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Improved Extrusion Cooking Technology (IECT): Utilization of Milder Conditions for Better Starch Modification

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Abstract

This review aimed to analyze improved extrusion cooking technology (IECT), a novel food processing methodology that uses milder conditions, longer screws, and an extended residence time to physically modify food ingredients, primarily starches and cereal flours. This process improves the ingredients' physicochemical, textural, and nutritional properties while minimizing the degradation of bioactive components. The review also explored the versatility of IECT for application to a wider range of raw materials, including tubers, legumes, fibers, and proteins. IECT modifies starch structure through low temperature and high-pressure gelatinization, destructing the granular and crystalline structure and increasing the gelatinization degree to above 60%. These changes reduce retrogradation and improve functional properties like the water absorption and solubility indices (WAI and WSI). While successful applications include the development of texturized rice and whole buckwheat noodles, research has focused largely on cereals and derivative starches. Future research must focus on applying IECT to tubers and legumes and materials rich in fiber and proteins, as well as conducting bioavailability studies of phenolics *in vivo*, and performing a comparative analysis against conventional single and twin-screw extruders.

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Introduction

Extrusion cooking is a process that is characterized by its short duration, elevated temperature, and continuous operation. It involves the physical modification of the material through the application of a unique combination of high temperature, pressure, and shear forces. The properties of the foods are modified considerably, including microstructure, texture, flavor, and color (Téllez-Morales & Rodríguez-Miranda, 2025; Téllez-Morales et al., 2022a,b,c; Téllez-Morales et al., 2021; Téllez-Morales et al., 2020). Improved extrusion cooking technology (IECT) is a novel technology for the physical transformation of starch, obtained from the traditional screw extruder, which was designed at the State Key Laboratory of Food Science and Technology, Nanchang University, China, and manufactured in Jinan Saixin Machinery Ltd., China (Liu et al., 2011; Ye et al., 2016). The technology is designed with longer screws (1950 mm) and processing conditions, such as higher feed moisture content and pressure, longer residence time, lower screw speed, and extrusion temperature, to improve the properties of extrudates. The machine is equipped with five heating zones, each comprising an electrical resistance heater and a thermocouple sensor to monitor temperature (Cheng et al., 2020; Gao et al., 2022; Li et al., 2021; Ye et al., 2016). Additionally, the novel forming mold and rotary cutting blade have been incorporated, a feature absent from certain conventional extruders (Liu et al., 2011; Zhang et al., 2014). As Liu et al. (2019) have previously indicated, critical IECT control parameters, including screw speed and temperature, have the capacity to influence the molecular structure of starch, thereby affecting its properties. In addition, Liu et al. (2011) were the first to introduce IECT for the development of textured rice from broken rice flour and rice bran as raw materials. The principle of operation is analogous to that of traditional extrusion cooking, but with longer screws. Consequently, this novel technology could serve as a substitute for conventional food processing methodologies (Cheng et al., 2020; Wang et al., 2023a,b).

Therefore, the objective of this review was to analyze improved extrusion cooking technology (IECT) and validate it as a multi-matrix modification platform, characterizing its precise molecular mechanisms,

