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Review

Evolution of Dried Food Texturization: A Critical Review of Technologies and Their Impact on Organoleptic and Nutritional Properties

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Abstract: The evolution of food texturization techniques has opened new possibilities for producing healthy, ready-to-eat (RTE) snacks with improved sensory and nutritional properties. Originating from traditional methods such as deep frying and popping, the field has now embraced advanced technologies, including mechanical extrusion, puffing, Détente Instantanée Contrôlée (DIC), and the more recent Intensification of Vaporization by Decompression to the Vacuum (IVDV). These methods focus on enhancing texture and flavor and preserving nutritional value, while also prolonging shelf life, effectively meeting the increasing consumer demand for healthier snack options. This review explores the various food texturization methods, highlighting the key parameters for the optimization of organoleptic and nutritional properties. The strengths and limitations of each method were systematically evaluated and critically assessed. The development of innovative approaches for potential industrial applications, alongside efforts to mitigate the drawbacks of conventional methods, has become imperative. A comparative analysis was conducted, focusing on aspects such as productivity, efficacy, and operational conditions, demonstrating that the novel methods tend to be more environmentally sustainable and cost-effective while delivering the best-quality product in terms of texture, color, expansion factor, and nutritional content attributes.

Keywords: food expansion; snacks; IVDV; texturization; organoleptic enhancement

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1. Introduction

Dehydrated foods have been utilized since ancient times, with evidence dating back to 12,000 BCE, when early civilizations harnessed natural elements like sunlight and wind to dry and preserve foods [1,2]. In modern times, dehydration has become a crucial technique in the food industry, as it reduces moisture content to levels that inhibit microbial growth and limit spoilage [3]. This method is widely recognized for its effectiveness in extending products' shelf life, minimizing food waste [4], and lowering costs related to storage and

transportation [2]. However, the process is often associated with the phenomenon of shrinkage, which can lead to a decline in food quality [5], adversely impacting nutrient contents, texture (resulting in a rubbery consistency), color, and flavor [6]. These quality deteriorations render dehydrated foods less appealing to a considerable segment of consumers [7]. To address these limitations, contemporary researchers have extensively studied and refined texturization techniques designed to restore desirable sensory attributes and enhance the texture (crunchiness, hardness (HARD), etc.), color, and flavor of dehydrated food products [8].

These methods typically involve exposing partially dehydrated food products to mechanical strain under high temperatures and pressures, promoting alveolation and, thus, leading to expansion by the formation of small air pockets within the food product [9–11]. Texturized food products are characterized by enhanced mass transfer, which accelerates dehydration following expansion [12]. These advancements represent a concerted effort to balance the industrial advantages of dehydration while preserving food quality, ensuring that consumer expectations are met. This process is widely applied in producing fruit [13–15] and legumes [16,17], snacks and cereals [18,19], extruded snacks [20], cheese-based snacks [21,22], meat [23], and fish analog snacks [24], as well as grain [25–27] and seed-based products [28,29]. This list is growing longer, with new food products entering the market nearly every day [20].

The process of texturization/expansion dates back to approximately 5000 BCE [30], when ancient Indians utilized the popping method to produce chapati, an unleavened flatbread made from whole-wheat flour. As chapati is exposed to an open flame, moisture within the dough vaporizes into steam, creating air pockets that lead to its characteristic expansion [31]. More recently, in the 1980s, researchers studied the popping process in grains, where food undergoes rapid and explosive expansion [32]. During this process, the moisture within the grain is exposed to high temperatures, vaporizing into steam [33] that accumulates within the grain's rigid outer shell, causing its internal pressure to rise. When the pressure reaches a critical point, the outer shell ruptures, releasing steam [34].

Shallow frying techniques have been used since ancient Mesopotamian times. Furthermore, archaeological evidence suggests that deep frying (DF) was practiced by the Egyptians as early as 1000 BCE to prepare fried dough-based foods. These foods were cooked in hot oil using clay pots over open fires [35]. More recently, DF as a texturization method has been the subject of scientific studies since 1937 [36]. This technique involves simultaneous heat and mass transfer, during which water is expelled from the food while oil is absorbed.

During the 1970s, another expansion method involving mechanical extrusion (ME) [37,38] was applied to food items such as grains, starches, or dough, to produce expanded products like cereals and snacks. In this method, the food items are fed into an extruder, which commonly involves a barrel with one or two rotating screws [39,40]. As the food moves through the barrel, it is subjected to increasing heat and pressure [41,42]. Upon exiting the die, the food undergoes a pressure drop, generating steam, which expands within the food, causing the extruded product to increase in volume [43].

In India, the cultivation of paddy dates to ancient times, during which a traditional puffing method was employed to produce puffed rice through hot sand roasting. The feeding of conditioned rice for roasting in the sand is performed manually, which is a time-consuming and laborious process that can take multiple days to complete [44]. In the 20th century, advancements were carried out to improve the puffing process through machinery to make it more efficient, autonomous, and commercially viable [44]. Notably, in 1950, puffing was studied as a texturizing technique using self-vaporization, where partially dehydrated food products are subjected to high temperatures and pressures, followed by

rapid decompression to atmospheric pressure [45]. This process relies on the expansion caused by the vaporization of internal moisture when the pressure is suddenly released. Between 1977 and 1983, Sullivan et al. enhanced the puffing method by developing a novel system that enables continuous-flow puffing [46]. This significantly increases the production capacity to a range of 200 to 450 kg/h for partially dehydrated products to 25% d.b. water content [47]. Subsequent research investigated additional systems, including fluidized-bed techniques [48,49] and methods utilizing soluble gases such as CO_2 and NO_2 [50,51]. Notably, all of these advancements still used a decompression stage back to atmospheric pressure [52]. From the original concept of expansion by self-vaporization, the treatment cycle remained relatively unchanged, typically involving exposure to steam pressure at a high temperature, followed by decompression to atmospheric pressure. This standard cycle poses challenges for heat-sensitive food products. Consequently, modifications were limited primarily to increasing production capacity and, occasionally, to automating processes and reducing processing costs [53].

In the 1990s, a new method was introduced, known as "Controlled Sudden Decompression" (DIC), building upon the original concept of expansion through self-vaporization. This process involves subjecting the product to a thermo-mechanical treatment, followed by a rapid decompression to the vacuum [53]. The generation of steam through self-vaporization is significantly enhanced at lower final equilibrium temperatures of around 40 °C, compared to the 100 °C typically observed when decompression to atmospheric pressure occurs, as in the puffing process. This innovative method is particularly effective in processing the majority of heat-sensitive biological products [8], involving mild treatment conditions characterized by a short treatment duration of 15 s at temperatures below 150 °C, followed by decompression to a vacuum of 0.1 bar [12]. However, many heat-sensitive food products may experience additional thermal degradation, as studies have reported that it can take up to 10 s to reach the treatment temperature.

More recently, an improved version known as Intensification of Vaporization by Decompression to the Vacuum (IVDV) has emerged, demonstrating superior effectiveness as a texturizing treatment. IVDV enables a rapid pressure surge up to 12 bar in less than 1 s. This rapid compression is particularly advantageous for treating heat-sensitive food products, as it involves treatment durations of less than a few seconds under high pressure, minimizing the risk of damage to products that cannot withstand extended exposure to elevated pressures for prolonged periods [54,55].

The increasing global interest in the production of expanded, healthy, and ready-to-eat (RTE) snacks has garnered significant attention from research teams worldwide. This review delves into the scientific basis of the expansion processes, providing a comprehensive understanding of the mechanisms driving structural and functional modifications in expanded food products. Additionally, it systematically compiles and analyzes a comprehensive array of methods for the expansion and texturization of various snacks and food products. The primary objective is to discuss and compare different expansion techniques applied to various food products based on factors such as the expansion factor (EF), expansion ratio (ER), specific volume (in mL/g), increase in thickness (in mm), nutritional value, and organoleptic properties of the expanded products. This review highlights the pre-treatments, post-treatments, and optimal parameters utilized in each process. Additionally, it underlines the advantages, disadvantages, and improvements made over the years for each method. The chronological evolution of the expansion process through technological and methodological advancements is also elucidated.

2. Popping Expansion

Popping in food expansion is a process wherein a food product undergoes rapid heating and expansion, resulting in a light, airy, and crispy texture. The mechanism involves subjecting the food product to high temperatures, which cause the internal moisture to vaporize and generate steam [56,57]. This steam accumulates pressure within the food matrix until it expands explosively, forming a porous, expanded structure [32]. Simultaneously, the starch inside gelatinizes and expands upon the release of pressure, leading to a swift cooling phase, which gives the product its light and airy texture [58]. Details regarding the experimental parameters, pre- and post-treatment methods, nutritional value, and EF as a ratio or specific volume (in mL/g) are included in Table 1. This is followed by a comprehensive discussion that examines each reference, compares them chronologically based on the desired end product, and offers critiques providing further insights into each study.

Table 1. Popping texturization of dehydrated food.

Methods/Year/ Reference	Target Product(s)	EFs (Ratio, mL/g)	Pre-Treatment	Post-Treatment	Parameters and Outcomes
Popping (2002) [59]	Popped amaranth snacks	5.2	-Drying: 30 °C → W = 10–11% d.b. -Hydration → W = 12% d.b. -Storage: 48 h	N/A	-T = 240 °C -Load = 22 g -Airflow = 0.013 m^3/s -Crunching = 13 ± 3.7
Popping (2004) [60]	Popcorn	Specific volume: -Microwave popping: 33.1 mL/g -Conventional popping: 37.3 mL/g	-Moisture: 12.2% d.b. -Mixing of coating ingredients -Corn coating	Cooling: 3 min	Microwave popping: -Coating mixture: 4.4% salt, 5.9% vegetable oil, 0% sodium bicarbonate, and 16.4% butter -P (microwave) = 715 W/t = 2 min -Un-popped kernel ratio = 4.2%. Conventional popping: -Coating mixture: 3.5% salt, 6% vegetable oil, 0.10% sodium bicarbonate, and 12.9% butter -Un-popped kernel ratio = 0.2%
Microwave Popping (2004) [61]	Popcorn	Specific volume: 42.1 mL/g	-Drying -Hydration: distilled water -Storage: 5 °C, 35–40 days	N/A	-W = 14% d.b. -P (microwave) = 1200 W/ t = 2.5–3 min -Flake size = 4.81 cm^3 -Popping yield = 97.61%
Popping (2008) [62]	Popped sorghum	Specific volume: 16 mL/g	-Cleaning -Tempering: 25 °C, 4 h and 4 °C, 44 h -Drying → W = 12, 14 or 17% d.b. -Storage: 4 °C	-Separation of un-popped kernels. -Storage: plastic zip bags	-T = 200.3 °C/W = 17% d.b. -Popping yields ≥ 80% -Foam: L^* = 75.8 ± 6.31 -Husk: L^* = 27.3 ± 5.13
Baking Popping (2010) [63]	Popped amaranth flour, gluten-free breads and cookies	-Cookies: 5.84 -Bread: 3.4	-Mixing dough -Molding dough -Fermentation: 52 min, 86% relative humidity, 36 °C	N/A	-T = 205 °C/t = 17 min -HARD (cookies) = 10.88 N -Amaranth bread composition: 60:40 (popped/raw)
Popping (2014) [64]	Protein-rich popcorn	Specific volume: 5.63 ± 2 mL/g	-Overnight dipping in salt solution -Draining -Drying: 3–4 h, 150 °C	-Cooling -Packaging: polythene bags	-T = 250 °C/t = 5 min -15% salt in solution -Bulk density = 0.19 g/mL -L^* = 54.13/a^* = 10.79/ b^* = 22.3
Microwave Popping (2015) [65]	Popped sorghum	14.56	-Hydration → W = 12, 16, and 20% w.b. -Storage: microwavable paper bag, room temperature	N/A	-W = 16.62% w.b. -Microwave power density = 18 W/g -P = 900 W/t = 140 s -Mixture: 0.55% salt and 10% oil -Popping yield = 82.3%

Table 1. *Cont.*

Methods/Year/ Reference	Target Product(s)	EFs (Ratio, mL/g)	Pre-Treatment	Post-Treatment	Parameters and Outcomes
Microwave Popping (2015) [66]	Popped sorghum	14.5	-Hydration → 16.5 ± 0.5% w.b. -Coating: salt solution (0.5%) -Drying -Coating: oil 10 mL/100 g of grain -Packaging: microwave paper bags	-Cooling of chamber: 3 min -Handpicking of un-popped grains	-P = 900 W/t = 140 s -Grain size = 3.04 mm -Bulk density = 833.4 kg/m^3 -Popping yield = 81.2% ± 0.6 -HARD = 103.46 N
Popping (2015) [67]	Popped sorghum	Specific volume: 6.5 mL/g	Hydration → 14% d.b.	N/A	-Popping yield = 87.4% -Processing losses < 3.7% -Size: extra-large white fully opened and excellent
Popping (2016) [68]	Popped brown rice snacks	6.85	-Soaking: water, 80 °C, 4 h -Autoclaving: 1.47 bar, 10 min -Drying: 40 °C -Mixing: salt solution -Drying	Sieving	-Salt content = 1.75 g/100 g raw material -W = 15% d.b./T = 225 °C -HARD = 15.68 ± 1.3 N -L^*= 67.78/a^* = 7.13/b^* = 23.27 -Bulk density = 137.85 ± 2.8 kg/m^3
Popping (2017) [69]	Grain-based gluten-free snacks	N/A	Manual cleaning: remove impurities	-Grinding (T < 40 °C) → flour -Dough preparation -Cutting: cubes -Drying: 60 °C → W = 20% d.b. -Flake toasting: 180 °C, 3 min	-T = 260 °C -t = 30 s -HARD = 13.6 N -L^* = 44.8/a^* = 8.3/ b^* = 21.2/ΔE^* = 56.9
Popping (2018) [70]	Pseudo-cereal based on popped amaranth flour	4.36	-Cleaning and washing -Drying: 50 °C, 4 h -Grinding raw seeds → flour	-Sieving: 20 mesh size -Milling: popped seeds → flour	-T = 190 °C/t = 15 s -Popping yield = 76.2% -Flour recovery yield = 74.3% -Bulk density = 0.36 g/mL
Baking Popping (2018) [71]	Wheat bran-based bread	N/A	-Wheat bran addition: 5% flour basis -Water addition: 66.5, 67.75, and 69 mL	N/A	-Mean bubble size = 31.4 ± 1.1 µm -T (gelatinization) = 73.2 °C -HARD = 32 N
Microwave Popping (2018) [72]	Popcorn	9.57	-Drying → W = 11% w.b. -Placing grains in glass beaker -Covering glass beaker: aluminum foil -Puncturing aluminum: 2–3 holes	N/A	-Popping yield = 87.81% -T = 200 °C/t = 150 s -P (microwave) = 720 W
Microwave Popping (2020) [73]	Popcorn snacks	13.5	-Sieving and cleaning -Drying: 40 °C, V (air) = 0.5 m/s	N/A	-P (Microwave) = 1600 W/ t = 2.9 min -Residue: 11% -11.39 ≤ W ≤ 12.91% d.b. -Toughness = 61 kg.s -L^* = 86.8/a^* = −0.6/b^* = 4.5
Baking Popping (2020) [74]	Lima bean aquafaba-infused eggless cupcakes	N/A	-Drying → 16% d.b. -Storage: 30 °C -Soaking: 2 L water, 12 h, room temperature -Air drying -Cooking: bean/water ratio 1:4) -Microwave: 840 W, 15 min -pH adjustment > 4	N/A	-t (baking) = 60 min -Springiness = 8.79 mm -Gumminess = 2.47 g -Chewiness = 21.76 mJ Crumb: -HARD = 4.03 ± 0.55 N -L^* = 79.54/a^* = −1.20/ b* = 26.13 Crust: -HARD = 3.3 ± 0.5 N -L^* = 76.65/a^* = −0.92/ b^* = 25.68
Popping (2021) [75]	Popped sorghum	4.3	-Drying → 11% w.b. -Equilibration: 4 °C, 48 h	Cooling: 27 °C, 30 s	-T = 210 °C/t = 90 s -Popping yield = 71% -Peak temperature = 76.8 °C -ΔH (gelatinization) = 5.07 J/g -Double-helix degree = 0.987
Popping (2022) [76]	Air-popped starch snacks	N/A	-Drying: 105 °C, 2 h -Grinding -Sieving: 106 µm -Rehydration: steam water 50 °C	-Molding: diameter 45 mm, depth 10 mm -Heat pressing: 230 °C, 4 s, 4 bar	-15 ≤ W ≤ 21% d.b. -T = 210 °C/t = 10 s -Density < 100 kg/m^3

