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REVIEW ARTICLE

High-Pressure Processing (HPP) Energy Efficiency and Scalability Challenges in Ultra-Processed Meat: A Review

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Abstract

The growing demand for clean-label, safe, and nutritious ultra-processed meat products (e.g., sausages, nuggets) presents challenges to conventional thermal processing due to its negative impact on sensory and nutritional quality. High-Pressure Processing (HPP) offers a non-thermal alternative that effectively inactivates pathogens while preserving product integrity. However, its broader industrial adoption remains limited by significant energy demands and scalability issues. HPP requires 2.5–3.2 kWh/kg—up to 26 times more than traditional pasteurization—primarily due to the energy-intensive hydraulic system and adiabatic heat loss during pressurization cycles. Scalability is further constrained by batch-based operation (3–7 minutes per cycle), small vessel capacities (<500 L), and high capital costs (up to USD 2.5 million per unit), resulting in only 18% adoption among large-scale producers. Additional barriers include low energy recovery efficiency and variability in food matrices, such as lipid protection in emulsified meats, which can reduce microbial inactivation effectiveness. Recent innovations—such as semi-continuous systems (increasing throughput by ~35%), pulsed pressure protocols (reducing energy use by ~18%), and solar-assisted HPP systems (cutting emissions by ~40%)—demonstrate technical promise, though economic feasibility remains a concern. In conclusion, while HPP presents considerable advantages in terms of food safety and quality, overcoming its energy and scalability limitations will require integrated advancements in process engineering, renewable energy utilization, and cooperative industry strategies to enable sustainable and cost-effective implementation.

Keywords: High-pressure processing, ultra-processed meat, energy efficiency, scalability challenges, food safety, non-thermal processing, meat product preservation

1. Introduction

Ultra-processed foods (UPF) are a group of foods that undergo various stages of industrial processing and contain additives that are not commonly used in conventional food processing [1]. Ultra-processed meat products such as sausages, nuggets and hams have become a dominant component of global consumption patterns as shown in Figure 1, which the highest was represented by the United States (58.8%), and the lowest by Columbia (15.9%) [2]. In addition, the market growth reaching 5-10% per year in middle-income countries [3]**.** This trend is driven by the demand for ease of presentation, shelf stability, and sensory appeal. However, these products are susceptible to microbiological contamination (e.g., *Listeria monocytogenes*, *Salmonella*) and quality degradation due to conventional thermal processes. USDA-FSIS data for 2023 shows that 15% of *foodborne illness* cases in the US are related to processed meat products [4], emphasizing the urgency of alternative preservation technologies that are able to maintain safety without compromising organoleptic attributes [5]. On the other hand, epidemiological studies link excessive consumption of ultra-processed meat with increased risk of obesity and cardiovascular disease, demanding technological innovations that address the "safe-healthy-tasty" paradigm simultaneously [3].

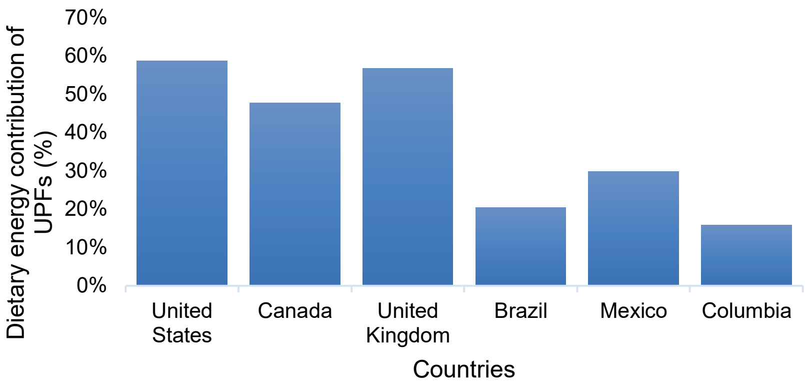

Figure 1. Dietary energy contribution of ultra-processed foods in some countries

High-pressure processing (HPP) is the most successfully adopted non-thermal processing technology in the food industry for distributing safe and healthy meat products without the use of chemicals or heat treatments [6], [7]. HPP is a commercial pasteurization technology used to extend the shelf life of both solid and liquid foods [8]. This technology serves as an alternative to the use of preservatives and additives to ensure food safety, particularly in ready-to-eat meat products that are sliced or preserved. However, HPP at room temperature is not a sterilization technology, as microbial spores often survive the process. Therefore, high-pressure processed foods have a limited shelf life and must be stored or distributed under refrigerated conditions, below 7°C, similar to thermally pasteurized foods. HPP enables the inactivation of microorganisms and extends the shelf life of food when pressures between 200–600 MPa are applied [9]. Unlike thermal processing, this technique allows the use of lower temperatures, causing minimal changes to the nutritional properties and overall quality of the product. Meat products hold a significant market share in the application of HPP in the industry, with approximately 25 to 30% of all high-pressure processed foods being meat products [6].