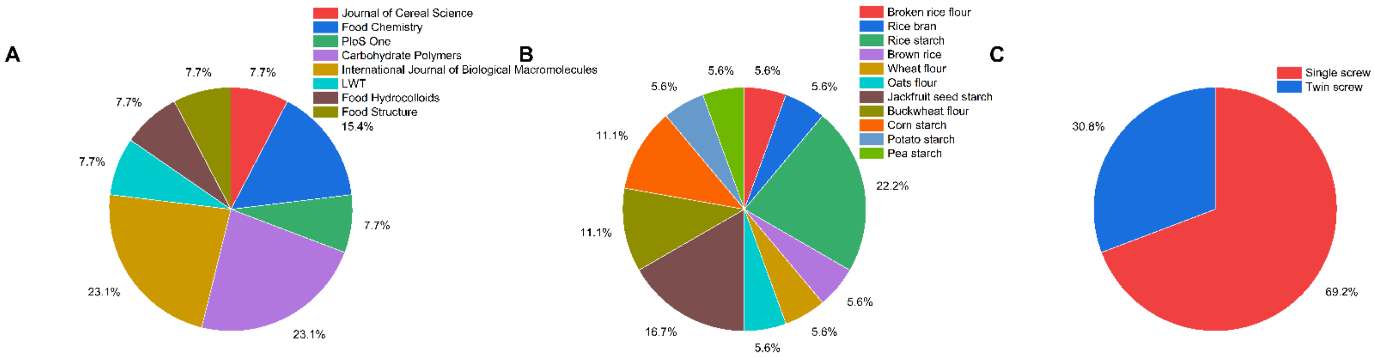

Figure 1. A) Journals, B) Raw materials, C) Type of extruder, used in the IECT.

biological efficacy, and industrial viability compared to conventional extrusion. The review also explores the versatility of IECT for application to a wider range of raw materials.

Trends in improved extrusion cooking technology (IECT)

Analysis of recent studies (Figure 1A) shows that IECT research primarily focuses on altering the structure of polymers. This is clear from the many articles in Carbohydrate Polymers and Int. J. Biol. Macromol. Most interest lies in how extrusion changes polymers such as starches and proteins and affects their functionality. Research is focusing on starch-rich mixtures (Figure 1B). Also, there is a clear trend toward using by-products (such as jackfruit seeds or rice bran) with extrusion to turn them into useful products. Although twin-screw extrusion is generally more versatile for complex mixtures, single-screw extrusion remains the dominant technology in these specific studies (Figure 1C). This could suggest that the technological improvement being researched focuses on cost-effectiveness (single-screw extrusion is cheaper) or on modifying pure starch, in which case single-screw extrusion is sufficient.

Advantages and characteristics of IECT

IECT is presented as a superior physical modification technology compared to conventional extrusion cooking (Figure 2), primarily due to its milder processing conditions and extended residence time. IECT operates at lower temperature (50–150 °C) and lower screw speed (15–75 rpm) than traditional extrusion cooking extruders (Liu et al., 2017). This contrasts with conventional extrusion (Figure 3), which involves high temperature and high shear, which often results in the degradation of bioactive components and reduction of functional activity (Cheng et al., 2020). The technology utilizes a "longer screw (1950 mm), longer residence time (18–90 s), higher die pressure (13.356–19.102 MPa)" (Liu et al., 2017). This combination allows for "gelatinization... by means of low temperature and high pressure" (Liu et al., 2011). Unlike conventional extruders that cause 2–5 times and even larger expansion, IECT makes the expansion of extrudate be hardly changed (Liu et al., 2011). This is achieved by forming complexes between starch and fat as well as protein, resulting in products with similar texture properties and shape with polished rices (Liu et al., 2011). A significant advantage of IECT is its ability to improve the retention rate of bioactive components (Cheng et al., 2020). Studies show retention rates of TFC and TPC in modified buckwheat flour ranged from 68.3% to 89.6% and 64.0%–91.4%, respectively, which is much higher than that extruded by conventional high temperature extrusion process (Cheng et al., 2020). Similarly, IECT minimizes nutritional quality decay of starch (Wang et al., 2023a).