Table 1. *Cont.*

Methods/Year/ Reference	Target Product(s)	EFs (Ratio, mL/g)	Pre-Treatment	Post-Treatment	Parameters and Outcomes
Infrared (IR) Popping (2022) [77]	Popcorn	22.5	-Cleaning and sieving -Drying → 14% d.b.	N/A	-P (IR) = 550 W/ d (lamp-grain) = 10 cm -Popping yield = 100% -Bulk density = 0.03 ± 0.01 g/cm^3 -L^* = 76.297/a^* = −2.566/ b^* = 9.502
Popping (2023) [78]	Rice flour-based bread	Specific volume: -Milyang260: 4.39 mL/g -Milyang261: 3.19 mL/g -Goamibyeo: 2.96 mL/g -Suweon: 2.18 mL/g	Preparation of rice flour: -Centrifugal disk dry-milling -Sieving < 125 µm -Storage: plastic bag, 4 °C Gelatinization of rice flour: -Hydration -Heating phase 1: 50 °C, 1 min -Heating phase 2: 95 °C, 3.8 min -Holding heat: 7 min and 18 s -Cooling: 30 min -Storage: 4 °C for 1 day	N/A	-20.82 $\pm$ 1.03 $\leq$ Amylose content $\leq$ 31.79 $\pm$ 1.48 -3.85 $\leq$ Crumb firmness ratio $\leq$ 6.25

2.1. Amaranth Grain Popping and Flour Applications

The popping process of amaranth grains has been extensively studied across several key research efforts. Optimal conditions for popping amaranth grains were identified, finding that grains hydrated to 12% d.b. and subjected to 240 °C with an airflow rate of 0.013 m^3/s resulted in a sponge-like structure with an ER of 5.2 [59]. However, the study did not address the popping duration, a critical parameter that significantly impacts the efficiency and quality of the process, nor did it include popping yield data, limiting the understanding of the process's effectiveness for commercial viability. Moreover, the impact of the high popping temperature on the color of the grains, which is an important quality attribute affecting consumer acceptance, was not examined. Later studies evaluated the mixing properties, bread-making quality, cookie-making quality, and gluten content of flour derived from raw and popped amaranth. These studies found that bread formulations containing 60–70% popped amaranth flour and 30–40% raw amaranth flour produced loaves with a homogeneous crumb structure and higher specific volume (3.5 mL/g) compared to other gluten-free breads. For soft cookies, the best recipe included 20% popped amaranth flour and 13% whole-grain popped amaranth, resulting in an ER of 5.84 for cookies and 3.4 for bread when popped at 205 °C for 17 min [63]. While the study suggests that these ratios are optimal, it does not provide detailed insights into how different ratios within these ranges affect the texture, flavor, and nutritional profile of the final products. Further investigation into the functional properties of varying ratios and their specific impacts would strengthen the robustness and applicability of the findings. This would help determine whether the differences within these ranges are significant or whether a more precise optimal ratio can be identified. Lastly, in 2018, Khan et al. examined the physicochemical and nutritional properties of amaranth flour in both raw and popped forms to assess the effects of the expansion popping technique, conducted at 190 °C for 15 s, resulting in a popping yield of 76.2%, a flour recovery yield of 74.3%, and an ER of 4.36 [70]. However, the relatively low popping and flour recovery yields raise concerns about industrial scalability, as they suggest that a significant proportion of raw material is not converted into the desired product, resulting in increased waste and higher production costs. For commercial production, moderate temperatures and controlled popping durations are likely more scalable and cost-effective. Future research should focus on refining the technique to improve yields, ensuring a more economically viable production process, and minimizing waste while maintaining product quality.

2.2. Diverse Popping Methods of Maize (Popcorn)

The popping process has also been widely studied and implemented across different maize varieties to optimize popcorn quality. Researchers have determined optimal formulations of ingredients to maximize the expansion volume and minimize the proportion of un-popped kernels. When corn was microwaved at 715 W for 2 min with a coating mixture of salt, vegetable oil, and butter, an expansion volume of 33.1 mL/g was achieved, with an un-popped kernel ratio of 4.2%. By contrast, conventional popping using another coating mixture resulted in a lower un-popped kernel ratio of 0.2% and an expansion volume of 37.3 mL/g [60]. Nevertheless, this study has limitations that affect the comparability and applicability of the findings. Future research should aim for standardized ingredient formulations, consider the variability of microwave appliances, and include sensory and nutritional analyses to provide a more holistic understanding of the advantages and disadvantages of the two popping methods. Moisture content, genotypes, and popping methods have also been analyzed to understand their effects on expansion volume in popcorn. Corn kernels were dried to 14% moisture content and popped using a 1200 W microwave, yielding an expansion volume of 42.1 mL/g and a popping yield of 97.61% [61]. However, that study did not sufficiently explore the unique responses of each genotype to varying moisture levels and popping methods. A deeper analysis of the structural and chemical properties of each genotype could provide valuable insights for optimizing popping conditions. Further research evaluated the physical, sensory, and nutritional characteristics of various maize varieties. One prominent variety, pre-treated by dipping in a 15% salt solution and popped at 250 °C for 5 min, produced an expansion volume of 5.63 mL/g with a specific lightness value [64]. However, the study's reliance on a single temperature and duration, coupled with a large margin of error (±2), highlighted the necessity of a broader variety selection and a range of popping conditions to ensure consistent product quality. In another study, optimal popping yield with minimal time and energy consumption was targeted. Maize kernels were dried to 11% w.b. before being popped in a 720 W microwave at 200 °C for 150 s, achieving a high ER of 9.57 [72]. However, the absence of experimental repetitions undermines the reliability and statistical significance of the findings. Moreover, the limited scope of microwave settings, with only three power levels (60, 80, and 100%) and three moisture content levels (11, 13, and 15% w.b.), restricts the ability to fully explore and optimize the popping conditions. A more comprehensive experimental design would enhance the robustness and applicability of the study's findings. The impact of moisture content and expansion techniques on white popcorn's sensory attributes was also explored. Optimal popping was achieved using a 1600 W microwave for 2.9 min, resulting in a popping yield of 89%, with the kernels exhibiting a toughness of 61 kg.s and a high lightness value of 86.8 [73]. Nonetheless, the sensory analysis, although thorough, used a small sample of 20 trained evaluators, which may not reflect broader consumer preferences and limits the generalizability of the findings. A larger, more diverse panel could yield more representative sensory data. Furthermore, the exclusive use of the BR440 popcorn genotype ignores potential variability in popping characteristics across different genotypes. Including multiple genotypes would provide a more comprehensive understanding of how genetic diversity interacts with moisture content and expansion methods. In other research, scientists examined the influence of the IR popping process on the physicochemical properties of popcorn. Using an IR system at 550 W, with a regulated distance of 10 cm between the lamp and grains, a popping yield of 100% and an ER of 22.5 were achieved. The resulting popcorn exhibited color parameters primarily characterized by a lightness value of 76.297 [77]. Despite these impressive results, the study's lack of sensory evaluation (such as taste, texture, and aroma) underscores the

importance of integrating sensory analysis to link technological findings with consumer preferences, providing a holistic evaluation of the IR popping process.

2.3. Process Optimization of Popped Sorghum and Genotype Selection

The technique of popping has been applied to produce popped sorghum, with the process being refined through various studies documented in the literature. In an initial investigation conducted by Gaul et al., the researchers examined the influence of tempering methods and moisture levels on sorghum's popping characteristics. Grains dried to 17% d.b. and popped at 200 °C achieved an expansion volume of 16 mL/g and a popping yield exceeding 80% [62]. However, without a precise popping duration, it is challenging to replicate the experiment or to fully understand the kinetics of the popping process under the given conditions. This omission undermines the comprehensiveness of the study and suggests the need for more detailed reporting in future research. Later studies focused on optimizing the pre-treatment processes and microwave parameters for sorghum. Using a microwave at 900 W for 140 s, scientists achieved an ER of 14.56 and a popping yield of 82%. However, the waste percentage approached 19%, raising concerns about the process's efficiency [65]. A second study, conducted by the same researchers, evaluated the impact of the sorghum variety, characterized by kernel physicochemical properties, on microwave popping performance. Using the same popping process—microwaving at 900 W for 140 s—the Mugad variety achieved a maximized ER of 14.5 ± 0.3. The study also recorded a popping yield of 81.2% ± 0.6 and a HARD of 103.46 N [66]. Nonetheless, the reported popping yields suggest a waste percentage close to 19%, indicating inefficiencies that must be addressed to reduce wastage and improve overall yield. Furthermore, the second study recorded a kernel HARD value of 103.46 N, raising concerns about the texture of the popped sorghum and its consumer acceptability. A more robust textural evaluation, considering additional parameters such as crispness and brittleness, is necessary to ensure that the final product is both high-yielding and palatable. A third study aimed to identify the optimal genotype for commercial popped sorghum production. The study determined that the RPOSV 3 genotype was ideal. Grains of this genotype were dried to 14% d.b. and then popped, achieving a popping yield of 87.4% and an expansion volume of 6.5 mL/g. The resulting product was described as extra-large, fully opened, white, and of excellent quality [67]. Nevertheless, the limited sample size of only four sorghum genotypes raises concerns about the representativeness of the results, as it may not capture the full genetic diversity of sorghum. The selection criteria for these genotypes were also not clearly outlined, which may have introduced selection bias. Additionally, the statistical analysis section lacks detail on the specific tests used and their justification, with some results showing large standard errors, indicating the need for a more extensive sample size to ensure robust conclusions. Lastly, in another study, the researchers aimed to explore the impact of the popping process on the structural, rheological, and thermal properties of sorghum starch. Paloma variety grains were dried to 11% w.b. and then popped at 210 °C for 90 s. This yielded a 71% popping yield, with an expansion volume of 4.3 cm^3. The researchers also recorded a peak temperature of 76.8 °C and a ΔH (gelatinization) of 5.07 ± 0.042 J/g [75]. However, the study's standardized popping conditions of 210 °C and 90 s failed to explore the effects of varying temperatures and durations on the sorghum's properties, potentially missing key optimization parameters.

2.4. Popped Rice Applications

The popping technique has been applied to the production of rice-based products. In one study, brown rice grains were pre-treated to achieve a 15% moisture content and a 1.75% salt concentration, and then popped at 225 °C using hot sand. This method produced

a porous matrix with cavities of various sizes, highlighting a maximized ER of 6.85 and a reduced HARD of 15.68 N. The color analysis revealed an increase in lightness, with a slight reduction in yellowness and redness post-popping [68]. However, this method poses a contamination risk, as sand may introduce dirt, microbes, or unwanted particles, compromising the food's safety and quality. Furthermore, popping with hot sand may be less energy-efficient compared to methods like hot-air popping, which more effectively transfers heat to the rice grains, with less energy loss. Researchers also investigated the bread-making functionality of rice. The Milyang260 variety achieved a maximized expansion volume of 4.39 mL/g and formed a firm gel that maintained its shape after baking and storage [78]. Nevertheless, the emphasis on amylose content as the primary determinant of baking potential might overlook other significant factors, such as protein quality and minor starch components, which also influence the bread's characteristics. Additionally, the comparison with wheat flour is somewhat narrow, lacking a diverse range of wheat flour types and comprehensive consideration of various baking additives, which could provide a more robust benchmark for evaluating rice flour's performance. Addressing these issues could enhance the study's applicability and depth.

2.5. Grain Applications in Snack Production

Over the years, a broader scope of non-wheat grain applications has been explored in snack production. In 2017, the preparation of grain-based snacks using a combination of popping and hot-air toasting was investigated. Finger millets underwent popping at 260 °C for 30 s, and then they were ground and blended with black gram to form a dough. This dough was subsequently shaped into rectangles, dried to 20% d.b., and toasted at 180 °C for 3 min [69]. However, there was a lack of detailed analysis regarding the impact of different toasting times on the sensory attributes, which is essential for optimizing production processes. Additionally, although the study extensively covered instrumental color parameters, it did not adequately consider potential variations in consumer perception of the color deviation (ΔE^* = 56.9), an aspect critical for market acceptance. Another study analyzed the influence of wheat bran's addition on dough's rheological transformations around the glass transition state, correlating these changes with the final product's volume and texture. The addition of bran was found to increase the peak gelatinization temperature, raise the glass transition temperature, and slow down the reduction in elastic modulus at temperatures exceeding the gelatinization point. Additionally, bran reduced the dough's extensibility, resulting in smaller bubbles due to expansion resistance during baking [71]. However, this study relied solely on dynamic oscillatory rheometry, omitting other rheological methods and long-term stability assessments. It also overlooked consumer acceptability factors like taste, aroma, and mouthfeel, and it provided limited microstructural analysis through confocal laser scanning microscopy. Addressing these gaps could enhance the study's practical relevance. A subsequent study examined the impact of processing methods, alongside the addition of table salt and lime juice, on the foam properties of the product and its potential as an egg replacement in cupcakes. Optimal foam properties were achieved by cooking lima beans at a bean/water ratio of 1:4 (wt/wt) for 60 min, while the addition of table salt diminished the foam quality at higher concentrations. The study demonstrated that lima beans could fully replace egg whites in cupcake formulations, preserving a desirable texture and structure [74]. Despite these findings, sensory evaluations for taste and consumer acceptability were not included. Comparative studies with other egg replacements, sensory testing, and a thorough nutritional analysis could provide a more comprehensive assessment. Another study explored the relationship between water content and expansion behavior in starch samples. An optimal water content range of 15–21% d.b. was identified for starch expansion during popping at 210 °C for 10 s [76]. However, this range lacks

specificity, necessitating further investigation to determine the precise value that maximizes expansion. Additionally, the study did not measure the ER of starch products, leaving an incomplete evaluation of how these variables affect the final product's quality.

2.6. Economic Feasibility and Scalability Considerations

Across the different studies targeting different popped grains, a critical economic feasibility assessment was overlooked. This omission leaves uncertainty around the practicality and scalability of using popped products in commercial food production. Factors like raw material costs, energy consumption, equipment investment, and yield efficiency are crucial for determining whether these techniques can be scaled up cost-effectively. Without this analysis, it is unclear whether the popping processes can translate successfully from experimental setups to large-scale operations.

Popping offers many advantages but is also associated with many drawbacks, despite the improvements achieved since its ancient application. This is why alternative, more advanced methods, subsequently discussed in upcoming parts of this review, have been adopted by researchers to mitigate the issues presented in the critiqued studies.

3. Frying Expansion

Frying is a food processing technique where food is cooked by submerging it in hot oil or fat. This method is mainly used for its capability to rapidly cook food while expanding its structure. Food is typically fried at temperatures between 148 and 185 °C, with durations ranging from 30 s to 2 min. The process is driven by the rapid transfer of heat from the oil to the food, causing the internal water to boil and generate steam before the food becomes saturated with oil [79–81]. The generation of steam causes the food to expand and facilitates transformations like starch gelatinization, protein denaturation, nutrient loss, non-enzymatic browning, and lipid oxidation [82].

Details on experimental parameters, pre- and post-treatment methodologies, nutritional value, and EF as a ratio or thickness increase (in mm) are provided in Table 2. Subsequently, a detailed discussion explores each reference, initiates a chronological comparison, and provides a critique that can offer additional insights into each study.

Table 2. Frying texturization of dehydrated food.

