: it enhances starch gelatinization and protein denaturation but can also degrade sensitive nutrients and reduce expansion if excessively high. Hence, modern TSEs are equipped with **variable frequency drives (VFDs)** to allow dynamic adjustment of screw speed to balance shear intensity and thermal load [7].

3.3 Pitch and Channel Depth: Tuning Conveying and Shearing

The **pitch** of screw elements refers to the axial distance over which the thread completes one revolution. A larger pitch promotes forward conveying with minimal compression, whereas a reduced pitch increases residence time and internal pressure. Similarly, **channel depth** controls volumetric capacity: deeper channels allow higher throughput but reduce shear, while shallower channels increase shear intensity at the cost of throughput [8].

Optimization of pitch and channel depth is particularly important when dealing with nutrient-rich composites. For example, soy–maize blends require shallower channels and shorter pitch to achieve sufficient mixing and expansion, while starch-based snacks may use deeper channels for efficient conveying [9]. Engineers often design screws with a progressive reduction in channel depth along the barrel to gradually increase compression and shear as the material approaches the cooking and die zones [10].

3.4 Length-to-Diameter Ratio (L/D Ratio): Residence Time and Mixing Balance

The **L/D ratio** of an extruder, typically ranging from **20:1 to 40:1**, is another defining design parameter. A higher L/D ratio extends the residence time of material within the barrel, promoting uniform mixing and thorough thermal treatment. This is especially beneficial for formulations requiring enzyme inactivation or fiber dispersion [11].

However, excessively high L/D ratios increase mechanical energy consumption and impose greater torque on drive components. Moreover, longer residence times may risk nutrient degradation in heat-sensitive formulations. Conversely, shorter L/D ratios may not provide adequate mixing, leading to heterogeneous texture and incomplete cooking. Hence, an optimal L/D balance is required based on the product: shorter ratios for puffed cereal snacks, and longer ratios for high-protein or fiber-rich blends [12].

3.5 Zonal Design for Shearing, Mixing, Conveying, and Cooking

A TSE barrel is typically divided into functional zones:

1. **Feeding zone** – large pitch, deep channels to ensure stable material intake.
2. **Compression/mixing zone** – reduced pitch and shallower channels to apply shear and promote starch gelatinization or protein unfolding.
3. **Cooking zone** – high-temperature, moderate-shear environment for HTST treatment.
4. **Metering and die zone** – controlled pressure build-up to ensure consistent shaping and expansion.

Each zone is mechanically configured with different screw elements to achieve specific objectives. For instance, kneading blocks are placed in the mixing zone, while reverse elements may be added before the die to stabilize pressure [13]. Such zonal design ensures efficient material processing while preventing issues like surging, incomplete cooking, or excessive die pressure.

3.6 Mechanical Wear Considerations and Screw Material Selection

Given the abrasive nature of many ingredients (especially composites with legume husks or high mineral content), mechanical wear is a critical design consideration. Screw wear alters geometry, reduces conveying efficiency, and destabilizes torque distribution.

Common materials for screw fabrication include **nitrided steels, tool steels, and hardened alloys**. In high-abrasion scenarios, **tungsten carbide-coated or bi-metallic screws** are employed for extended life [14]. Wear is most severe in kneading zones where high shear is concentrated. Preventive maintenance strategies include periodic torque monitoring, inspection of screw elements, and replacement before critical wear thresholds are exceeded [15].

Material selection is not only about wear resistance but also **food safety compliance**. Alloys must meet food-grade standards to prevent contamination. Modern research has also focused on coatings that reduce friction, thereby minimizing energy consumption and extending service life [16].

3.7 Integration of Torque Sensors and Mechanical Control Systems

Advancements in mechatronics have transformed mechanical control of extruders. Modern TSEs incorporate **torque sensors, pressure transducers, and motor load monitors** that provide real-time feedback on process conditions. Torque sensors, in particular, are valuable for predicting screw wear, detecting abnormal material resistance, and maintaining safe operating conditions [17].

Integration of **PLC (Programmable Logic Controller) systems** enables automatic adjustment of screw speed, feeder rates, and barrel heating based on torque and pressure feedback. This reduces operator dependency and ensures consistent product quality [18]. Predictive maintenance systems now analyze torque fluctuations over time to forecast wear progression, allowing proactive replacement of screw elements before failure [19].

These control systems not only enhance mechanical reliability but also optimize energy efficiency by dynamically balancing external heating with shear-induced internal heating. Such integration represents the shift of TSEs from purely mechanical devices to **cyber-physical systems** aligned with Industry 4.0 principles [20].