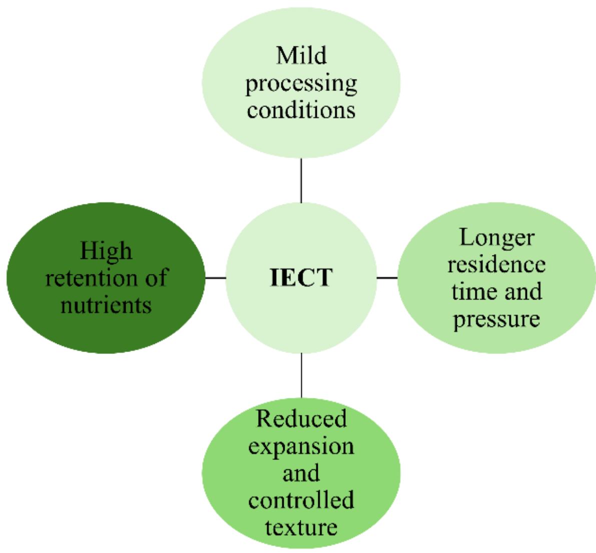

Figure 2. Advantages and characteristics of IECT.

IECT operates at significantly lower temperatures (Figure 3A, median around 100 °C) compared to conventional extrusion (median around 130 °C, with a range up to 200 °C or more). Furthermore, conventional extrusion applies much more thermal heat, and its chamber is longer, indicating greater variability in the process. Compared to conventional extrusion, IECT's more controlled, cooler process better protects heat-sensitive (thermolabile) nutrients, making it advantageous for preserving nutritional quality. In Figure 3B, there is a drastic difference: IECT works with high moisture (median around 37-40% and ranges exceeding 60%), while conventional extrusion works with low moisture (median below 20%). Conventional extrusion requires drier ingredients to generate friction and heat, which helps develop texture. In contrast, IECT uses more water, which allows gentler mixing and easier ingredient hydration, potentially protecting temperature-sensitive nutrients and resulting in a moister product. IECT operates at very low speeds (Figure 3C, less than 50-60 rpm), while conventional extrusion operates at high speeds (median above 250 rpm and reaching up to 600 rpm). The screw speed is directly related to the shear

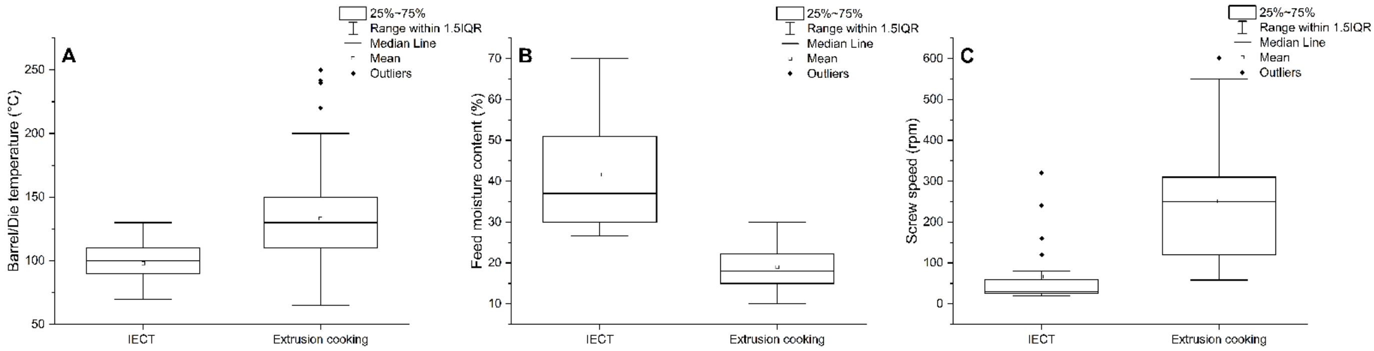

Figure 3. Box plots of IECT and conventional extrusion. A) Barrel/Die temperature, B) Feed moisture content, C) Screw speed. Note: The operating data for conventional extrusion cooking was obtained from Téllez-Morales et al. (2022b) previously.

stress, which breaks molecular structures and aggressively texturizes, while low shear treats the material gently. Based on these three parameters, IECT is emerging as a low-shear, low-temperature, high-moisture technology. Unlike conventional extrusion, which is aggressive, hot, and fast, IECT appears to be designed to save energy (lower temperature and lower motor speed), preserve nutritional quality by avoiding excessive heat, and possibly process materials that require greater initial hydration.