Methods/Year/ Reference	Target Product(s)	EFs (Ratio, mm)	Pre-Treatment	Post-Treatment	Parameters and Outcomes
DF (1996) [79]	Tapioca starch crisps	1	-Mixture of tapioca starch and water -Steaming: 30 min -Cooling: room temperature -Conditioning: 5 °C, 21 h -Drying: 50 °C for 7 h	-Cooling -Surface de-oiling using filter paper	-T = 200 °C/t = 40 s/ W = 15% d.b.
DF (2009) [83]	Rice crackers	6.55	-Soaking: 20 °C water, 16–18 h → W = 38% w.b. -Crushing -Steaming: 115 °C, 12–13 min -Resting and kneading -Mixing with fish powder -Cooling: 2–4 °C, 3 days -Cutting to pieces -Drying: 50–60 °C → 16% w.b.	-Centrifugation: 500 rpm, 30 s -Storage: 4 °C	-T = 220 °C/t = 60 s -Oil content: 20.22% -Fish powder: 10% -HARD = 6.27 N
DF (2011) [84]	Cassava-starch based crackers	1.2	-Boiling with water: 5 min -Drying: 96–98 °C, 50 min -Cooling: room temperature -Refrigeration: 4 °C, 12 h -Cut into slices -Drying: 60 °C, 4 h	-Cooling: 1 h, room temperature -Storage: plastic bags	-T = 160 °C/t = 30 s -HARD = 2.943 N

Table 2. *Cont.*

Methods/Year/ Reference	Target Product(s)	EFs (Ratio, mm)	Pre-Treatment	Post-Treatment	Parameters and Outcomes
Vacuum Frying (2011) [85]	Banana snacks	0.2	-Ripening: 1–4 days -Peeling -Cutting: 3.5–4.5 mm slices	-Centrifugation (de-oiling): 5 min, 450 rpm	-P = 8.0 kPa/T = 110 °C/ t = 20 min -Ripeness: 2nd day -HARD = 12.17 N
DF (2011) [86]	Snack products (legumes and cereal byproduct flours)	0.71	-Dehulling -Milling -Sieving: 100 µm -Cooling and storage	-Cooling: room temperature -Storage: 29 °C, humidity (67%), sealed polypropylene pouches	-T = 165 ± 2 °C/t = 3 min -Flour blend: red gram (20%), green gram (20%), black gram (20%), rice (40%) -Maximum shelf life: 24 days -Bulk density = 0.4 g/mL -HARD = 0.477 N -1st fracture deformation = 0.363 mm
DF (2018) [87]	Dough-based potato snacks	N/A	-Extrusion: 90 °C → square-tube potatoes -Drying: 10 ≤ W ≤ 12% d.b.	N/A	-T = 185 °C/t = 8 s -W (after frying) = 3% d.b AA concentration: Yellow square-tube potatoes: 20 µg/kg Green square-tube potatoes: 28 µg/kg Red square-tube potatoes: 92 µg/kg.
DF (2019) [88]	Wheat- and fish-based snacks	Thickness increase: 3.6 mm	Fish meat: -Grinding -Storage: polyethylene bags, –20 °C Fish bone: -Thawing and cutting -Cooking: pressure cooker (15 psi, 121 °C, 1 h) -Rinsing and mincing -Adding to bone: distilled ice water at a 0.9:1 ratio -High-pressure dispersion: 20 min, 7500 and 10,000 rpm -Milling: 5 min -Storage: 20 °C Dough: -Hydration -Shaping: 3 × 3 squares -Drying: 50 °C, 2 h	-Cooling -Storage: room temperature	Blend: wheat flour: 35.71%/potato powder: 28.57%/fish meat: 21.42%/fish bone: 14.28% -Bioavailable calcium: 37% -T = 165 °C/t = 30–35 s -HARD = 40.87 N -Water-holding capacity = 3.45 mL/g
DF (2020) [89]	Deep-fried potato crisps	N/A	Potato flakes production: -Boiling and mashing -Drying Potato crisp production: -Blending: parboiled rice flour and extruded rice flour, 2 min -Mixing and sheeting -Cutting: oval dough pieces	-Draining: 12 s. -Cooling: room temperature	-13.3 ≤ HARD ≤ 19.7 N. -0.199 ≤ density ≤ 0.241 g/cm^3 -T = 180 °C/t = 12 s
DF (2023) [11]	Potato-based snacks	N/A	Grinding of carrots → pulp: particle size < 400 µm	Draining: oil with paper towels	-T = 180 °C/t = 15 s -Fresh carrot pulp: 10% -Total porosity = 67.30 ± 4.4% -Fracturability = 21.13 ± 2.91 N -Crispiness = 16.63 ± 1.72 N -HARD = 74.27 ± 6.36 N
DF (2023) [90]	Fried snacks (wheat flour, cassava flour, and corn bran)	1.48	-Mixing: 2 min -Hydration: W = 37.8% w.b. -Dough rest: 1 h -Sheeting -Cutting into disks	Centrifugation (de-oiling): 1400 rpm, 3 min	-Blend: wheat flour = 92%/ cassava flour = 8% -Oil: refined bleached deodorized palm olein (2 L) -T = 170 °C/t = 5 min
DF (2023) [91]	Surimi-based deep-fried fish snacks	1.75	-Cutting: 600 g blocks -Storage: −80 °C -Hand blending: 1 min -Blending: 5 min -Molding dough -Drying: 50 °C, 4 h → 8.3 ≤ W ≤ 10.9% d.b.	N/A	-T = 190 °C/t = 40 s -Oil content: 32% -HARD = 350 N -L^* = 68/a^* = 16/b^* = 38

3.1. Impact of Frying Parameters on Expansion

A study examined the impact of frying parameters on the physical changes in tapioca chips, using a mixture of tapioca starch and water pre-treated to achieve a 15% d.b. water content, followed by frying at 200 °C for 40 s [79]. However, it should be noted that an ER of 1 is not notable, proving that the parameters considered for frying might not be optimal if the target is to produce expanded chips. Future research should focus on optimizing the parameters used for frying to attempt to expand the product. Another study evaluated the impact of fish powder content, frying temperature, and frying time on the physicochemical properties of fried rice crackers. The procedure used DF dough containing 10% fish powder fried at 220 °C for 60 s, producing rice crackers with an ER of 6.55 and a HARD of 6.27 N. Despite efforts to reduce the oil content through centrifugation and the incorporation of fish powder, the oil content remained high, at 20.22% [83]. Nonetheless, the two studies did not consider the implications of residual oil content. Future research should incorporate analyses of oil content in the final product and explore alternative frying methods and improved oil-reducing techniques to address health concerns.

Another study assessed the effects of varying levels of reducing sugars and asparagine, alongside time and temperature combinations, on AA formation during frying in the production of square-tube potatoes. The methodology involved extruding potato dough, enhanced with micro-ingredients like dried tomato or spinach concentrates, at 90 °C to form square tubes. These were then dried to a moisture content of 10–12% d.b. and fried at 185 °C for 8 s to maximize their expansion [87]. Nonetheless, the research could benefit from a broader scope. Investigating modifications in the preparation of potato dough, such as the alteration of ingredient concentrations or the introduction of AA-inhibiting additives before frying, could provide new pathways for reducing AA formation. Further research could also evaluate the impact of varying the frying temperature and time more extensively, exploring the lowest possible temperatures and shortest times that still achieve desirable product qualities but with minimal AA formation.

3.2. Influence of Ingredient Composition on Product Quality

Additional studies examined the quality attributes of fried snacks, including cassava crackers, crispy banana snacks, and deep-fried snacks from cereal and legume byproducts. One study assessed the influence of temperature and frying duration on cassava crackers' quality, employing a two-stage dehydration of cassava slices, followed by DF at 160 °C for 30 s. The resulting crackers displayed a mean force peak of 2.943 N and an EF of 120%, highlighted by a porous structure, making the crispy product easy to chew [84]. However, this expansion effect was minimal. The study lacked detailed water content analysis at each dehydration stage and prior to frying, limiting the reproducibility and understanding of the expansion mechanism. Additionally, critical factors like the type of oil, slice thickness, and dehydration uniformity, each impacting the final product's expansion and texture, were not examined.

Another study investigated the production of crispy banana snacks, involving ripening, peeling, slicing, and frying at 110 °C for 20 min. Rapid diameter shrinkage within the first 5 min signaled significant water loss, reducing the moisture content from 74% w.b. to 44% w.b. and the thickness by approximately 20%. Throughout the frying process, the pores became larger, suggesting that the expanding gas vapor inside the product led to a 20% expansion [85]. However, it should be noted that this study lacks clarity regarding whether the reported 20% expansion reflects a net increase or a partial recovery in the volume of the shrunk material during the initial stages of frying. Finally, a study explored the physicochemical properties and shelf life of deep-fried snacks made from cereal and legume byproducts. The mixture was formed into a semi-dough and fried at 165 ± 2 °C

for 3 min, achieving 71% expansion, with a shelf life of up to 24 days [86]. Nevertheless, the study's sensory evaluation presents significant limitations. The evaluation, which included assessments of color, texture, taste, and overall acceptability, was conducted by 15 untrained student panelists aged 21–23 years. This lack of training and the narrow age range of the panelists raise questions about the reliability and generalizability of the sensory data. The absence of quantitative methods for evaluating texture and color further undermines the study's robustness. Future studies should address these issues to enhance the practical applicability of their findings.

Another study examined the effects of incorporating fish meat and fish bone on the nutritional profile, texture, and microstructure of fried snack formulations. The optimized dough contained 35.71% wheat flour, 28.57% potato powder, 21.42% fish meat, and 14.28% fish bone, fried at 165 °C for 30–35 s. This process resulted in significant expansion, as evidenced by a 3.6 mm increase in thickness [88]. However, while thickness was used to measure expansion, the initial thickness of the dough before frying was not specified. Additionally, the stated frying time range of 30–35 s may be misleading, as even slight variations in frying time can influence Maillard reactions and affect both the texture and color of the final product.

A study investigated methods for reducing the caloric content of potato crisps by analyzing various samples with differing compositions. The starch content in these samples ranged from 77.1% to 82.5%, while the protein content varied between 6.1% and 9.8%. These compositional differences produced variations in the physical properties of the fried snacks, with densities ranging from 0.199 to 0.241 g/cm^3 and HARD values between 13.3 and 19.7 N [89]. Nevertheless, the research presents a major gap, as it did not evaluate the ER of the crisps, a critical factor in the consumer perception and textural quality of snack foods. Moreover, the focus solely on HARD as a measure of texture neglects other essential textural attributes such as crunchiness, crispiness, and chewiness, which significantly influence consumer satisfaction. A more holistic approach could help in better tailoring the product to meet consumer expectations and industry standards.

3.3. Textural and Sensory Evaluation of Fried Snacks

Another study examined the effects of frying on the textural and sensory attributes of snack foods. The procedure involved frying potato dough, enhanced with 10% fresh carrot pulp, at 180 °C for 15 s, followed by oil removal using paper towels. This process resulted in a porosity of 67.3% in the snack, with a measured crispiness of 16.63 N and a notably high HARD of 74.27 N [11]. However, it should be noted that this recorded HARD is shockingly high for products typically valued for their easy consumption and low bite resistance, potentially reducing consumer acceptability. Furthermore, the use of paper towels for oil removal in this study, though practical, may not standardize the residual oil content effectively, potentially leading to higher fat content, raising nutritional concerns among health-conscious consumers.

One study assessed the impact of ingredient composition on the quality attributes of high-fiber fried snacks. The dough was prepared with 92% wheat flour and 8% cassava flour, and then fried in refined, bleached, and deodorized palm olein at a controlled temperature of 170 °C for 5 min, achieving an ER of 148.41%. The larger cavities improved the material's permeability, promoting increased oil absorption. To minimize oil uptake, the snacks were centrifuged at 1400 rpm for 3 min [90]. However, the force applied during centrifugation may alter the snack's texture, possibly leading to decreased crispiness. Consequently, while centrifugation is a practical de-oiling method, its potential effects on the textural integrity of high-fiber fried snacks warrant further investigation to ensure that it does not compromise the overall quality and consumer appeal of the product.

Another study investigated the effects of deep frying on the textural properties of expanded potato-based pellet snacks, incorporating 10% carrot pulp into the base material and then subjecting it to deep frying at 180 °C for 15 s. This process yielded a total porosity of 67.30 ± 4.4%, crispiness of 16.63 ± 1.72 N, and HARD of 74.27 ± 6.36 N. Interestingly, when microwave technology was used for expansion instead of frying, a higher total porosity of 74.50 ± 1.49% was achieved [11]. Future research should incorporate more precise methods to measure color, flavor, and taste characteristics, to ensure accurate and reliable findings. The current study's reliance on a panel of 15 semi-trained members may limit the generalizability of the results, as this sample may not fully capture the preferences of the broader target audience for whom the product is intended.

3.4. Health Considerations and Future Directions

The consumption of fried foods is correlated with numerous health risks [92]. Consequently, health-conscious individuals often reduce their intake of oil-rich foods and prefer healthier options with lower caloric contents [93] and lower AA concentrations [94]. Therefore, alternative expansion techniques that avoid the usage of oil, thereby minimizing cost (like ME) have gained attention. The next section explores how this method offers healthier options while maintaining desirable textural qualities.

4. Mechanical Extrusion Expansion

ME in food expansion is a process that involves blending ingredients to create a uniform feed material, which is then fed into a screw-driven extruder [95,96]. Inside the extruder, the material undergoes intense mechanical shear, friction, and heat, which cook it and induce physical and chemical changes such as starch gelatinization and protein denaturation [97]. The cooked material is then forced through a die that shapes it into the desired form, expanding as the extrudate exits it. The expanded extrudates are subsequently cooled and dried to stabilize their structure and ensure a long shelf life [98]. Recent advancements are evaluating the effect of combining the traditional process with microwave treatment to increase the ER of the food products [99,100]. They are also exploring the upcycling of food waste from fruit and vegetables to produce extruded snacks, which have the potential to offer significant economic advantages while also providing notable health benefits [101,102]. Details on the experimental parameters, pre- and post-treatment methods, nutritional value, and ER are provided in Table 3. This is followed by a detailed discussion that examines each reference, compares them chronologically, and provides critiques offering further insights into each study.

Table 3. Mechanical extrusion texturization of dehydrated food.