4. Effect of Process Parameters on Product Quality (Data-Centric Review)

Extrusion cooking is a **multi-factorial process**, where small variations in moisture, screw speed, temperature, and ingredient ratio can lead to significant changes in final product quality. Key properties such as **Expansion Index (EI), Bulk Density (BD), Water Absorption Index (WAI), Water Solubility Index (WSI), and Specific Mechanical Energy (SME)** are strongly dependent on process parameter optimization. This section provides a data-centric review of how each parameter influences product attributes, with tabular comparisons of findings from different studies to highlight key trends and numerical benchmarks.

4.1 Expansion Index (EI): Influence of Moisture, Screw Speed, and Blend Ratio

The **Expansion Index (EI)** measures the extent of puffing during extrusion, serving as a primary quality indicator for snacks. EI is largely governed by **feed moisture content, screw speed, and formulation ratios**.

- **Moisture**: Low moisture (~12–14%) typically favors higher EI because of rapid flash-off at the die exit. High-moisture feeds (>18%) suppress expansion due to lower vaporization potential.
- **Screw speed**: Increased screw speed enhances shear, elevates barrel pressure, and promotes greater superheating, which in turn increases EI. However, very high speeds may cause excessive shear thinning, leading to collapse of structure.

- **Blend ratio**: Protein- and fiber-rich blends (soy, chickpea, pomace) dilute starch content, decreasing EI. Thus, starch-protein composites usually have lower EI compared to cereal-only extrudates.

Table 1 presents benchmark values for EI as influenced by process parameters.

Table 1. Expansion Index under Different Process Conditions [6]

Feedstock	Moisture (%)	Screw Speed (rpm)	Blend Ratio (Starch:Protein)	EI Range
Maize grits	12–14	300–400	100:00:00	3.2–3.8
Rice–soy blend	14–16	250–350	70:30:00	1.6–2.1
Wheat–chickpea blend	14–15	250–300	60:40:00	1.3–1.7
Maize with apple pomace	12–14	300–400	85:15:00	1.8–2.4
Oat extrudates	15–17	300–350	100:00:00	2.5–3.0

4.2 Sectional and Longitudinal Expansion

Expansion in extrusion is not only radial but also **axial (longitudinal)**. Radial or sectional expansion determines product porosity and crispness, whereas longitudinal expansion influences shape retention and product aesthetics.

- **Sectional expansion** is more sensitive to die pressure and moisture content. Low-moisture conditions yield higher sectional expansion, producing light, porous structures.
- **Longitudinal expansion** tends to increase at higher feed moisture and moderate screw speeds, as a result of elongational stresses during die swell.
- Fiber-rich additives reduce sectional expansion but can promote slight longitudinal elongation due to increased melt viscosity.

These differences mean that snacks with identical EI values may differ significantly in **shape and texture** depending on whether expansion is more sectional or longitudinal.

4.3 Bulk Density (BD): Impact of Pomace Addition, Speed, and Moisture

Bulk Density (BD) is inversely related to EI. Lower BD values (~0.2–0.3 g/cm³) are associated with light, crisp snacks, whereas higher values (>0.6 g/cm³) indicate dense and less palatable products.

- **Pomace addition**: Incorporating fruit or vegetable pomace increases BD due to the high fiber fraction, which restricts bubble growth. For example, 10–15% pomace inclusion can double BD compared to starch-only controls.
- **Screw speed**: Higher screw speed generally lowers BD by enhancing shear and expansion. However, excessively high speeds may destabilize the melt, causing collapse and increased BD.
- **Moisture**: Higher feed moisture increases BD by limiting vaporization and expansion.

Table 2. Bulk Density Values under Different Process Conditions [6]

Feedstock + Additives	Moisture (%)	Screw Speed (rpm)	Pomace (%)	BD (g/cm³)
Maize grits	12–14	300–350	0	0.22–0.28
Rice–soy blend	14–16	250–300	0	0.35–0.42
Maize + apple pomace	12–14	300–350	10	0.45–0.55
Maize + carrot pomace	14–15	300–400	15	0.60–0.70
Oat extrudates	15–17	300–350	0	0.28–0.35

4.4 Water Absorption Index (WAI) and Water Solubility Index (WSI)

WAI measures the ability of extrudates to absorb water, reflecting starch gelatinization, whereas **WSI** indicates solubilization of components such as dextrins and soluble fibers.

- **Moisture**: Higher feed moisture reduces WAI because gelatinization is incomplete. Moderate moisture levels (~14–16%) maximize WAI by enabling full starch swelling.
- **Screw speed**: Higher screw speed increases WSI due to greater shear-induced dextrinization.
- **Fiber addition**: Legume or pomace fibers generally decrease WSI while increasing WAI, as they absorb water but do not solubilize readily.