IECT's mild processing conditions are central to its advantages (Figure 4), allowing for desirable structural and property changes without the severe degradation seen in conventional high-temperature, high-shear extrusion (Cheng et al., 2020; Liu et al., 2011).

Impact on starch structure and gelatinization

IECT profoundly alters the multi-scale structure of starch, leading to increased gelatinization and a shift in crystalline types (Figure 5, Table 1). IECT destructed the granular and crystalline structure of starch, X-ray diffraction (XRD) analysis confirms that the semicrystalline structure of native buckwheat starch was destructed to some extent (Cheng et al., 2020). For corn, potato, and pea starches, IECT damaged the crystal structure of starch granules (Wang et al., 2023a). Increased gelatinization degree (DG) of modified buckwheat flour (MBF) samples was significantly increased after extrusion treatment, ranging from 17.4%–65.7% compared to 7.01% for native flour (Cheng et al., 2020). Similarly, for indica rice starch, DG increased to >60% (Liu et al., 2017). The A-type crystalline structure of jackfruit seed starch (JFSS) was turned into the V-type after extrusion cooking (Li et al., 2021). Corn starch also showed formation of V-type crystal structure (Wang et al., 2023a). This V-type crystallinity is often due to amylose-lipid complexes formed during the extrusion of cereal starch (Liu et al., 2017). IECT causes molecular degradation in starches, particularly affecting amylopectin due to its large size (Liu et al., 2017; Li et al., 2021). This leads to a large reduction in the size of molecules, the degradation primarily occurs in chains between clusters (Liu et al., 2017) and involves the breakage of α-1,4-glycosidic bond in amylopectin (Li et al., 2021).

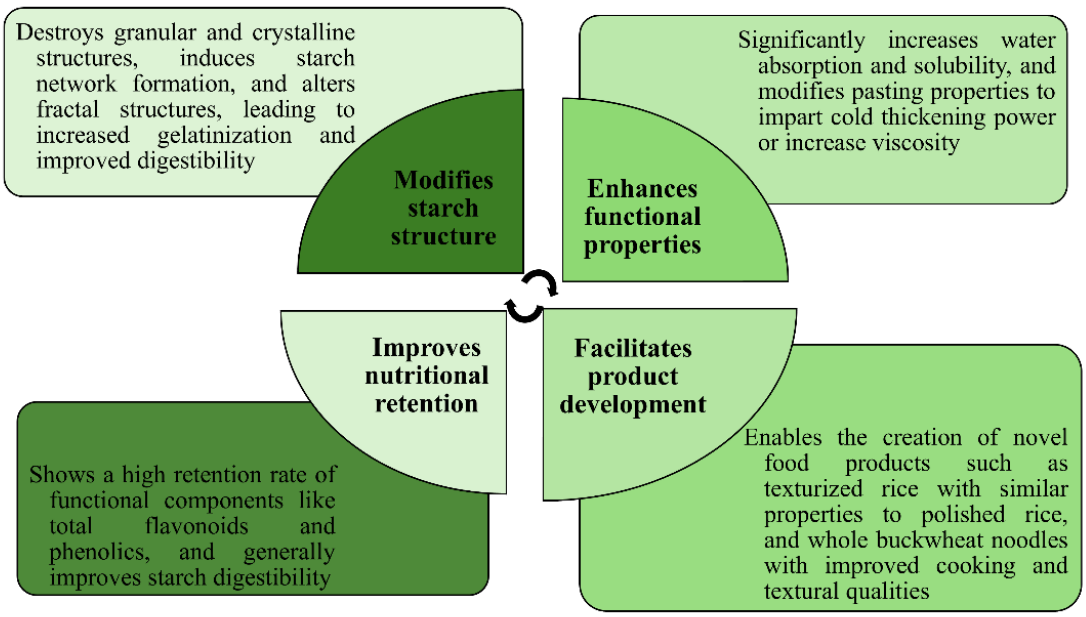

Figure 4. Changes that occur with IECT (Cheng et al., 2020; Li et al., 2021; Wang et al., 2023a; Zhang et al., 2021; Liu et al., 2017; Zeng et al., 2016; Gao et al., 2022; Liu et al., 2011).