Methods/Year/ Reference	Target Product(s)	ER	Pre-Treatment	Post-Treatment	Parameters and Outcomes
Twin-Screw Extrusion (TSE) (1997) [103]	Corn-based extrudates	-Fine flour: 4.69 -Flour: 4.51 -Meal: 4.45 -Grits: 4.47 -Coarse grits: 3.99	Dry-milling into different granulations (50 → 1622 µm)	-Drying: W = 7% d.b. -Storage: polyethylene bags	-50 ≤ Particle size ≤ 1622 µm -19 ≤ W ≤ 22% d.b. -200 ≤ V (screw) ≤ 400 rpm
TSE (2010) [104]	Whole-wheat flour product and fish feed	N/A	N/A	-Drying: 100 °C, 12 min → 5 ≤ W ≤ 8% d.b. -Storage: 4 °C	-101 ≤ T ≤ 149 °C -9.2 ≤ W ≤ 15.8% d.b. -208 ≤ V (screw) ≤ 393 rpm

Table 3. *Cont.*

Methods/Year/ Reference	Target Product(s)	ER	Pre-Treatment	Post-Treatment	Parameters and Outcomes
TSE (2012) [105]	Corn flour and apple pomace-based extruded snacks	17% AP: 6.1 22% AP: 5.5 28% AP: 4.3	-Blend preparation of corn starch: AP: 0% AP, 17% AP, 22% AP, and 28% AP. -Hydration: 17.5, 20 and 25% d.b.	-Manual cutting -Drying: 103 °C, 10 min	-d (screw) = 18 m/ feed rate = 2.1 kg/h -V (screw) = 350 rpm -Addition 17% AP: W = 17.5% d.b./Specific Mechanical Energy (SME) = 840 kJ/kg/ Density = 210 kg/m^3 -Addition 22% AP: W = 17.5% d.b./ SME = 550 kJ/kg/ density = 190 kg/m^3 -Addition 28% AP: W = 17.5% d.b./ SME = 580 kJ/kg/ density = 195 kg/m^3
TSE (2012) [106]	Rye-based snacks	4.49	N/A	-Cooling: room temperature -Storage in sealed polyethylene bags	-T (barrel) = 190 °C/ W = 12% d.b. -Density = 0.08 g/cm^3 / Force = 15.98 N -Number of force peaks = 47.96 -Number of sound peaks = 339.77 -Mean of sound = 52.88 dB
TSE (2014) [107]	Maize-based extruded product	1.61	-Blend preparations: spirulina powder (7.5%) and maize flour (92.5%) -Hydration → 16% d.b.	-Cooling: room temperature, 20 min -Drying: 60 °C, 12 h -Storage: polyethylene bags, room temperature	-T (barrel) = 109.2 °C/ V (screw) = 280 rpm -Overall acceptability = 6.12 -Desirability = 0.809
TSE (2019) [108]	Expanded maize starches	7	N/A	N/A	-W = 22% d.b./T = 175 °C -SME = 120 kWh/t -η = 250 Pa.s
TSE (2022) [109]	Extruded mung–oat snacks	3.79	-Milling to particle size of >100 mm -Hydration → W = 14.797% d.b. -Homogenization of W: refrigeration overnight	-Drying: 100 °C, 30 min -Storage: polyethylene pouches	-V (screw) = 220 rpm/ V (cutter) = 25 rpm -Die diameter = 3 mm -T (barrel) = 193.85 °C -Desirability = 0.793 -Bulk density = 0.021 g/cm^3 (minimum)
TSE (2022) [110]	Pea flour snacks	Expansion avoided	N/A	N/A	-Starch/protein ratio = 2/1 -Flow rate (powder): Q_F = 0.24 kg/h -T (die) = 95 °C/ W = 18–35% d.b. -V (screw) = 120–700 rpm -SME = 150–2000 kJ/kg
TSE (2023) [111]	Wheat bran-based flour dough	N/A	-Dough preparation -Sealing of dough: 30 min	-Drying: 50 °C, overnight -Grinding -Passing through a 60-mesh screen (particle size < 250 µm)	-rRtio length/diameter = 25 -V (screw) = 600 rpm -W = 25% d.b. -Stability ratio increase: 4.82 -Degree of softening decrease: 25.81%
TSE (2023) [112]	Extrudate expanded dried ripe jackfruit powder cornmeal	2.8	Jackfruit: within 7 days of harvest: storage in vacuum-sealed packs at 19 °C	Drying in oven: 2 h, 60 °C	-V (screw) = 150 rpm/feed rate = 400 g/h -Particle size = 500–1000 µm -W < 16% d.b. -30/70% (w/w%) ripe jackfruit/cornmeal -HARD = 23.8 N

Table 3. *Cont.*

Methods/Year/ Reference	Target Product(s)	ER	Pre-Treatment	Post-Treatment	Parameters and Outcomes
Single-Screw Extrusion (2023) [113]	Corn-based crisps supplemented with fruits	Addition of -Apple: 4.05 -White mulberry: 3.85 -Goji berry: 4.14 -Elderberry: 4.21 -Blackberry: 3.74	Grinding: dried fruits to powder	N/A	-Apple: addition 5%/V (screw) = 80 rpm/L^* = 81.14/ a^* = 6.75/b^* = 24.16 -White mulberry: addition 5%/V (screw) = 100 rpm/ L^* = 81.55/a^* = 6.63/b^* = 24.14 -Goji berry: addition 5%/V (screw) = 100 rpm/L^* = 78.70/ a^* = 8.15/b^* = 34.10 -Elderberry: addition 5%, V (screw) = 120 rpm/L^* = 68.00/ a^* = 8.76/b^* = 13.71 -Blackberry: addition 5%/V (screw) = 120 rpm/L^* = 73.98/ a^* = 8.21/b^* = 18.13
TSE (2023) [114]	Extruded white and red beans	-Toska red bean: 4.4 -Aura white bean: 5.25	-Grinding -Sieving: d = 1 mm	Cooling: room temperature	-V (screw) = 700 rpm -Feeding rate: 20 kg/h -Water addition: 0.8 L/h

4.1. Process Parameters and Modeling Approach

A study examined the impact of parameters such as particle size, screw speed, and moisture content on the TSE of cornmeal, finding that the highest ER of 4.69 was achieved with the finest flour, characterized by a particle size of 50 µm [103]. However, the research lacked a thorough analysis of the interactions among these independent variables. Future research would benefit from employing a response surface methodology (RSM). This approach would allow for a more systematic exploration of the interdependencies among variables and potentially reveal optimal conditions for extrusion.

Another study introduced a modeling framework to correlate extrudate expansion with extrusion process parameters through dimensional analysis. The co-rotating TSE was performed within specific ranges of temperature ($101 \leq T \leq 149$ °C), moisture content ($9.2 \leq W \leq 15.8\%$ d.b.), and screw speed ($208 \leq V$ (screw) ≤ 393 rpm) [104]. However, the model failed to establish a definitive relationship among these parameters to identify optimal conditions for maximum expansion. Additionally, none of the models accurately predict bulk density, as shown by the scatter of the points. This suggests that other factors, not included in the equations, might affect the bulk density, or that the models themselves require further refinement. These limitations call for further investigation and refinement in future research.

Another research team examined the viscous properties of pulse-based ingredients and developed pulse-based extruded foods and composites through rheology-based process simulation. The experiment used various extruder scales, operating at moisture contents between 18 and 35% d.b. and screw speeds ranging from 120 to 700 rpm, resulting in large intervals for melt temperature (95–165 °C) and SME (150–2000 kJ/kg). Notably, expansion was deliberately avoided during the process [110]. Nevertheless, the variability in melt temperature and SME suggests significant impacts on the final product's characteristics, highlighting the need to identify optimal parameters for consistent product quality. Future research should focus on narrowing these intervals to optimize the rheological properties and structural integrity of pulse-based extruded foods.

4.2. Ingredient Interactions and Production Optimization

Two studies evaluated different aspects of extrusion processing using twin-screw extruders [105,106]. One study focused on the impact of apple pomace on corn-based extrudates. Under optimal conditions, with 17% apple pomace incorporated into a blend hydrated to 17.5% d.b., an SME of 840 kJ/kg and an ER of 6.1 were achieved [105]. However,

the study did not include analysis of sensory properties such as flavor, color, and aroma, which are crucial for consumer acceptance and marketability. Future research should incorporate comprehensive sensory evaluations to provide a holistic understanding of the product's quality and acceptability. Another study investigated the effects of process temperature and moisture content on the physical properties, texture, and sound emission of rye-based extrudates. The optimal extrusion conditions were determined to be a temperature of 190 °C and a blend moisture content of 12% d.b., yielding an extrudate with a maximized ER of 4.49, a force measurement of 15.98 N, and a mean sound emission of 52.88 dB during cracking. These findings emphasize that greater expansion results in a thinner layer of starch molecules around the air pockets, which means that less force is needed to break the crisps [106]. However, the study's limited range of moisture content (12% and 16% d.b.) and temperature (150 °C and 190 °C) values restricts the ability to generalize the findings. Future research should explore a broader range of these parameters to optimize extrusion conditions, thereby enhancing product quality and facilitating industrial-scale applications.

Another study investigated the impact of various extrusion parameters on the characteristics and nutritional quality of maize–spirulina blend extruded products. The blend was hydrated to 16% d.b. before extrusion, which was conducted at a temperature of 109.2 °C and a screw speed of 280 rpm. This process achieved an expansion of 161.46% [107]. However, the acceptability score of 6.12 indicates relatively low consumer acceptance. This suggests that, despite achieving a significant ER, the product may have fallen short in meeting sensory or other quality criteria valued by consumers. Future research should focus on optimizing not only the physical and nutritional properties but also the sensory attributes to enhance overall acceptability.

A research team developed a protein-rich snack using mung beans and oat flour through TSE. The particles were milled and hydrated to achieve a water content of 14.797% d.b., with extrusion conducted at a screw speed of 220 rpm and a cutter speed of 25 rpm at 193.85 °C, resulting in an ER of 3.793. Following extrusion, the product was dried at 100 °C for 30 min before packaging [109]. However, the elevated drying temperature could have degraded some of the product's nutritional components, suggesting that future studies should investigate a lower drying temperature paired with a longer drying time. Additionally, the product's low desirability necessitates further assessment to determine its commercial viability.

Researchers investigated the interaction between extruded bran and gluten protein in dough systems with varying gluten levels, assessing the effects of extruded bran on the structural and rheological properties of wheat dough. The dough was hydrated to 25% d.b., extruded at a screw speed of 600 rpm, dried at 50 °C, and ground to a particle size under 250 μm [111]. However, the study only examined one extrusion condition, neglecting variations in screw speeds, barrel temperatures, and moisture content, and overlooked practical aspects like cost-effectiveness, scalability, and consumer acceptance. Another study examined the influence of macronutrient composition, jackfruit ripeness, and feed powder particle size on cornmeal–jackfruit extrudates, which were extruded at 150 rpm with a feed rate of 400 g/h, yielding an ER of 2.8 and a HARD of 23.8 N [112]. However, the study lacked detailed nutritional and sensory analyses and failed to address the long-term storage stability of the extrudates, which are critical for consumer acceptance and product marketability. Similarly, research focused on the incorporation of various dried fruits into gluten-free corn-based crisps, with adjustments in screw speeds: 80 rpm for apple, 100 rpm for white mulberry and goji berry, and 120 rpm for elderberry and blackberry. These processes achieved ERs of 4.05, 3.85, 4.14, 4.21, and 3.74, respectively [113]. Nonetheless, the

study did not comprehensively analyze the nutritional composition and sensory acceptance of the final products, which are essential for promoting them as healthy snack options.

4.3. Rheological Properties and Structural Optimization

A study developed and validated a model to predict the expansion and cellular structure of starchy extruded foams based on rheological properties and extrusion conditions, aiming to optimize the processing conditions for a targeted structure. The results showed that a maximum ER of 7 produced a cellular structure fineness of 1.3, which did not yield optimal textural properties. Instead, optimal texture was achieved by limiting the ER to 3 and increasing the fineness to 2.5. The results indicate that thermal and shear energies work together to transform starch, while thermal energy appears to govern protein cross-linking by forming disulfide (S-S) bonds [108]. This disparity between maximal expansion and optimal textural properties highlights the need for further research to enhance our understanding and improve the balance between expansion and texture in extruded foams.

Additionally, a study investigated the effects of varying processing parameters during extrusion-cooking of two common bean cultivars, Toska and Aura, at a screw speed of 700 rpm, feed rate of 20 kg/h, and water addition of 0.8 L/h. This resulted in ERs of 4.4 for Toska and 5.25 for Aura [114]. The study's limitation to two bean cultivars and lack of exploration of other extrusion parameters (like temperature profiles and feed composition variations) restricted its scope.

Addressing the issues in all of these studies would provide a more comprehensive understanding and practical utility of the extrusion processes for producing high-quality, marketable extrudates.

Implementing ME in the food expansion industry for reconstituted or dehydrated foods offers many advantages and is associated with many drawbacks that will be discussed in a subsequent section. Therefore, adopting more advanced and versatile techniques has become essential in the food expansion industry.

5. Puffing Expansion

Puffing is a technique used to transform dehydrated food products into a diverse array of expanded snacks [115]. The explosion puffing phenomenon is directly related to a complex mechanism of alveolation, which depends on specific operating conditions such as temperature, initial and final pressures (just before and after decompression), treatment time, and the duration of decompression [116]. During decompression, the product undergoes an irreversible adiabatic transformation, inducing partial evaporation of the water within. Steam creates mechanical constraints within the product, leading to alveolation. The maintenance of the product in this expanded state depends on its hardening, which is determined by temperature and water content [117,118]. Partial dehydration is crucial for effective expansion, ensuring that the product neither disintegrates nor expands insufficiently [52]. This process not only alters the texture of the dehydrated food but also enhances its flavor and digestibility. The expanded structure improves the absorption of flavors and seasonings. Additionally, the light and airy texture enhances the sensory appeal and palatability of puffed foods, making them more enjoyable to consume [21,33]. Early research demonstrated this effect with potato cubes, which were heated to 163 °C for a few minutes before undergoing rapid pressure release [45]. This method allows for a production rate of 30 kg/h in an industrial setting, which proved quite advantageous at the time compared to its traditional counterpart [119,120].

The general treatment procedure and the explosion puffing equipment system are presented in Figure 1.

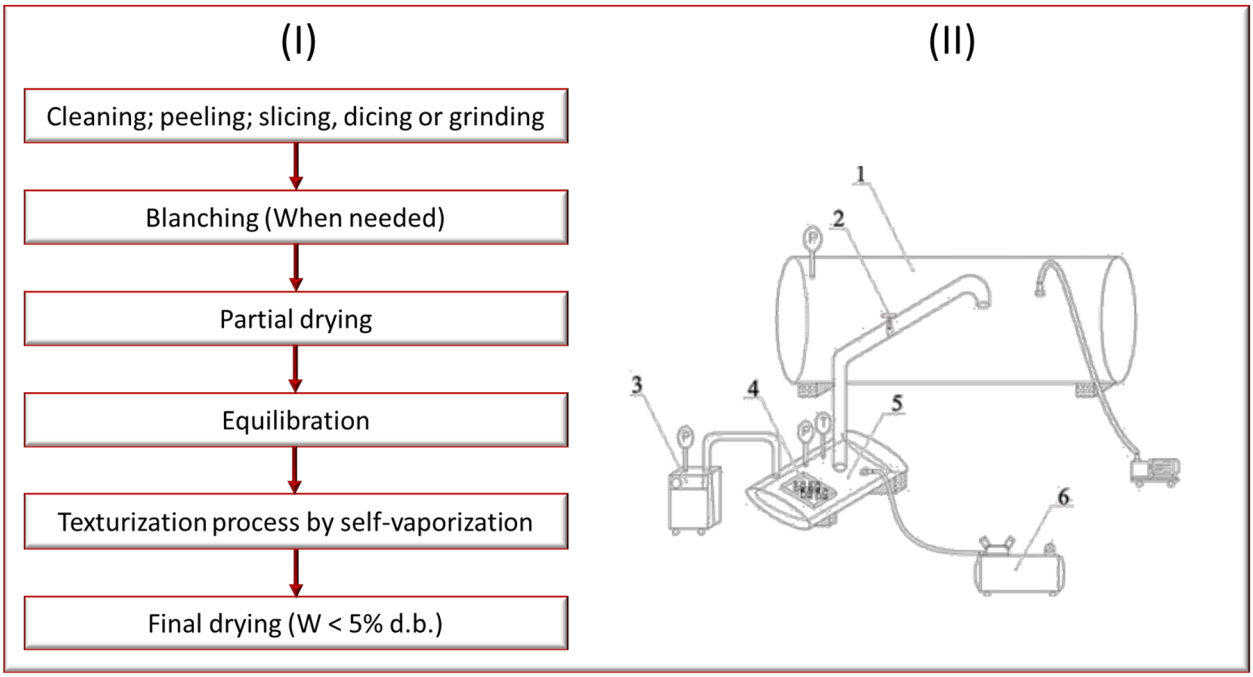


Figure 1. (**I**) Schematic diagram of the global treatment involving texturization by self-vaporization. (**II**) Schematic diagram of explosion puffing drying device and accessories: 1, vacuum chamber; 2, decompression valve; 3, steam generator; 4, samples; 5, puffing chamber; 6, air compressor [121].

Details regarding the experimental parameters, pre- and post-treatment methods, nutritional value, and EF as a ratio or specific volume (in mL/g) are provided in Table 4. This is followed by a discussion examining each reference, comparing them chronologically based on the desired end product, and offering critiques that provide further insights into each study.

Table 4. Puffing texturization of dehydrated food.