Table 3. WAI and WSI Trends under Different Conditions [6]

Feedstock/Blend	Moisture (%)	Screw Speed (rpm)	WAI (g/g)	WSI (%)
Maize grits	12–14	300–350	5.2–5.8	20–25
Rice–soy blend	14–15	250–300	4.0–4.5	18–22
Maize + pomace (10%)	13–14	300–350	6.0–6.8	15–20
Oat extrudates	15–16	300–350	5.0–5.6	22–28
Chickpea-based extrudates	14–16	250–300	4.5–5.2	16–21

4.5 Specific Mechanical Energy (SME) and Gelatinization Thresholds

Specific Mechanical Energy (SME) quantifies the mechanical energy input per unit mass of feed material, serving as a key indicator of shear intensity and cooking efficiency.

- **Higher screw speeds** increase SME, enhancing starch gelatinization and protein denaturation.
- **Moisture** inversely affects SME: higher feed moisture lubricates the melt, lowering SME.
- **Gelatinization threshold**: Studies show that complete starch gelatinization typically requires SME levels of **120–180 kJ/kg**, depending on starch type and blend composition. Beyond this threshold, further SME may cause molecular degradation, leading to reduced expansion and nutrient loss.

Table 4. SME Ranges and Gelatinization Behavior [6]

Feedstock/Blend	Moisture (%)	Screw Speed (rpm)	SME (kJ/kg)	Gelatinization (%)
Maize grits	12–14	350–400	150–180	>95
Rice–soy blend	14–16	300–350	130–160	85–90
Wheat–chickpea blend	14–15	250–300	110–130	70–80
Maize + pomace (15%)	12–14	300–350	140–160	80–85
Oat extrudates	15–16	300–350	120–140	75–82

4.6 Tabulated Comparison of Process Parameters and Product Quality

To consolidate findings across subsections, **Table 5** summarizes how major process parameters—moisture, screw speed, and additive level—affect the primary product quality indicators.

Table 5. Comparative Effects of Process Parameters on Product Quality [6]

Parameter	Expansion Index (EI)	Bulk Density (BD)	WAI	WSI	SME
Low Moisture	High (EI > 3.0)	Low (0.2–0.3)	High (5.5–6.0 g/g)	Moderate (18–22%)	High (150–180 kJ/kg)
High	Low (EI < 2.0)	High (>0.5)	Low (4.0–4.5	Low (15–	Low (100–

Moisture			g/g)	18%)	120 kJ/kg)
High Screw Speed	High (EI > 3.0)	Low (0.2–0.3)	Moderate (5.0)	High (22–28%)	High (160–180 kJ/kg)
Low Screw Speed	Low (EI < 2.0)	High (>0.5)	Low (4.0–4.5 g/g)	Low (15–18%)	Low (100–120 kJ/kg)
Pomace Addition	Reduced (EI < 2.0)	Increased (>0.5)	High (6.0–6.8 g/g)	Decreased (15–20%)	Moderate (140–160)

6. Nutritional Retention and Material Interaction

Nutritional quality is one of the most critical aspects in evaluating the success of extrusion processing for cereal- and legume-based foods. While extrusion offers high-temperature short-time (HTST) processing that improves safety and digestibility, it can also cause losses of sensitive compounds such as vitamins or promote undesirable changes in amino acid profiles. The following subsections review three key nutritional factors: protein denaturation, vitamin degradation, and mineral retention, emphasizing the underlying mechanisms and experimental findings reported in extrusion research.

6.1 Protein Denaturation and Digestibility Enhancement

Proteins are highly sensitive to thermal and mechanical stress. During extrusion, **shear forces and elevated barrel temperatures** disrupt hydrogen bonds and non-covalent interactions, leading to protein denaturation [1]. Although denaturation often implies loss of native structure, it is generally beneficial in food extrusion since it exposes peptide chains to enzymatic attack, thereby **enhancing digestibility**. Studies on maize–soy and wheat–chickpea extrudates have shown protein digestibility increases by **15–25%** after extrusion, largely due to unfolding of storage proteins and destruction of enzyme inhibitors such as trypsin inhibitors [2].

Another benefit is the reduction of **antinutritional factors**. Extrusion inactivates trypsin inhibitors, lectins, and tannins commonly found in legumes [4]. In chickpea extrudates, trypsin inhibitor activity decreased by more than 90% at 150 °C, improving amino acid bioavailability [5].

However, prolonged residence time or excessively high SME (above ~180 kJ/kg) can induce **Maillard reactions** between amino groups and reducing sugars, reducing lysine availability [6]. Lysine loss has been estimated at 10–20% in cereal–legume blends processed above 170 °C [7]. Thus, optimal extrusion balances denaturation for digestibility improvement while minimizing amino acid degradation.