Table 1. Reported effects on starch structure and gelatinization using IECT.

Reference	Starch material	Impact on starch structure and gelatinization by IECT
Cheng et al. (2020)	Modified buckwheat flour	IECT destroyed the granular morphology, altered the crystalline structure, and modified the fractal structure of buckwheat starch. The degree of gelatinization increased significantly (from 7.01% to 17.4%–65.7%). Destruction and packing of starch granules were observed. Viscosity decreased, and the water solubility index and swelling capacity index increased.
Gao et al. (2022)	Modified buckwheat flour	Crystallinity decreased markedly (from 30.93% to 7.82%) with increasing temperature and decreasing humidity, promoting gelatinization. A type V crystalline structure (amylose-lipid complexes) was formed. Destroyed and partially fused starch granules were observed.
Li et al. (2021)	Jackfruit seed starch (JFSS)	The relative crystallinity decreased significantly (from 29.39% to 11.86%–13.72%). The crystalline structure changed from type A to type V.
Lin et al. (2025)	Corn starch (CS) and CS-LA-MA complexes (Palmitic acid, Maltitol)	Treatment with CS alone increased the water absorption index (from 1.72 g/g to 4.22 g/g) due to the alteration of the crystalline structure. Peak viscosity, break viscosity, and final viscosity decreased significantly. Relative crystallinity decreased.
Liu et al. (2011)	Texturized rice (TR)	It enabled gelatinization with minimal extrudate expansion by forming complexes among starch, fat, and protein. Increasing moisture content and screw speed increased the WAI.
Liu et al. (2017)	Pregelatinized indica rice starch (IPS)	IPS showed greater solubility and absorbency in water at low temperatures. Substantial reduction in the molecular size of amylopectin. The starch granules lost integrity, forming a honeycomb-like structure. Crystallinity decreased significantly (from 25.69% to 4.42%). Type V crystallinity formation was observed. Break viscosity and setback viscosity decreased, suggesting improved gel stability and reduced short-term retrogradation.
Liu et al. (2019)	Rice starch	The molecular size of the starch decreased (degradation was concentrated in amylopectin, with negligible effects on amylose). IECT accelerated long-term retrogradation (increased crystallinity and retrogradation enthalpy).
Wang et al. (2023a)	Corn starch (Type A), potato starch (Type B) and pea starch (Type C)	IECT caused similar structural variations across the three types of starch. It reduced the relative crystallinity, the gelatinization enthalpy, the gelatinization temperature, and the viscosity. The crystalline structure suffered severe damage (disappearance of Malta crosses). A V-type crystalline structure was observed. Short-range order and double helix values decreased overall.
Wang et al. (2025)	Corn starch (CS) and CS-Lauric Acid (LA) complexes	IECT-NCS (CS without LA) showed a significant reduction in crystallinity (from 27.27% to 24.36%). Extractability increased significantly, and viscosity decreased dramatically. The amount of bound and semi-bound water increased. When CS-LA complexes were formed, IECT facilitated LA penetration, resulting in a higher Complex Index (up to 91.7%). Two distinct endothermic peaks were detected by DSC (one for gelatinization and one for the starch-lipid complex).
Ye et al. (2016)	Rice starch	Improved freeze-thaw stability. Inhibited starch retrogradation, particularly amylose retrogradation. The formation of amylose-lipid complexes (type V crystallinity) was confirmed by XRD.
Zhang et al. (2014)	High amylose rice starch	It delayed starch retrogradation. Low retrogradation enthalpy values (0.69 J/g of amylopectin) were obtained, and the retrogradation rate was low. Relative crystallinity was low after IECT (4.22%). The crystalline structure changed from type A to amorphous. The proportion of short-range order decreased (FTIR ratio 1047/1022 cm^{-1}).
Zhang et al. (2021)	Jackfruit seed starch (JFSS)	The enthalpy, relative crystallinity, and molecular order decreased significantly, indicating the disruption of the double helix and of short- and long-range order. A conversion of the crystalline structure from type A to type V was observed. Amylopectin was more susceptible to shear degradation than amylose. Extruded starches exhibited a looser, more porous structure.