Methods/Year/ Reference	Target Product(s)	EFs (Ratio, mL/g)	Pre-Treatment	Post-Treatment	Parameters and Outcomes
Barrel Puffing (2007) [122]	Puffed naked barley	4.7	-Grinding -Polishing -Hydration -Storage: 20 °C, 48–72 h	N/A	-T = 550 °C/P = 0.9 MPa/ W = 16.5% d.b.
High-Temperature Short-Time (HTST) Air Puffing (2008) [123]	Potato–soy snacks	3.69	Mixture preparation: -Mixing: soy flour with potato flour, water (5 °C) and salt -Kneading: 10–15 min -Shaping the dough	N/A	-W (initial) = 36.74% d.b. -T = 230 °C/t = 25.5 s -V (air) = 3.99 m/s -HARD = 27.02 N -Flour ratio: 10.31% soy flour: 89.69% potato flour
HTST Whirling-Bed Puffing (2010) [124]	Soy-fortified wheat-based snacks	4.42	-Blend of wheat and soy flour (ratio of soy: 7.5%) -Addition: 5 °C, salt water: 2% -Kneading: 12–15 min -Cutting: rectangles -Steaming: 70 kPa, 11 min	N/A	-W = 46.17% d.b./t = 30 s/ T = 220 °C -V (air) = 3.95 m/s -Diffusivity = 1.15×10^{-9}–2.58×10^{-9} m^2/s -Activation energy = 2341.8 kJ/kg
Microwave Puffing (2011) [125]	Puffed rice snacks	6.2	-Parboiling milled rice -Addition of salt -Packaging and sealing	N/A	-P (microwave) = 850 W/t = 35 s -Salt content in rice = 5% -Puffing yield = 99.27% -Input energy = 29.75 KJ
Superheated Steam Puffing (2012) [126]	Puffed banana crisps	0.675	-Slicing: 3.5 mm thick -Blanching: 95 °C, 60 s -Osmotic treatment: 310 min -Drying: 90 °C, V (air) = 2 m/s	Drying: 90 °C → W (final) = 4% d.b.	-W (initial) = 30% d.b. -t = 150 s/T = 220 °C -V (air) = 2 m/s/P = 200 kPa -L^* = 54.19/a^* = 5.27/b^* = 17.7

Table 4. *Cont.*

Methods/Year/ Reference	Target Product(s)	EFs (Ratio, mL/g)	Pre-Treatment	Post-Treatment	Parameters and Outcomes
Explosion Puffing Drying (2013) [127]	Puffed mango chips snacks	1.88	-Washing, peeling -Slicing: 26 × 26 × 5 mm pieces -Hot-air drying: 50 °C, V (air) = 2 m/s → W = 30% d.b. -Storage: 4 °C, 24 h	Vacuum drying: 180 min	-T = 95 °C/t = 5 min/W = 7.5% d.b. -Water activity (a_w) = 0.470 ± 0.005 -HARD = 16.4 N ± 6.0 -Crispness = 7 N ± 3.1 -L^* = 47.4/a^* = 15.7/b^* = 37.8/ ΔE^* = 22.9 -Odor = 5.6/overall quality = 5.4 -Texture = 4.9/flavor = 4.9
Fluidized-Bed Puffing (2013) [128]	Puffed banana crisps	N/A	-Peeling and slicing -Soaking sodium metabisulfite solution: 700 mg/L, 5 min -Drying: 90 °C, V (air) = 2 m/s → 26% d.b.	Drying: W (final) = 4% d.b.	-T = 163 °C/t = 1 min -V (air) = 3.5 m/s -HARD = 22.3 N -Number of peaks = 16 -L^* = 44.3 ± 0.9
Microwave Puffing (2014) [129]	RTE food based on millet flour and potato or sweet potato mash	2.04	-Steaming -Cooking: 98,066.5 Pa, 15 min	N/A	-P (microwave) = 1080 W/t = 60 s -W = 19.22% d.b. -HARD = 15.89 N -Number of peaks = 22
Microwave Puffing (2014) [130]	Pre-cooked puffed sorghum	8.67	-Cleaning -Soaking: water, 150 min -Surface drying: 10 min	N/A	-W = 21% d.b./t = 3 min -P (microwave) = 100% -Flake size = 0.28 mL/grain -Puffing yield = 89%
Microwave Puffing (2014) [131]	Expanded hull-less barley snacks	3.3	-IR treatment: 200 °C, 2 min -Hydration -Storage: 4 °C overnight	-Drying: 100 °C, 5 min → W < 4.7% w.b. -Storage: room temperature	-W = 29.5% d.b. -P (microwave) = 850 W/ t = 45–75 s -HARD = 10 N -L^* = 68.4/a^* = 6.7/b^* = 18.2/ ΔE^* = 3.7
HTST Whirling-Bed Treatment (2015) [132]	Puffed carrot cubes	2.14	-Dicing -Steam branching -Solution treatment: $K_2S_2O_5$ and $NaHSO_3$ -Partial drying: 70 °C, V (air) = 1.1 m/s	Toasting: 125 °C, 15 min	-T = 175 °C/t = 30 s -W (final) = 0.0456 d.b. -HARD = 2.231 N -a^* = 24.65
Explosion Puffing Drying (2016) [133]	Puffed apple chip snacks	1.09	-Refrigerating red Fuji apples: 4 °C, 2 weeks -Peeling, slicing -Drying: vacuum dryer, 60 °C -Sample equilibration: 4 °C, 12 h	Drying: 60 °C → W < 5% d.b.	-W (initial) = 90.32 ± 0.57% d.b. -W (final) = 5.7% d.b. -L^* = 53/a^* = 1/b^* = 15.5/ ΔE^* = 7.5 -HARD = 40.8 ± 2.3 N -Crispness = 8.8 ± 0.7 N/mm
Microwave Oven Puffing (2019) [134]	Puffed rice snacks	Specific volume: 2.22 mL/g	-Cleaning -Soaking: distilled water, 24 h	Cooling: 2 min	-W = 14% w.b. -P (microwave) = 800 W/t = 60 s
CO_2 High-Pressure and Low-Temperature Explosion Puffing (2020) [135]	Puffed apple chips snacks	1.7	-Soaking: 1 g apples/ 10:6:7:7 mL (citric acid–ascorbic acid–sodium chloride–distilled water), 20 min. -Agitating every 5 min -Rinsing: distilled water -Hot-air drying (HAD): V (air) =2 m/s, 60 °C, 15 ≤ W ≤ 20% d.b. -Storage: 4 °C, 6–12 h	N/A	-T = 74 °C/W = 17% d.b./ ΔP = 1.25 MPa -t (vacuum drying) = 33 min -Quantity of fractures = 29.3
Hot-Air Puffing (2020) [136]	Puffed white quinoa	4.20	-Hydration: spraying salt solution -Tempering: 27 °C, 30 min	N/A	-W = 2% d.b./T = 253.8 °C/ t = 60 s -Desirability = 0.962 -Flake size = 11.43 mm^3 -Bulk density = 0.34 g/mL
Vacuum Cannon Puffing (VCP) (2021) [137]	Half-puffed purple corn snacks	2.18	Soaking methods: -Water, room temperature, 48 h -Boiling water, 40 min, ratio: 1 g kernels: 5 mL water	Drying: 185 °C, 5 min, V (fan) = 3.4 m/s	-P = 7.7 × 10^5 Pa/t = 14 s/ W = 32.8% d.b.

Table 4. *Cont.*

Methods/Year/ Reference	Target Product(s)	EFs (Ratio, mL/g)	Pre-Treatment	Post-Treatment	Parameters and Outcomes
Explosion Puffing Drying (2021) [138]	Puffed pumpkin chips	4.97	-Washing and peeling -Slicing -First freeze-drying: –18 °C, 24 h -Second freeze-drying: –55 °C, P (vacuum) = 0.10 mbar, W = 45%, 120 min	Vacuum drying: 25 kPa, 70 °C, 70 min	-T = 90 °C./t = 10 min/ P = 190 kPa -W initial = 88.73% ± 0.90 w.b. -W final < 10% w.b. -Total phenolic content (TPC) = 1375.86 mg 100 g/DM -Bulk density = 26.98 ± 9.91 kg/m^3 -HARD = 200 N -L^* = 67.72/a^* = 17.23/b^* = 49.74 -ΔE^* = 19.47
Sand-Frying Puffing (2021) [139]	Puffed–dried cassava starch gel and snacks	10.69	-Suspension of starch in 50 mL water -Steaming: 15 s -Boiling: 30 s -Cooling: 15 s -Storage: 4 °C, 24 h -Shaping: disk -Drying: 50 °C → W = 12% d.b.	-Packaging: polyethylene bags -Cooling: room temperature -Storage: desiccator	-W = 3.25% -Porosity = 89.04% -Surface temperature = 181.67 °C -L^* = 66.84/a^* = 1.35/b^* = 4.64/ ΔE^* = 29.13 -Bulk density = 0.21 g/mL -True density = 1.95 g/mL -HARD = 24.55 N -First peak force = 9.98 N
Puffing (2022) [140]	Puffed quinoa snacks	8.2	N/A	N/A	-T = 230 °C/t = 30 s/ W = 6.70% d.b. -Density = 0.29 g/mL -Water absorption = 260% -L^* = 81.30/a^* = 1.90/b^* = 19.45
IR Radiation Puffing (2022) [141]	Puffed rice snacks	2.24	-Cleaning -Sieving -Storage -Hydration → W = 14% d.b.	N/A	-Distance (lamp) = 10 cm/P (IR) = 550 W -TPC = 0.06 mg GAE/g -Peroxide value = 0.9 mEq O_2/kg oil -Bulk density = 0.29 ± 0.03 g/cm^3 -L* = 72.56/a^* = 1.27/b^* = 16.51 -ΔE^* = 10.98
Microwave Oven Puffing (2022) [142]	Puffed tofu skin snacks	4	-Heating: 80 °C, 20 min -Rolling along the Teflon belt -Storage: 4 °C -Cutting: rectangles -Pre-drying: 40 °C → W = 55% w.b.	Drying: 135 °C, 2 h → 3.31% w.b.	-P = 1071 W/t = 111 s -HARD = 4.78 N -L^* = 59.27/a^* = 0.49/b^* = 27.09

5.1. Barley Puffing Techniques

Two research teams have investigated puffed barley processing. One study involved grinding, polishing, and hydrating naked barley to achieve a moisture content of 16.5% d.b., after which the barley seeds were puffed at 550 °C and 0.9 MPa, resulting in an ER of 4.7 [122]. Another study applied a preliminary IR treatment to barley kernels at 200 °C for 2 min, followed by puffing in an 850 W microwave for intervals between 45 and 75 s, achieving a maximum ER of 3.3. The puffed barley showed a decrease in HARD from 30.5 N to 10 N, with improved color parameters [131]. However, it is important to highlight the lack of precision in the treatment durations. This variability raises concerns about how reproducible and reliable the findings are. Future studies should aim to control the treatment parameters more strictly to ensure consistent and reliable results that other researchers can confidently replicate and build upon.

5.2. HTST Air Puffing for RTE Snacks

Two studies focused on optimizing the process parameters for HTST air puffing in the development of RTE snacks. In the first study, RTE potato–soy snacks were prepared by soaking peeled potatoes in diluted potassium metabisulfite ($K_2S_2O_5$), forming a dough with 10.31% soy flour, 89.69% potato flour, cold water (5 °C), and salt, followed by puffing at 230 °C for 25.46 s. This process achieved an ER of 3.69 and a HARD of 27.01 N [123]. In another study, the HTST whirling-bed dehydration puffing method was applied to develop RTE puffed carrots. The process included treating steamed diced carrots with $K_2S_2O_5$ and

sodium bisulfite ($NaHSO_3$), partially drying them at 70 °C, and expanding the carrot cubes at 175 °C for 30 s, leading to the formation of a hollow structure with thin walls. The final product showed an ER of 2.14 and a HARD of 2.231 N, with subsequent toasting at 125 °C for 15 min to reach the desired water content [132]. Despite advances in puffing techniques, the use of chemicals raises concerns regarding taste and potential toxicity. Off-tastes from chemical treatments could affect consumer acceptability, and the safety implications of residual sulfites, including possible allergic reactions and toxicity, were not thoroughly addressed. Addressing these concerns in future research will be essential to ensure the safety and palatability of the products.

Over the years, both processed and unprocessed RTE snacks have been produced using various puffing treatments. Two research teams investigated the factors influencing the hot-air puffing of different RTE snacks. In 2010, Pardeshi et al. studied soy-fortified, wheat-based RTE snacks. The dough formulation comprised wheat flour, soy flour, and saline water, achieving a moisture content of 46.17% d.b. The dough was cut into rectangular pieces, steamed at 70 kPa for 11 min, and subsequently puffed at 220 °C for 30 s. This experimental procedure resulted in an optimal ER of 4.418 [124]. Nevertheless, the researchers did not report the water content of the dough after steaming for 11 min prior to puffing. This gap is critical, as the moisture content directly influences the puffing behavior and, consequently, the final ER. Additionally, this omission undermines the reproducibility of the experiment and limits the ability to generalize the findings. Determining the water content would have enabled the researchers to examine the influence of this variable on the final ER, potentially resulting in more optimal results. In contrast, in 2020, Deepak et al. investigated the puffing of RTE quinoa. They reported an ER of 4.2 for RTE white puffed quinoa when treated at 253.8 °C for 60 s with a water content of 2% d.b. [136]. However, the reported water content of 2% d.b. is exceptionally low and, in combination with the alarming high temperature, could increase the risk of burning the quinoa during the puffing process. This might lead to a poor texture and darkened, unfavorable color of the puffed product. Future studies should focus on validating the effectiveness of this method when applying these controversial conditions.

5.3. Puffing Process Evaluation in Fruits and Vegetables

Two studies investigated the effects of various processing parameters on the drying and puffing characteristics of banana slices. One study focused on the influence of osmotic solution concentrations and puffing conditions on the drying characteristics and quality of puffed banana, specifically examining color, shrinkage, and texture [126]. Their methodology included blanching the banana slices for 60 s, subjecting them to osmotic treatment for 310 min, and partially drying them at 90 °C to achieve a moisture content of 30% d.b. The slices were then puffed at 220 °C and 200 kPa for 150 s, resulting in significant shrinkage due to structural collapse, as indicated by an ER of 0.675. Another study analyzed the effects of operating parameters during fluidized-bed puffing on the organoleptic characteristics of puffed bananas [128]. This study involved soaking banana slices in a sodium metabisulfite solution for 5 min, partially drying them at 90 °C to a moisture content of 26% d.b., and then puffing at 163 °C for 1 min with a superficial air velocity of 3.5 m/s. This process yielded shrunken crisps with a HARD of 22.3 $\pm$ 5.6 N and a lightness value of 44.3 $\pm$ 0.9. In both studies, the puffed banana crisps were further dried to a water content of 4% d.b. While both studies provide valuable insights into the processing of puffed bananas, potential limitations need to be considered. Both reported producing shrunken products rather than expanded ones, suggesting that the puffing techniques employed, typically aimed at increasing product volume, may not be optimal for expanding banana crisps. Future research should conduct comparative studies focusing on the sensory evaluation

of products puffed under varied conditions with a consistent technique to optimize the expansion process, ensuring volume increase and enhanced organoleptic characteristics for the snack product.

Various puffing processes are employed to produce chips, with numerous studies exploring healthy chip alternatives from fruits and vegetables. One study investigated the impact of osmotic dehydration on the quality of mango chips produced through explosion puffing drying, evaluating key quality attributes. Mango slices were initially dried at 50 °C to a water content of 30% d.b. and then puffed at 0.2 MPa and 95 °C for 5 min, followed by depressurization to 100 Pa and 75 °C. This process resulted in an ER of 1.88, a HARD of 16.4 N ± 6.0, a crispness of 7 N ± 3.1, and color characteristics of L^* = 47.4, a^* = 15.7, and b^* = 37.8 [127]. However, the substantial error margins, which constitute approximately 36.59% for HARD and 44.29% for crispiness, suggest high variability, likely due to inconsistencies in sample preparation, processing, or measurement techniques. Such variability presents challenges for quality control and standardization in commercial production. Another study applied a hybrid drying technique to investigate the physical, textural, and antioxidant properties of pumpkin chips. Pumpkin slices underwent an initial freezing phase at –18 °C for 24 h, followed by secondary drying at 55 °C under a vacuum of 0.10 mbar for 2 h, to a moisture content of 45% w.b. This was followed by explosion puffing drying at 90 °C and 190 kPa for 10 min, resulting in an impressively expanded and highly porous structure. The final product exhibited an ER of 4.97 and a HARD of 200 N [138]. However, the study's major drawback was the extensive 26 h dual-phase freeze-drying process, which poses challenges for efficiency and practicality in industrial settings. This prolonged period could lead to high operational costs, increased energy consumption, and reduced throughput. Alternative drying techniques or optimizations are needed to enhance the efficiency and viability of producing pumpkin chips commercially.