6.2 Vitamin Degradation: β-Carotene

Carotenoids such as **β-carotene** are essential antioxidants and vitamin A precursors, but they are highly sensitive to oxygen, light, and thermal processing. Extrusion-induced degradation occurs via **oxidative cleavage** and **isomerization**, converting trans-β-carotene into less bioactive cis-isomers [8].

Retention rates are strongly influenced by **barrel temperature, moisture, and screw speed**. Moderate extrusion conditions (120–140 °C, 14–16% moisture) have been shown to retain 60–70% of β-carotene in fortified maize extrudates [9]. At higher temperatures (160–180 °C), retention drops drastically to 30–40% [10].

Pomace-enriched extrudates illustrate a dual effect: while fiber increases mechanical resistance and limits expansion, it can also provide some protective effect by entrapping carotenoids within the fiber matrix [11]. For example, extrusion of carrot-pomace blends at 140 °C preserved more than 55% of β-carotene, compared to <40% at 160 °C [12].

Another consideration is **screw speed**: higher speeds increase shear heating but reduce residence time, sometimes yielding higher retention compared to slow extrusion at the same temperature [13]. Hence, optimization of speed–temperature combinations is critical to balance retention with structural quality.

In recent work, microencapsulation of β-carotene in starch or protein matrices prior to extrusion improved retention significantly, achieving >75% stability under optimized conditions [14]. Such strategies demonstrate that extrusion can be adapted to retain sensitive vitamins through pre-processing interventions.

6.3 Iron and Zinc Retention in Cereal-Legume Extrudates

Mineral retention during extrusion is influenced less by direct degradation (since minerals are heat-stable) and more by **interactions with antinutritional factors** such as phytates, tannins, and fibers. Extrusion alters these interactions by breaking down phytate complexes, thereby improving mineral bioavailability [15].

In maize–soy and wheat–chickpea extrudates, iron and zinc retention levels after extrusion have been reported between **85–95%**, with improved in vitro solubility compared to unprocessed blends [16]. The reduction of phytic acid content (20–40% degradation at 140–150 °C) explains this improvement [17]. For example, in a study on fortified maize extrudates, extrusion reduced phytic acid content by 25%, while enhancing **dialyzable iron** from 8% in raw flour to nearly 15% in extrudates [18]. Similarly, zinc solubility was shown to increase by ~30% in chickpea-based extrudates after extrusion at 150 °C [19]. However, excessive fiber addition (such as fruit pomace) can reduce mineral retention by physically entrapping minerals or increasing bulk density, thereby limiting solubility [20]. Careful formulation is therefore necessary to ensure that the mineral bioavailability benefits of phytate breakdown are not offset by new binding interactions with added fibers.

Synthesis

Overall, extrusion is a **double-edged process** with respect to nutritional retention. Proteins benefit significantly due to denaturation and inhibitor inactivation, enhancing digestibility. Vitamins such as β-carotene suffer degradation, requiring mitigation strategies such as encapsulation or optimized parameter control. Minerals like iron and zinc are generally well retained, with extrusion improving their bioavailability through phytate breakdown.

The interplay of thermal, mechanical, and compositional factors ultimately defines the nutritional outcome. Emerging trends such as **multi-objective optimization models** and **predictive machine learning approaches** are increasingly applied to simultaneously maximize digestibility, vitamin retention, and mineral bioavailability. By integrating real-time torque and temperature monitoring, it is possible to fine-tune extrusion to preserve sensitive nutrients while ensuring functional textural properties of the product.

Conclusion

This review demonstrates that extrusion cooking is a powerful platform technology for producing fortified and functional foods, provided that its mechanical and thermal parameters are precisely controlled. Mechanical design—particularly screw geometry, speed, pitch, and L/D ratio—dictates the distribution of shear and residence time, while thermal design governs starch gelatinization, expansion, and nutrient stability. The analysis of process parameters confirms that low feed moisture (~12–14%) and moderate-to-high screw speeds (300–400 rpm) optimize expansion and reduce bulk density, whereas excessive moisture or fiber additions suppress puffing and increase product density. Quality indices such as WAI, WSI, and SME provide quantitative benchmarks for evaluating process efficiency and product performance. Nutritionally, extrusion enhances protein digestibility and improves iron and zinc bioavailability through phytate degradation, but simultaneously threatens heat-sensitive micronutrients like β-carotene, necessitating strategies such as encapsulation or optimized HTST conditions. The collective evidence highlights extrusion as both a technological backbone for modern snack foods and a field requiring further innovation in sensor integration, predictive modeling, and smart process control. Future research should focus on multi-objective optimization to balance textural, sensory, and nutritional outcomes, ensuring extrusion remains central to the development of sustainable, nutrient-dense foods for global markets.

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