Effects on functional properties

The structural modifications induced by IECT (Table 1) translate into significant improvements in the functional properties of flours and starches, enhancing their utility in food applications. IECT treatment significantly increased the water absorption index (WAI) and water solubility (WSI) indices of texturized rice (Liu et al., 2011). For MBF, WAI ranged from 7.84 to 9.67 g/g compared to 7.49 g/g for native flour, and WSI increased significantly from 0.17 to 0.36 g/g, this is attributed to the disruption of crystalline structure and exposure of more hydroxyl groups (Cheng et al., 2020). IECT results in lower peak viscosity, breakdown value, setback value, and final viscosity for MBF, making them easier to swell and thicken in contact with water, some MBF samples also exhibited a cold thickening power (Cheng et al., 2020). IECT-pregelatinized starch (IPS) showed improved gel stability and reduced short-term retrogradation, indicated by significantly ($p < 0.05$) lower breakdown and setback viscosities (Liu et al., 2017). Studies on high-amylose rice starch confirm that IECT leads to a low retrogradation percentage and low retrogradation rate (Zhang et al., 2014; Ye et al., 2016). This is partly due to the formation of amylose-lipid complex which inhibits re-association (Ye et al., 2016).

Starch digestibility and mechanochemical theory

IECT significantly impacts starch digestibility, with the extent of modification influencing how rapidly starch is broken down *in vitro*. This effect is linked to the mechanochemical changes occurring during the extrusion process. IECT-treated starches are easier to be digested than native starches, showing a higher hydrolysis rate (Gao et al., 2022). For jackfruit seed starch, the RS content of JFSS significantly decreased from 77.60% to 17.32%, while the RDS and SDS content improved (Zhang et al., 2021). Cooked IECT-modified starch also showed improved digestibility, reaching about 90% compared to 80% for native cooked starch (Wang et al., 2023a). The improved digestibility is due to destruction of starch supramolecular structure (Li et al., 2021). Higher extrusion temperature could promote the water diffusion rate, leading to a higher gelatinization degree of starch, and lower feeding moisture content could increase the specific mechanical energy (SME) and result in a severe gelatinization of starch as well as molecular breakdown, all contributing to enhanced digestibility (Gao et al., 2022). The effects of IECT treatment on starch digestibility would be interpreted in terms of mechanochemical theory if similar three stages were found during IECT (Wang et al., 2023a). IECT is proposed to cause three stages similar to mechanochemical theory on starch granules, where appropriate IECT treatment resulted in most of starch granules in the agglomeration stage, which significantly improved the digestibility by exposing a large number of enzyme binding sites. This is because mechanical force causes starch crystals were prone to dislocation which increased the active sites of starch molecules (Wang et al., 2023a).

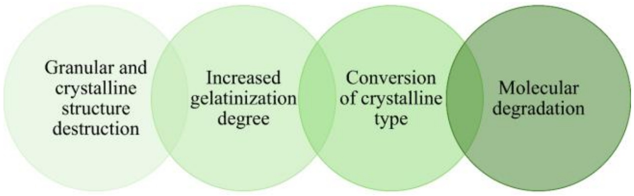

Figure 5. Impact on starch structure

Applications in food products

IECT modified flours and starches show strong potential for developing improved and novel food products, especially gluten-free options (Table 2).