5.4. Microwave and IR Puffing Applications

Two studies focused on optimizing parameters for the development of various microwave-puffed products. One study aimed to optimize the puffing process for sorghum grains to create a high-quality product suitable for multiple food applications. This involved microwaving soaked sorghum grains at 100% power for 3 min. A moisture content of 21% d.b. was determined as essential to achieving a high ER of 8.67, with a puffing yield of 89% [130]. Concurrently, another study explored the production of RTE snacks using millet flour and mashed tubers, targeting an extended shelf life of 6 months. This mixture, with a moisture content of 19.22% d.b., was microwaved at 1080 W for 60 s, yielding an ER of 2.0416, a HARD of 15.89 N, and 22 crispiness peaks, reflecting its crispy texture [129]. Nevertheless, we should note that the visual representation of the final products is absent in both studies. The lack of accompanying images or detailed descriptions regarding color attributes poses challenges in assessing the reliability of the puffing process for obtaining a high-quality product that is desirable to consumers. Incorporating visual documentation in future research endeavors will be essential for enhancing the credibility and applicability of microwave puffing technology in food product development.

Two other studies examined processes for producing apple chips, with a focus on the influence of puffing parameters on quality. One study evaluated the impact of multiple puffing cycles on the physicochemical attributes, such as the color, texture, and microstructure, of explosion-puffed dried apple chips. This experiment subjected the apple chips to five consecutive puffing cycles, each lasting 5 min at 90 °C. The resulting product exhibited a hollow and a puffy structure, with an ER of 1.097, and with measured HARD and crispness values of 40.8 ± 2.3 N and 8.8 ± 0.7 N/mm, respectively [133]. Nevertheless, the reported outcome raises some questions. Despite undergoing five puffing cycles, the resulting apple

chips exhibited a very low ER of 1.097, indicating a minimal puffing effect. Additionally, the measured HARD of 40.8 N ± 2.3 N suggests a relatively hard product, which might not be desirable for puffed chips. Further exploration into the puffing parameters or the suitability of explosion puffing for apple chips might be necessary to achieve the intended puffed texture and increased volume. Another study focused on optimizing the puffing and drying parameters to enhance the quality of expanded apple chips. Apple slices with a moisture content of 17% d.b. were subjected to a puffing temperature of 74 °C and a pressure difference of 12.5 bar, followed by a 33 min vacuum-drying stage at 60 °C, resulting in an ER of 1.7 [135]. However, while the study mentions a 33 min vacuum-drying step at 60 °C, it does not explicitly discuss how this drying stage affects the final product quality. Moreover, further research is needed to analyze factors such as texture, rehydration capacity, color, and overall sensory characteristics to validate the use of this method to obtain visually appealing apple crisps characterized by a highly porous structure.

Three research teams have investigated various aspects of puffed rice production. One study sought to optimize the microwave puffing process for rice by subjecting parboiled milled rice with added salt to 35 s of microwave puffing at 850 W. The rice with a 5% salt content exhibited the most favorable puffing performance, achieving a puffing yield of 99.27% and an ER of 6.2. A sensory evaluation conducted by 10 semi-trained judges indicated that the rice with 5% salt had the best color, texture, and taste [125]. However, the limited number of judges may not represent broader consumer preferences, possibly introducing bias. Additionally, the study did not specify the type of salt used, a critical detail given the high 5% concentration, which may affect both outcomes and safety. Future research should include specific details on salt type to ensure transparency, reproducibility, and safety. Another study investigated the influence of moisture content and microwave power on the puffing yield and expansion volume of a Malaysian rice variety. This process produced an RTE breakfast cereal with an expanded volume of 2.22 mL/g at a puffing yield of 23%. This result was achieved by hydrating the rice to 14% w.b. and puffing at 800 W for 60 s [134]. Nevertheless, a puffing yield of 23% indicates substantial inefficiency, with a raw material waste rate of 77%, which may not be acceptable in industrial contexts. These findings suggest that a reevaluation of the experimental design and processing parameters could improve the yield and reduce material waste. In a different approach, one study evaluated the physicochemical attributes of rice snacks produced through IR puffing. Puffed rice-based snacks were produced with a notable phenolic content of 0.06 mg GAE/g and an ER of 2.24 ± 0.31 using IR power at 550 W, with the samples positioned 10 cm from the IR lamp. Color measurements of the final product showed promising results [141]. However, this study did not consider key factors like puffing duration, sensory evaluation, shelf-life stability, and consumer acceptability, all of which are essential for product development. Further research with a more comprehensive analytical approach will be necessary to assess the practical applications of IR puffing on rice for snack production and consumer satisfaction.

5.5. Other Puffing Technologies and Novel Applications

Two research teams conducted studies to optimize parameters for the development of various puffed food products. One study employed VCP technology to develop half-popped purple corn. Corn kernels were soaked in water at room temperature for 48 h, then in boiling water for 40 min, and puffed at 7.7×10^5 Pa for 14 s, causing the grains to explode and disintegrate. The puffed kernels, achieving an ER of 2.18, were then dried at 185 °C for 5 min [137]. While the study provided thorough data analysis, it lacked a detailed exploration of variable interactions, limiting nuanced optimization. Additionally, practical challenges in large-scale production, such as equipment durability and consistent

quality, were not addressed. Another study examined the mechanisms underlying the sand-puffing process of dried cassava starch gel. The method involved preparing a water–starch dough that was steamed, boiled, cooled, and stored before being shaped into disks. These disks were then dried at 50 °C to a moisture content of 12% d.b. and puffed at 181.67 °C, resulting in an ER of 10.69, ΔE^* of 29.13, and HARD of 24.55 N [139]. However, potential sand residues in the final product could pose health risks, affecting safety and quality by introducing unwanted textures and flavors, and potentially reducing consumer acceptability. Future research should investigate post-puffing techniques to ensure complete sand removal.

Two other studies focused on refining production parameters for puffed foods. One study compared the nutritional and physical properties of raw and puffed quinoa. A maximum expansion volume of 8.2 cm^3 was achieved by puffing quinoa at 230 °C for 30 s, resulting in significant increases in protein content (+6.82%), carbohydrate content (+7.92%), in vitro protein digestibility (+3.83%), and starch digestibility (+9.57%). However, there were notable decreases in crude fiber content (−29.39%), iron content (−23.80%), zinc content (−31.06%), calcium content (−44.87%), and magnesium content (−9.91%) in puffed quinoa compared to its raw form [140]. The absence of a clearly specified puffing technique in the article undermines its clarity and reliability. Additionally, the considerable nutrient losses in puffed quinoa raise concerns for individuals reliant on fortified foods for essential minerals, highlighting the need for nutrient retention strategies during food production. In another study, puffed tofu skin snacks were produced using a microwave oven. Soy milk was heated to 80 °C for 20 min to collect tofu skin, cut into rectangular pieces, and pre-dried at 40 °C to a moisture content of 55% w.b. Puffing was conducted using a microwave at 1071 W for 111 s, resulting in an ER of 4, HARD of 4.78 N, and color values of L^* = 59.27, a^* = 0.49, and b^* = 27.09 [142]. This study demonstrated robust statistical analysis and methodological rigor, especially through modeling and optimization techniques. However, the study's focus on specific independent variables and a geographically constrained sample may limit its applicability to broader markets. Expanding the scope and sample diversity could enhance the generalizability of the findings.

Implementing puffing techniques in the food industry offers several advantages and presents notable challenges, which will be discussed in subsequent sections. Given these limitations, it has become essential to refine the puffing process to achieve more optimal results.

6. Controlled Sudden Decompression (DIC Process)

In the 1990s, as an improvement on the traditional explosion puffing method, the DIC process was developed for texturizing heat-sensitive, partially dehydrated biological products [8]. This technique begins by establishing an initial vacuum phase, which facilitates improved heat transfer between the saturated steam and the food product [143,144]. In the subsequent thermo-mechanical treatment, the material is pressurized, followed by a rapid decompression to the vacuum, which enhances steam generation when the final equilibrium temperature is low and intensifies cooling when the equilibrium pressure is low [12]. This rapid cooling under mild conditions helps preserve the product's color and shape after the final drying stage post-expansion. The synergetic effect of temperature reduction and moisture removal through self-vaporization is crucial for achieving the desired product structure. Self-vaporization contributes to lowering the product moisture content, driving the product temperature closer to—but not exceeding—the glass transition temperature (Tg). This phenomenon, coupled with significant cooling due to rapid decompression to the vacuum, lowers the product temperature below the Tg, thereby solidifying its expanded structure. The resultant reduction in molecular mobility contributes to the

material's stiffening, inducing a transition from an amorphous, disordered state to a more ordered, glassy state [145].

The vacuum phase offers two main benefits: (1) a significant "ΔT" increase, allowing substantial steam generation, and promoting alveolation, with lower treatment temperatures (e.g., 150 °C to 30 °C instead of 220 °C to 100 °C with atmospheric decompression); and (2) reduced final temperatures, minimizing heat-induced deterioration and preserving the expanded structure of sensitive products [52].

Improvements to this method came in the form of introducing atmospheric air injections after decompression, effectively cooling the products with low hardening temperatures, preventing shrinkage, and maintaining expansion. Additionally, creating a vacuum before steam injection ensured uniform temperature distribution, allowing for the successful treatment of thick-layered products, and leading to the process's successful industrialization [53]. Figure 2 shows a photo of the DIC reactor [52].

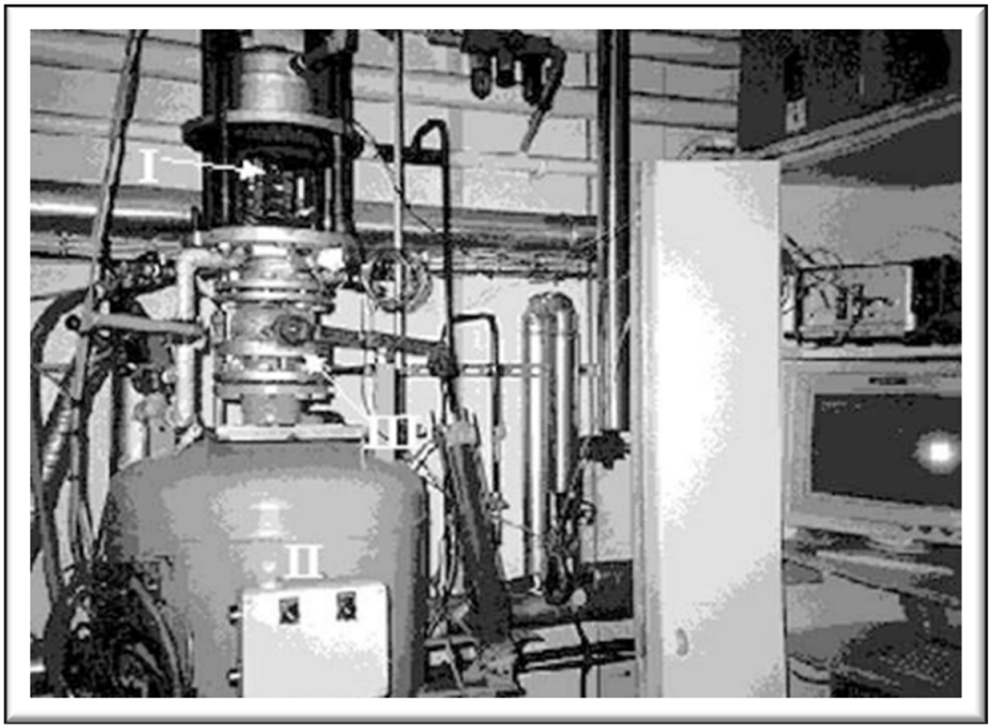


Figure 2. Photo of the DIC reactor: (I) processing vessel; (II) vacuum tank; (III) decompression valve [52].

The DIC treatment exhibits remarkable adaptability, as it has been used for the extraction of natural compounds [146–149], optimizing dehydration [150–152], and preservation processes across a variety of food matrices [153].

This section presents information on the experimental parameters, pre- and post-treatment methodologies, nutritional value, and ER (Table 5). This is followed by a detailed discussion of each reference, arranged chronologically, offering critiques that yield deeper insights into each study.

Table 5. DIC texturization of dehydrated food.

Methods/Year/ Reference	Target Product(s)	ER	Pre-Treatment	Post-Treatment	Parameters and Outcomes
DIC (2002) [52]	Expanded potatoes	2	-Washing and peeling -Cutting -Blanching: 95 °C, 7 min -Drying → W = 25% d.b. -Equilibration of water	Drying → W < 5% d.b.	-P = 5 bar/t = 45 s -Decompression → P = 0.15 bar -Drying kinetics: 400% time reduction
DIC (2004) [12]	Expanded potatoes, carrots, onions, broccoli, and tomatoes	-Potatoes: 2.3 -Carrots: 2.6 -Onions: 2.65 -Broccoli: 2.25 -Tomatoes: 4.55	-Washing and peeling -Cutting -Blanching -Partial drying -Equilibration of water	Drying → W < 5% d.b.	Potatoes: -P = 10 bar/t = 40 s/W = 28% db. Carrots: -P = 5 bar/t = 25 s/W = 20% d.b. Onions: -P = 4.5 bar/t = 15 s/W = 10% d.b. Broccolis: -P = 7 bar/t = 10 s/W = 30% d.b. Tomatoes: -P = 7 bar/t = 15 s/W = 20% d.b.
DIC (2004) [53]	Expanded potatoes, carrots, and onions	Trial 1: -Potatoes: 2.05 -Carrots: 2.42 -Onions: 2.75 Trial 2: -Potatoes: 2.35 -Carrots: 2.3 -Onions: 2.8	-Washing and peeling -Dicing -Blanching: potatoes (95 °C, 7 min) and carrots (95 °C, 5 min) -Drying → W (potatoes) = 13% d.b.; W (carrots) = 18% d.b.; W (onions) = 8.5% d.b. -Equilibration of water	Drying → W < 5% d.b.	Trial 1: Potatoes: -Step 1: 3 bar, 30 s/Step 2: 6 bar, 10 s Carrots: -Step 1: 2 bar, 30 s/Step 2: 6 bar, 6 s Onions: -Step 1: 2 bar, 20 s/Step 2: 6 bar, 8 s Trial 2 (with atmospheric air injection): Potatoes: -P = 7 bar/t = 45 s/W = 15% d.b. Carrots: -P = 6 bar/t = 20 s/W = 20% d.b. Onions: -P = 6 bar/t = 15 s/W = 10% d.b.
DIC (2007) [154]	Expanded apples	N/A	-Washing and peeling -Cutting: 1 cm cubes -Blanching: diluted lemon 50%, 10 min -Drying: 50 °C	Drying → W = 3% d.b.	-P = 5 bar/t = 20 s/W = 8% d.b. -Surface area = 466 m^2/g
DIC (2008) [155]	Expanded potatoes	1.45	-Cutting -Blanching: 7 min, 95 °C -Drying: 60 °C	Drying → W = 3% d.b.	-P = 6 bar/t = 20 s/W = 15% d.b.
DIC (2010) [156]	Expanded spray-dried skimmed milk powder	N/A	-Spray drying (SD) -Rehydration: 6 °C, 24 h	Drying: 50 °C → W = 3% d.b.	-P = 5.7 bar/t = 16 s/W = 18% d.b. -Bulk density = 390 kg/m^3 -Compressibility = 14.47% -Porosity = 71%
DIC-Assisted HAD (2014) [157]	Strawberry snacks	3.62	-HAD: 50 °C, 8 h → W = 18% d.b. -Storage/homogenization: 5 °C, 24 h	N/A	-P = 5.3 bar/t = 13 s -HARD = 7.65 N -Work done = 1.79 J
DIC (2015) [158]	Expanded powder granules	N/A	SD	-Drying: 50 ± 2 °C, 1.2 ± 0.2 m/s air stream -Storage	Skim milk powders: -P = 6 bar/t = 30 s/W = 12% d.b. -Specific surface area = 200 m^2/kg Whey protein powders: -P = 6 bar/t = 30 s/W = 16% d.b. -Specific surface area = 320 m^2/kg

6.1. DIC Texturization and Quality Enhancement

A study assessed the efficacy of DIC in processing heat-sensitive foods, aiming to preserve their nutritional contents and organoleptic qualities. Potatoes were blanched at 95 °C for 7 min, dried to a moisture content of 25% d.b., and then subjected to expansion at a pressure of 5 bar for 45 s. This process reduced the drying kinetics by 400%, achieving a final moisture content of 5% d.b. and an ER of 2 for the potato snack [52]. However, the study's focus on a single variety of potatoes limits the generalizability of its results, as the responses of different food products to the DIC process remain unexplored. Furthermore, the study provides limited data on the nutritional and sensory qualities of the processed products, which are critical for consumer acceptance and market success. Another study applied DIC texturization to Bintje potatoes, which were cut, blanched, and pre-dried to

15% d.b., and then expanded at 6 bar for 20 s, achieving an ER of 1.45 [155]. Nevertheless, the study's focus on the Bintje potato variety restricts the generalizability of its results, as the effects of DIC treatment on sorption characteristics may differ across other potato varieties and food products. A broader range of samples would have provided more robust and widely applicable conclusions.

A series of studies investigated the effects of various texturization parameters on food quality. One study focused on the impact of operating parameters on the quality of DIC-texturized vegetables. Potatoes, dried to 28% d.b., were expanded at 10 bar for 40 s, resulting in an ER of 2.3; carrots, dried to 20% d.b., were expanded at 5 bar for 25 s, achieving an ER of 2.6; onions, dried to 10% d.b., were expanded at 4.5 bar for 15 s, reaching an ER of 2.65; broccoli, dried to 30% d.b., was expanded at 7 bar for 10 s, attaining an ER of 2.25; and tomatoes, dried to 20% d.b., were expanded at 7 bar for 15 s, achieving an ER of 4.55 [12]. Another study in this series aimed to enhance the quality of processed food, focusing on ER and color outcomes. Potatoes dried to 15% d.b. and expanded at 7 bar for 45 s reached an ER of 2.35, while a two-stage expansion for carrots (2 bar for 30 s, then 6 bar for 6 s) yielded an ER of 2.42, and onions, expanded similarly (2 bar for 20 s, followed by 6 bar for 8 s), achieved an ER of 2.75 [53]. However, both studies lacked detailed statistical analysis, including confidence intervals and standard deviations, making it difficult to assess the variability and significance of the data. Additionally, using sensory analysis by a panel of 12 people to assess the degree of cooking introduces subjectivity. This subjectivity could be minimized by integrating objective, quantitative techniques such as mechanical texture analysis and spectrophotometry to provide more precise measurements.

One study determined the sorption isotherms for apples that were hot-air dried and texturized using the DIC method. Although hysteresis between adsorption and desorption was not pronounced, it was observable at temperatures of 20 °C, 30 °C, and 40 °C and relative humidity between 10% and 90%. DIC texturization influenced the sorption isotherm, with texturized products at 2 and 5 bar exhibiting slightly lower adsorption capacities compared to hot-air-dried samples at an $a_w < 0.3$, but significantly higher absorption for $a_w > 0.6$ [154]. However, the limited temperature range (20 °C to 40 °C) may not fully capture the thermal behavior of apples under diverse storage and processing conditions. Expanding the range would provide a more comprehensive understanding of temperature dependence. Additionally, although eight isotherm models were used, the study primarily validated the GAB and Ferro-Fontan models, without further analyzing the poor performance of models like BET and Halsey. A deeper exploration of these models could improve predictive accuracy and applicability across food products.

Another study examined the effects of DIC-assisted HAD on the textural properties of strawberries, comparing it with conventional HAD and freeze-drying. The expansion process was conducted at 5.3 bar for 13 s, producing strawberries with an ER of 3.62 and HARD of 7.65 N [157]. However, inconsistencies in drying conditions across methods complicate the validity of the comparisons, as varying time and temperature profiles could independently affect texture. Although the study employed RSM to optimize the DIC parameters, the statistical models reveal considerable unexplained variability, suggesting that the experimental design may not fully capture the complex interactions between drying parameters and texture outcomes.

6.2. DIC Applications in Powder Modification

A study investigated the structural modifications and quality attributes of spray-dried skimmed milk powders after DIC treatment. The milk was spray-dried, rehydrated to 18% d.b., and then expanded at 5.7 bar for 16 s. This treatment increased the porosity to 71% and decreased the bulk density to 390 kg/m^3 [156]. While this study provides insights into

the effects of DIC treatments on skimmed milk powder properties, certain limitations affect its scientific rigor. The rewetting of powder or its exposure to a high-moisture atmosphere could introduce variability that is not fully controlled. Additionally, empirical models for bulk density and compressibility show R^2 values from 0.68 to 0.84, indicating unexplained variability, which may impact the study's conclusions.

Another team of researchers investigated a new three-stage SD process that introduced "high pressure/room temperature air" as the primary DIC-texturing fluid. Skimmed milk powder, hydrated to 12% d.b., and whey protein powder, hydrated to 16% d.b., were treated at 6 bar for 30 s, resulting in specific surface areas of 200 m^2/kg and 320 m^2/kg, respectively [158]. Nevertheless, the analysis primarily focused on porosity, interstitial air volume, compressibility, specific surface area, and reconstitution aptitude as dependent variables, without a comprehensive justification for their selection or consideration of additional critical properties like thermal stability and nutrient retention. Additionally, the practical scalability and economic feasibility of the optimized process were not adequately addressed, limiting its real-world applicability. The study acknowledges potential thermal damage from high-temperature steam–DIC texturing but does not explore alternative methods to mitigate such effects, reducing its relevance for a broader range of heat-sensitive materials. These points collectively highlight the need for a more holistic and practically oriented approach to optimizing DIC treatments for spray-dried powders.

6.3. Industrialization and Future Considerations

DIC is a texturization method that was successfully implemented for the first time at an industrial level in 1994 in Laon, France. The process presents several advantages that mark it as a great improvement over the traditional puffing method. It is positioned as a viable method for scalable industrial applications in the food industry, due to its capacity to shorten drying durations, preserve the integrity of bioactive compounds, and enhance sensory qualities. Nevertheless, a major limitation that needs to be addressed involves a relatively gradual increase in pressure, which may cause potential damage to heat-sensitive products. These products may not withstand prolonged exposure to high pressures without compromising their desirable color characteristics or advantageous textural properties.

7. Intensification of Vaporization by Decompression to the Vacuum (IVDV)

Recently, a novel process called IVDV has been developed, upgrading the efficiency and effectiveness of the DIC method, which was already considered to be an improved version of puffing. This advanced system employs an extremely rapid pressurization mechanism capable of reaching 12 bar in less than 1 s [159]. By substantially shortening the product's exposure to the increased pressure, it mitigates the thermal degradation of heat-sensitive constituents such as vitamins, antioxidants, and proteins. Moreover, the rapid pressure drop to the vacuum in a very short duration is critical for processing thermo-sensitive products that cannot withstand prolonged exposure to high pressures and temperatures (Figure 3). Originally designed as a texturization technique for fruits, vegetables, and other biological products, IVDV preserves their nutritional content and enhances their sensory properties. Moreover, the IVDV technique has shown considerable promise in enhancing extraction efficiency from plant materials [160,161] and serving as an effective method for microbial decontamination [162]. The IVDV process exhibits a notable versatility in mitigating peanut allergenicity by effectively degrading proteins and significantly reducing allergenic markers, thereby enhancing food safety [163–165].

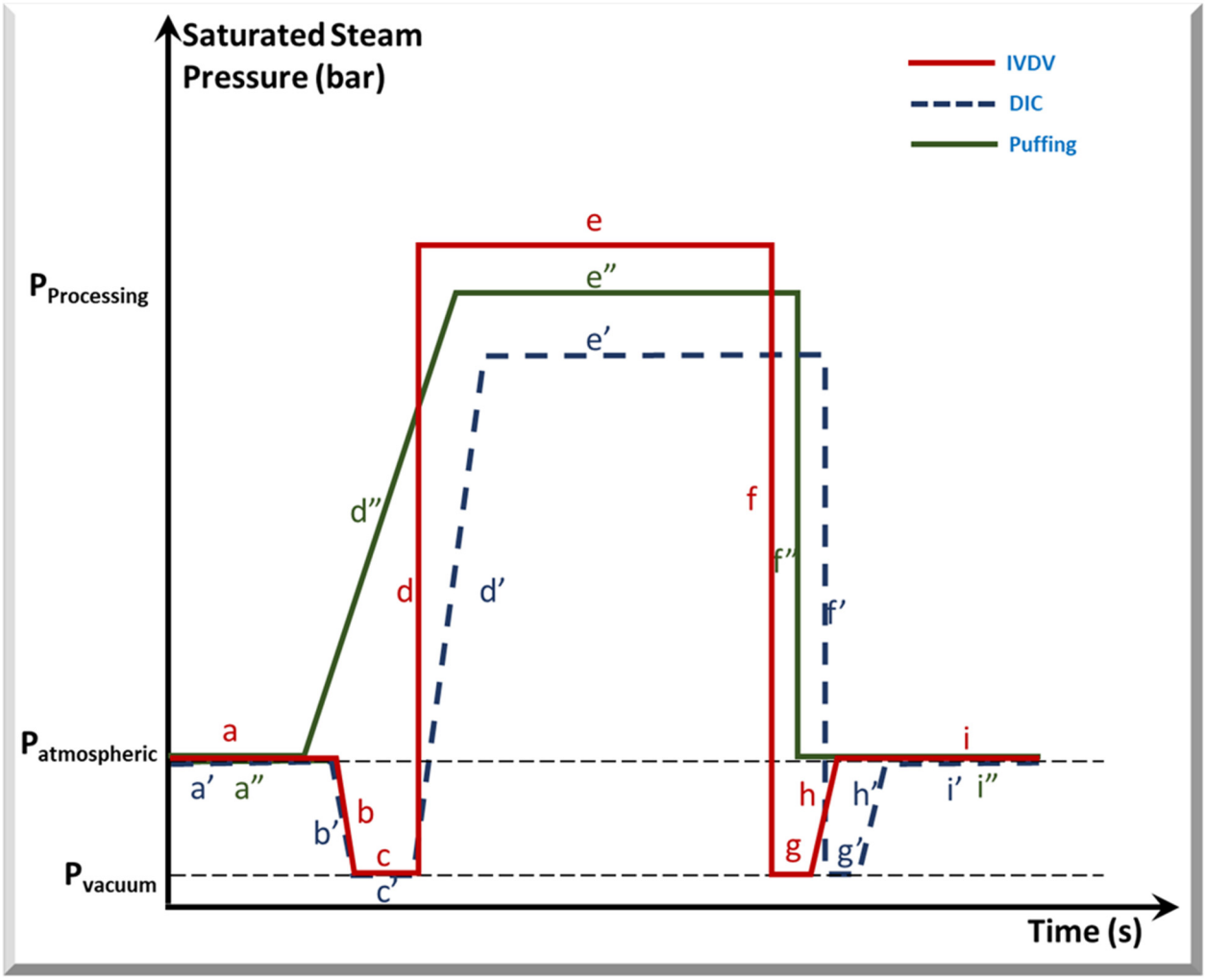


Figure 3. Pressure–time profiles of IVDV (red), DIC (blue), and puffing (green) processing cycles: a, a', a": sample in the processing vessel at atmospheric pressure; b, b': establishment of an initial vacuum within the treatment chamber (~0.1 s for IVDV and DIC); c, c': sample under vacuum for a few seconds; d, d', d": steam generation (<1 s for IVDV and >1 s for DIC and puffing); e, e', e": processing at the selected pressure for a certain time; f, f', f": decompression duration (<1 s); g, g': sample under vacuum for few seconds, with the possibility of air injection; h, h': return to atmospheric pressure within the treatment chamber; i, i', i": sample recovery. Steps b' and c' are sometimes skipped during the DIC process.

The IVDV processing reactor, as depicted in Figure 4, comprises five primary components: A treatment vessel (Figure 4A), where the samples undergo a thermal treatment involving saturated steam at high pressure (up to 12 bar) and the corresponding temperature. A steam generator (boiler) participates in the generation of high-pressure steam (Figure 4B). The required pressure is rapidly achieved within 1 s using the rapid steam generation system (Figure 4D). The vacuum system consists of a vacuum tank (Figure 4C) with a volume 500 times larger than the treatment vessel. The vacuum within the tank is ensured through the utilization of a vacuum pump (Figure 4E).

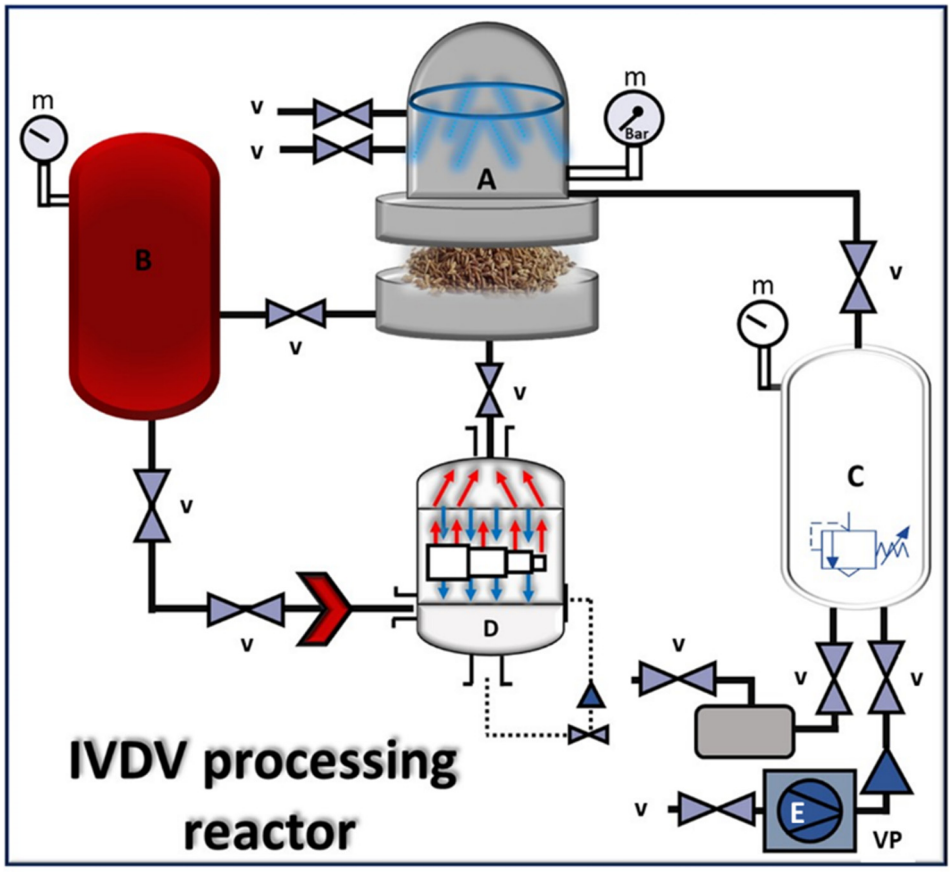


Figure 4. Schematic diagram of the IVDV system: (**A**) treatment chamber; (**B**) steam generator; (**C**) vacuum tank; (**D**) ultra-speed pressure-increase system; (**E**) vacuum pump; v: valve.

The rapid pressure increase via part "D" (Figure 4) and the ultra-rapid pressure release via part "v" (Figure 4) give this new technology the ability to process dry solid foods.

Comprehensive details on the experimental parameters, pre- and post-treatment methods, nutritional value, and ER are elucidated in Table 6. This is followed by an in-depth discussion that meticulously examines each reference, arranges them chronologically, and provides critical analyses that offer further insights into each study.

Table 6. IVDV texturization of dehydrated food.