- *Whole Buckwheat Noodles:* MBF promoted the formation of continuous dough structure, enhanced the stability and viscoelastic properties of the dough, and significantly decreased the cooking loss and broken rate of noodles, while improving texture properties. Sample 70-30 yielded the best cooking properties with the lowest cooking loss of 2.73% and broken rate of 8.89% (Gao et al., 2022).
- *Texturized Rice:* IECT enables the preparation of texturized rice (TR) from broken rice and rice bran that possesses similar texture properties and shape with polished rices, while being rich in nutrients (Liu et al., 2011).
- *Gluten-Free Products:* The improved functional properties, such as cold thickening power and enhanced dough consistency, make MBF beneficial in gluten-free bakery products (Cheng et al., 2020).
- *Ready-to-Eat Cereals and Whipped Doughs:* The higher water binding capacity of IECT-modified flours makes them a suitable bulking agent in ready-to-eat breakfast cereals, whipped doughs (such as cakes, cupcakes or sponge cakes), and breads to improve bread volume, decrease initial hardness and delay staling (Cheng et al., 2020).

Gaps and future research directions

Sources mention shear degradation of amylopectin and breaking of α-1,4-glycosidic bonds. However, further studies are needed on precise molecular changes, such as the degree of polymerization and molecular weight distribution (Li et al., 2021; Zhang et al., 2014). Additionally, the high retention of phenolics and flavonoids is highlighted, suggesting that systematic studies correlating IECT parameters (temperature, moisture, screw speed) with the retention of heat-sensitive bioactive compounds would be beneficial. Moreover, sources note that bioaccessibility studies are limited to *in vitro* digestion; thus, future research should focus on the *in vivo* bioavailability of cereal phenolics to confirm health benefits (Zeng et al., 2016). The discrepancy between phenolic acid and total antioxidant compound bioaccessibility suggests that unidentified compounds contribute significantly, underscoring the need to identify and quantify these other bioaccessible antioxidant compounds (Zeng et al., 2016). Furthermore, Liu et al. (2017) state that 'Emulsifying activity and rheological behavior are areas for future work,' showing a need for more comprehensive characterization for broader food applications. In addition, while Wang et al. (2023a) explored different crystal types of starch, further optimization of IECT parameters for specific starch sources (e.g., tuber vs. cereal) could be considered to efficiently achieve desired properties. Finally, although short-term retrogradation is addressed, more studies on long-term stability and shelf-life of products made with IECT-modified ingredients would be valuable for commercial applications. Figure 6 summarizes research gaps and future directions.

Conclusions

IECT is established as a superior, more controlled alternative to conventional extrusion. It is distinguished by gentler processing conditions—low temperature, low screw speed, and high moisture. The mechanical design also features longer screws. At the structural level, IECT causes a profound transformation by destroying the granular and crystalline structure of starches. It raises the degree of gelatinisation above 60%. This often helps transition type A crystals to type V by forming amylose-lipid complexes. These molecular modifications lead to significant functional improvements. These include increased solubility and water absorption, reduced viscosity, and greater stability against retrogradation. From a nutritional perspective, the technology stands out for its dual capacity. It improves starch digestibility by exposing starch surfaces where enzymes can attach, a process driven by mechanical and chemical actions (mechanochemical effects). At the same time, it achieves superior retention

Table 2. Application of IECT in different food products.