Method/Year/ Reference	Target Product(s)	ER	Pre-Treatment	Post-Treatment	Parameters and Outcomes
IVDV (2014) [159]	Expanded chickpeas	1.65	-Soaking: distilled water, 25 °C -Homogenization: 3 to 4 days, 4 °C	Drying: 50 °C, 24 h	-P = 8.5 bar/t = 20 s/W = 42% d.b. -TPC = 32.3 ± 0.6 mg GAE/ 100 mg DM -HARD = 10.9 N -Work done = 18 ± 2.3 mJ
IVDV (2014) [166]	Expanded maize	2.65	-Soaking: distilled water, 25 °C -Homogenization: 3 to 4 days, 4 °C	-Drying: 50 °C, 24 h -Roasting: 3 min, 220 °C	-P = 10 bar/t = 20 s/W = 25% d.b.
IVDV (2014) [167]	Partially defatted peanuts	1.5	-Cleaning and sieving -Air roasting: 140 °C for 15 min -Hydration -Homogenization: 2 days, 4 °C -Mechanical pressing: 97 bar, 4 min	-Drying: 50 °C, 1.5 h → 7 ≤ W ≤ 10% d.b. -Roasting: 180 °C, 3.5 min	-Defatting ratio = 56% -P = 9 bar/t = 10 s/W = 10% d.b.
IVDV (2014) [168]	Purple maize snacks	2.97	-Soaking: distilled water, 25 °C -Homogenization: 3 to 4 days, 4 °C	Drying: 50 °C, 24 h	-P = 10 bar/t = 20 s/W = 25% d.b. -TAC = 29.43 mg GAE/100 mg DM -TPC = 510.87 mg GAE/100 mg DM -HARD = 44.17 N -Work done = 137.9 mJ

Table 6. *Cont.*

Method/Year/ Reference	Target Product(s)	ER	Pre-Treatment	Post-Treatment	Parameters and Outcomes
IVDV (2014) [54]	Purple maize snacks	3.13	-Soaking: distilled water, 25 °C -Homogenization: 3 to 4 days, 4 °C	-Drying: 50 °C, 24 h -Roasting: 3 min, 220 °C	-P = 10 bar/t = 20 s/W = 25% d.b. -TAC = 38.35 ± 3.3 mg GAE/ 100 mg DM -TPC = 602.87 ± 22 mg GAE/ 100 mg DM -HARD = 58.78 ± 1.61 N -Work done = 240.7 ± 7.6 mJ
IVDV (2015) [55]	Expanded chickpeas	1.61	-Soaking: distilled water, 25 °C -Homogenization: 3 to 4 days, 4 °C	-Drying: 50 °C, 24 h. -Roasting: 3 min, 190 °C	-P = 8.5 bar/t = 20 s/W = 42% d.b. -HARD = 10.9 ± 0.78 N -Work done = 11.8 ± 2.8 mJ -L^* = 46.39/a^* = 12.86/b^* = 24.28 -ΔE^* = 5.35 -TPC = 53.9 ± 1.5 mg GAE/ 100 mg DM
IVDV (2015) [169]	Expanded chickpeas	1.63	-Soaking: distilled water, 25 °C -Homogenization: 4 days, 4 °C	-Drying: 50 °C, 24 h -Roasting: 3 min, 190 °C	-P = 6.5 bar/t = 75 s/W = 42% d.b. -HARD = 12.29 N -Work done = 10.6 mJ -L^* = 43.43/a^* = 15.21/b^* = 24.51 -TPC = 43.94 mg GAE/100 mg DM
IVDV (2017) [170]	Partially defatted peanuts	1.9	-Dehulling -Drying: 2–3 days → W = 5.56 ± 0.24% d.b. -Cleaning and sieving -Light roasting: 140 °C, 15 min -Homogenization: PVC bags, 3 days, 4 °C -Mechanical pressing: bar, 240 s -Rehydration and homogenization	-Drying: 50 °C → 7.5 ≤ W ≤ 11% d.b. -Roasting: 180 °C, 210 s	-P = 11.9 bar/t = 17.4 s/ W = 7.1% d.b. -Defatting ratio = 45%
IVDV (2018) [171]	Partially defatted peanuts	N/A	-Drying: 140 °C, 15 min → 2.48% d.b. -Hydration → 5% d.b. -Storage: PVC bags, 4 °C, 3 days -Mechanical pressing: 62 bar, 240 s -Rehydration: 25 °C -Homogenization: 4 °C, 3 days	-Drying: 50 °C → 7.5 ≤ W ≤ 11% d.b. -Roasting: 180 °C, 210 s	-P = 9.1 bar/t = 17.1 s/ W = 19.9% d.b. -Defatting ratio = 45.02% -HARD = 5.94 N -1st fracture deformation = 6.72% -Work done = 5.76 mJ -Quantity of fractures = 14
IVDV (2020) [172]	Sprouts	N/A	-Soaking and germination. -Partial drying → W = 25% d.b.	-Drying: 50 °C → W = 4% d.b.	-P = 4.5 bar/t = 12 s/W = 25% d.b. -Energy consumption decrease = 55%
IVDV (2020) [173]	Partially defatted peanuts	N/A	-IR treatment: 88.5 °C, 56 min -Hydraulic pressing: 80 bar, 1 min	N/A	-Defatting ratio = 45% -IR treatment = 88.5 °C, 56 min -Pressing: 80 bar, 1 min
IVDV (2021) [174]	Expanded chickpeas	N/A	-Hydration -Homogenization: PVC bags at 4 °C for 1–2 days	-Drying: 50 °C, 24 h -Roasting: 200 °C, 6 min	-L^* = 83.43/a^* = 3.09/b^* = 24.58 -a_w = 0.08
IVDV (2024) [175]	Sprouts	1.6	-Soaking: 3 h, mineral water, mass-to-volume ratio of 1:5 (g/mL) -Germination: 22 °C ± 1 °C, 7 days	N/A	-P = 5.5 bar/t = 15.4 s/ W = 8.8% d.b. -Vit. B2 = 2.05 mg/kg -Vit. B6 = 5.02 mg/kg -Vit. E = 14.08 mg/kg
IVDV (2024) [176]	Expanded mangos	3.82	-Washing -Cutting: cubes 1 cm^3 -Hydration: <30 s → W = 880% d.b. -Drying: 60 °C → W = 22.5% d.b. -Homogenization: 4 °C, 4 days	-Drying: 60 °C → W = 5.5% d.b.	-P = 4.5 bar/t = 22.5 s -HARD = 8.49 N -Work done = 66.85 mJ -Drying time decrease: 50% -Phenolic content increases 9 times -Antioxidant activities increase 11 times

7.1. IVDV Applications in Processing Legumes and Cereals

One study applied the IVDV process to enhance chickpeas' texture by reducing their bulk density and HARD, imparting an alveolated structure. Chickpeas were hydrated to 42% d.b. and expanded at 8.5 bar for 20 s, resulting in a maximum ER of 1.65, TPC of 32.3 ± 0.6 mg GAE/100 mg DM, HARD of 10.9 ± 0.4 N, and work done of 18 ± 2.3 mJ [159]. However, optimizing the conditions to simultaneously maximize ER and TPC is necessary. The notable ± 2.3 mJ error in work done at maximum expansion raises concerns about measurement reliability, potentially due to inconsistencies in sample preparation or inherent

sample variability. Standardizing conditions, increasing replicates, and using more precise instruments would help address this.

Two additional studies evaluated the efficiency of the IVDV texturizing process as a pre-treatment for roasting chickpeas. In these studies, chickpeas hydrated to 42% d.b. and treated at 6.5 bar for 75 s achieved an ER of 1.63. Interestingly, when treated at 8.5 bar for 20 s, a similar ER of 1.61 was observed, suggesting that higher pressures can reduce the treatment time. Additionally, improvements in total TPC and lightness were noted, with TPC increasing from 43.94 mg GAE/100 mg DM to 53.9 mg GAE/100 mg DM, and lightness values rising from 43.43 to 46.39 [55,169]. Both studies were robust in their methodological approach, using RSM effectively to optimize multiple parameters simultaneously. However, the differences in optimal conditions suggest that more extensive comparative studies across different chickpea varieties could provide more universally applicable results. Additionally, the sensory analysis could be expanded to include a more diverse panel to better represent consumer preferences across different demographics.

The same research team conducted three studies to evaluate the effects of IVDV parameters on the physical properties (ER, texture) and antioxidant components of expanded maize kernels. In the first study, maize samples hydrated to 25% d.b. were treated at 10 bar for 20 s, achieving an ER of 2.65 [166]. The second study increased the ER to 2.97 using purple maize under the same conditions, with a notable TPC of 510.87 mg GAE/100 mg DM [168]. The third study further enhanced the ER to 3.13, with TPC reaching 602.87 $\pm$ 22 mg GAE/100 mg DM [54]. Nevertheless, balancing the process parameters to optimize both ER and TPC remains a challenge, as conditions favoring maximum expansion may not align with those that preserve high antioxidant levels. Future research should aim to fine-tune these parameters to avoid compromising either attribute. Additionally, analyzing polyphenol degradation pathways during IVDV could provide insights into mitigating these effects for truly optimized outcomes.

7.2. IVDV in Processing Defatted Peanut

Studies investigated the production of partially defatted peanuts utilizing IVDV. The researchers developed a defatting technique aimed at minimizing energy consumption and avoiding chemical agents, thereby reducing VOC emissions while preserving product integrity. In the first study, peanuts were defatted by 56%, rehydrated to 10% d.b., and expanded using IVDV at 9 bar for 10 s, achieving an ER of 1.5 [167]. While the study suggested cost-effectiveness, a detailed cost analysis and comparison with conventional methods are necessary. A comprehensive review of capital investment, operational costs, and potential market advantages would strengthen the case for MEPSI's economic viability in industrial applications.

In another study, peanuts were mechanically defatted to 45%, hydrated to 7.1% d.b., and expanded at 11.9 bar for 17.4 s, resulting in a maximum ER of 1.9 [170]. In a subsequent study, peanuts were hydrated to 19.9% d.b. and expanded at 9.1 bar for 17.1 s, achieving favorable textural parameters, including a HARD of 5.94 N, work done of 5.76 mJ, and 14 fracture points [171]. Both studies would benefit from evaluations of the long-term stability and shelf life of the processed products, as well as a detailed nutritional analysis to identify any changes in protein, vitamin, mineral, and bioactive compound contents resulting from the defatting and IVDV techniques.

7.3. IVDV for Sprout Preservation and Nutrient Retention

Two studies evaluated IVDV treatment for partially dehydrated sprouts. In the first, sprouts dried to 25% d.b. were treated at 4.5 bar for 12 s, reducing the overall drying time and achieving a 55% decrease in energy consumption compared to HAD while

preserving the nutritional contents [172]. A follow-up study treated sprouts dried to 8.8% d.b. at 5.5 bar for 15.4 s, achieving an ER of 1.6. This optimal IVDV treatment preserved vitamins B6 and E by 412% and 42%, respectively, compared to conventional HAD, without negatively impacting the vitamin B6, protein, or lipid contents. The resulting water content of 4.9% supports extended shelf life and ensures safety for consumption [175]. However, evaluating the stability of preserved nutrients under typical storage conditions is necessary to confirm these benefits over time. Additionally, integrating IVDV with other preservation technologies, such as pulsed electric fields, could potentially enhance nutrient preservation efficacy and broaden the scope and impact of these methods.

7.4. IVDV Applications in Fruit Processing

A study evaluated the impact of IVDV treatment on mangoes, focusing on ER, phenolic content, and antioxidant activities. The results indicated that IVDV treatment led to a fourfold increase in ER, a ninefold increase in phenolic content, and an elevenfold enhancement in antioxidant activities. Additionally, the drying time was reduced by 50% [176]. Although this study demonstrated the advantages of IVDV over conventional HAD, it did not include comparisons with other advanced drying methods, such as freeze-drying or microwave-assisted drying, which would provide a more comprehensive evaluation of IVDV's unique benefits. Future research should also evaluate long-term storage stability to better understand the technology's practical applications and commercial viability.

Pilot studies have optimized IVDV parameters, demonstrating that rapid, close control of pressure with precise exposure to high temperatures can minimize thermal degradation and protect heat-sensitive bioactive compounds. An industrial plant employing IVDV in dried apple texturization was built in 2019 in Jezzine, Lebanon, clearly illustrating the method's feasibility and successful industrialization.

8. Advantages and Disadvantages of the Expansion Methods

The food expansion techniques employed exhibit shared and distinct advantages and disadvantages. Table 7 presents details of these variations.

Table 7. Advantages and disadvantages of food texturization techniques.

Methods	Advantages	Disadvantages
DF	Rich, savory flavor; crispy texture; reduced cooking time [177]	Health risks associated with fried food consumption [178]
ME	Cost-effective; scalable [179]; handles diverse raw materials [180]; produces various textures [181]	Inconsistent expansion; potential flavor/color changes [180]
Popping	Minimal oil usage; low-calorie; airy snacks [33,182]	High energy consumption; risk of nutrient degradation [33]
Puffing	Convenient and versatile [33]; preserves many original organoleptic qualities [182]	Degradation at high temperatures and pressures; potential undesirable changes [33]
DIC	Significant microbial reduction [183]; extended shelf life [52]; improved color and texture [153]	Risk of additional thermal degradation during the initial pressure-increase phase [174]
IVDV	Rapid high-pressure treatment [159]; low degradation risk [176]; extended shelf life; improved color and texture [171]	Requires further improvements in the treatment of powdered products

The table presents a detailed comparison of various food processing techniques, each with specific advantages and drawbacks depending on their use. Although DF enhances flavor and texture, it is linked to numerous chronic health risks, potentially

deterring health-conscious consumers. In contrast, ME is highly effective in large-scale food production but struggles with maintaining consistent product quality, limiting its flexibility in customization and ingredient selection. Furthermore, both popping and puffing offer the advantage of producing low-calorie snacks, thus promoting healthier food alternatives. However, these processes are often energy-intensive and may lead to nutritional degradation due to high temperatures and pressures, which can negatively impact sensory qualities such as taste and texture. Newer methods like DIC and IVDV offer similar benefits in terms of organoleptic enhancements, microbial reduction, and nutrient retention. The IVDV method stands out, with no notable drawbacks, as it efficiently retains nutrients and minimizes degradation due to its rapid pressure increase in less than a second. Overall, selecting the appropriate food processing method involves weighing factors such as product quality, health implications, operational efficiency, and market needs, with each technique providing unique advantages and challenges that must be evaluated carefully. IVDV could potentially be the most effective and reliable of these techniques.

9. Conclusions

Conventional methods of food expansion pose significant challenges related to health and nutritional quality, primarily due to molecular degradation under high temperatures and pressures. In response, various novel expansion techniques have been proposed; however, few have achieved industrial-scale adoption. This can largely be attributed to inconsistent textural properties, ER, and potential adverse effects on the aroma, taste, and color of the final product. Although methods such as DF, ME, popping, and puffing have shown potential, concerns over product quality and economic viability have limited their widespread use. Recent techniques, resulting in improvements over the traditional texturization by self-vaporization, including DIC and IVDV, have demonstrated more consistent ER and improved organoleptic properties. Nonetheless, further research is needed to assess their effectiveness and feasibility for large-scale production. Notably, IVDV has also been successfully employed for the extraction of polyphenols from food products, highlighting its versatility for industrial applications. Moreover, IVDV represents a significant advancement over its predecessor, DIC, as it eliminates the risk of degradation at high pressures, reaching 12 bar in less than 1 s compared to the 10 s interval in the DIC process, therefore placing itself as the clear superior, where no clear notable drawbacks are identified. This review offers a comprehensive overview of food texturization methods and provides a valuable reference for future research and development in this field.

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Abbreviation List

AA Acrylamide
AP Apple pomace
A_w Water activity

DIC	Controlled Sudden Decompression/Détente Instantanée Contrôlée
DF	Deep frying
EF	Expansion factor
ER	Expansion ratio
HARD	Hardness
HTST	High-Temperature Short-Time
HAD	Hot-air drying
IR	Infrared
IVDV	Intensification of Vaporization by Decompression to the Vacuum
ME	Mechanical extrusion
RTE	Ready-to-eat
RSM	Response surface methodology
SME	Specific Mechanical Energy
SD	Spray drying
TSE	Twin-Screw Extrusion

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