Product type / Material	Starch source	Key IECT parameters	Functional and structural improvements	References
Modified flour	Common native buckwheat	Temp: 70–100 °C Moisture: 30%–70% Screw speed: 60 rpm	Significant increase in water absorption index; high retention rate of bioactive components (flavonoids and phenols) compared to conventional extrusion.	Cheng et al. (2020)
Whole wheat noodles	Whole grain common buckwheat	Temp: 70–100 °C Moisture: 30%–58%	Reduction in cooking loss and breakage rate; improvement in texture properties (hardness, elasticity) and formation of a denser, more continuous dough structure.	Gao et al. (2022)
Modified starch (A, B, C)	Corn (Type A), Potato (Type B), Pea (Type C)	Temp: 50–95 °C Screw speed: 80–320 rpm Moisture: 42%	Increase in rapidly digestible starch (RDS) due to structural damage (mechanochemical); reduction in crystallinity and gelatinization enthalpy; exposure of enzyme binding sites due to agglomeration.	Wang et al. (2023a)
Enzymatically modified starch	Corn starch + thermostable α-amylase	Temp: 50–95 °C Screw speed: 120 rpm Moisture: 42%	Destruction of the crystalline structure; increased solubility and light transmission; reduction in gelatinization temperature; favorable mechanochemical effect for enzymatic modification.	Wang et al. (2023b)
Textured rice	Broken rice and rice bran	Temp: 69.8–120.2 °C Moisture: 26.6%–33.4% Screw speed: 20.1–32.6 rpm	Properties similar to polished rice in terms of texture and shape, but with higher nutritional content (fiber, protein, vitamins); minimal expansion of the product.	Liu et al. (2011)
Pregelatinized starch	Indica rice	Temp: 50–100 °C Moisture: 30%–70% Screw speed: 37.5 rpm	High solubility and absorption in cold water; lower setback and breakdown viscosity (better gel stability); honeycomb structure formation; reduction in short-term retrogradation.	Liu et al. (2017)
Modified retrograde starch	Rice	Temp: 90 and 130 °C Speed: 15 and 50 Hz Moisture: 60%	Inhibition of short-term retrogradation but acceleration of long-term retrogradation (increase in crystallinity and enthalpy after storage); preferential degradation of amylopectin.	Liu et al. (2019)
Retrograded high amylose starch	High amylose rice (28.9%)	Temp: 50–100 °C Moisture: ~51% Screw speed: 37.5 rpm	Reduction in the rate and percentage of retrogradation compared to native starch; change in diffraction pattern from type A to amorphous/type B.	Zhang et al. (2014)
Starch with improved digestibility	Jackfruit seed (*Artocarpus heterophyllus*)	Temp: 90–110 °C Moisture: 27%–34% Screw speed: 20–30 rpm	Significant increase in *in vitro* digestibility (RDS and SDS) and estimated glycemic index; drastic reduction in resistant starch (from 77.6% to ~17%); change from compact to porous morphology.	Li et al. (2021); Zhang et al. (2019); Zhang et al. (2021)
Processed cereals	Brown rice, wheat, oats	Temp: 120 °C Moisture: ~30%	Decrease in free phenolics but increase in bound phenolics; reduction in the bioaccessibility of phenolics in rice and oats, with minimal effect on wheat.	Zeng et al. (2016)

of delicate, heat-sensitive bioactive compounds, such as phenols and flavonoids. This minimises compound breakdown, which usually happens during traditional intense mixing and heating processes (traditional high-shear processing). In food systems, IECT has proven to be a versatile tool for developing value-added products. For example, it enables the production of nutritionally enriched textured rice that mimics the texture of polished rice. Furthermore, it helps formulate high-quality gluten-free products, such as buckwheat noodles with improved dough consistency and reduced cooking losses. IECT-modified flours and starches also act as effective functional ingredients, serving as bulking agents (which add volume) and thickeners (which increase viscosity) in baked goods and ready-to-eat cereals. While IECT has demonstrated its technical feasibility for producing ingredients with improved physicochemical properties (such as texture, solubility, and stability), its full industrial relevance remains to be determined by future research. To establish this relevance, research must move beyond current cereal-focused models. Specifically, expanding IECT applications to more complex matrices, such as tubers (e.g., potatoes), legumes (e.g., beans), and proteins, is imperative. Additionally, health benefits should be validated through *in vivo* bioavailability studies. Addressing these gaps will make IECT a cost-effective, energy-efficient platform for modifications and reinforce its position as a key technology for producing processed foods that are functionally stable and nutritionally dense.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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