The working principle of HPP in meat involves the uniform application of extremely high pressure to the entire product, which has been packaged in flexible packaging, using a liquid medium as the pressure transmitter [10]. Based on the isostatic principle, the pressure is evenly distributed without damaging the physical structure of the product. This pressure can inactivate microorganisms without the use of heat, preserving sensory quality and nutritional value. During the process, there is an increase in temperature due to adiabatic heating, but the system is usually cooled to maintain low temperatures. Non-covalent molecular interactions are affected by the pressure, while covalent bonds remain stable, thereby preserving the primary structure of the compounds in the meat. Even though HPP provides significant advantages in maintaining the quality of ultra-processed meat products such as nuggets and sausages, this technology still faces challenges in terms of energy consumption. HPP works at very high pressures, generally ranging from 400 – 600 MPa which requires a large amount of electrical energy, especially to operate hydraulic pumps and pressure systems. This pressure also demands the use of robust and durable equipment, which indirectly increases power consumption and operational costs. An analytical study by Bolumar *et al*. [6] revealed that HPP's energy efficiency still faces challenges, especially on a large industrial scale. This is reinforced by the findings of Carrapiso *et al*. [11] , which highlights that the application of HPP to products such as chorizo requires special consideration of storage time and temperature variables to maintain product quality, which contributes to overall energy consumption. In terms of energy efficiency, HPP has advantages over conventional thermal technology. According to a study by Atuonwu *et al*. [12] HPP shows better energy efficiency than conventional thermal and irradiation processing, especially when considering the quality of the final product and the environmental impact. The implication is that high energy consumption in HPP has an impact on large operational costs. This is an important consideration for industrial-scale producers, especially in the mass processing of ultra-processed meat and oriented towards cost efficiency per unit.

In addition to energy constraints, scalability is another challenge in the application of HPP in the ultra-processed meat industry. These challenges include both technical and economic aspects that affect the adoption of HPP technology in the industry. Technically, the HPP system is still batch-based which results in limitations in production capacity, especially high-volume products. The limited batch size necessitates manual or semi-automatic filling which affects the daily troughput and prolongs the cycle time [13]. Study by Bolumar *et al*. [6] mentioned that the cycle speed and volume of the vessel are the main factors that hinder production efficiency when HPP is applied to meat products on a large scale. In addition, the initial investment and high maintenance costs for HPP equipment as well as the calculation of return on investment (ROI) are hindering the adoption of this system.

This review aims to analyze the energy efficiency of HPP in the specific context of ultra-process meat processing, drawing on the finding that HPP energy consumption is up to 26 times that of thermal pasteurization for similar products [14], and identifying scalability challenges and potential technological or management solutions of this technology, including batch capacity limitations (3-7 minutes/cycle) and equipment investment costs reaching $2.5 million/industrial unit [5], as well as providing insights for the development of efficient and sustainable future meat processing systems. Although HPP is proven to be effective in maintaining organoleptic and nutritional quality, studies reveal that only 18% of the large-scale meat industry adopts HPP due to techno-economic constraints [6]. Thus, this review is expected to serve as a foundation for the development of an economical, sustainable HPP system that is ready for massive adoption in the ultra-processed meat industry.

2. Research Methodology

This study will employ a Systematic Literature Review (SLR) [15] to analyze the energy efficiency and scalability challenges in applying HPP to ultra-processed meat. This methodology involves the collection, analysis, and synthesis of relevant literature from reputable scientific journals to identify definitions, key characteristics, and existing recommendations [16] as shown in Table 1.

Table 1. Literature Study Analysis

Aim of research	Results	Energy efficiency & Scalability challenges	Ref.
This research examines the effect of HPP on the lipid composition of donor breast milk compared to the Holder Pasteurization (HoP) method.	HPP increased C10:0 SFA (1.34% vs 1.20%) and decreased n-6 PUFA (20.65% vs 21.57%). Ceramides decreased, DOxS increased, while antioxidant capacity remained stable.	Energy Efficiency: HPP is conducted at low temperature (25°C) vs HoP (62.5°C/30 min), significantly lowering thermal energy requirements. Scalability Challenges: Small batch scale (3 mL per run); High pressure (600 MPa) requires expensive equipment & precision control.	[17]
This research evaluates the effect of HPP on the thermal and rheological properties of bean	Gel strength (G') increased significantly up to HHP600/5. For example, viscosity increased dramatically compared to HHP ≤450 MPa.	Energy Efficiency: Produce functional modifications with minimal heat energy compared to HT120 (boiling for 2 hours). Scalability Challenges:	[18]

flour (Phaseolus vulgaris).	Pasting profile: Full gelatinization only occurred at HHP600/5 and HT120 (heat control). Enthalpy: Protein denaturation increased from HHP150 to HHP600 (no explicit numbers mentioned but "correlates with pressure and time").	Dependence on high pressure (>600 MPa) for maximum effect = high cost for industry.	
This research reviews the use of HPPs and GRAS additives to control pathogens in raw meat-based pet foods (RMBDs).	HPP is effective in inactivating Salmonella, Listeria, and E. coli in raw meat up to >5 log CFU/g reduction (cited from reviewed literature). Syneresis and protein denaturation occur at high pressure, especially in fresh meat and texture quality is affected.	Energy Efficiency: No heating required, avoid nutrient deterioration & more energy efficient. Scalability Challenges: Large surface area in minced meat = reduced effectiveness → requires high pressure; Strict regulations on pet food = large-scale implementation challenges.	[19]
This research analyzes the impact of ultra-processed foods (UPFs) consumption on metabolic efficiency.	Food safety and nutritional retention are achievable through modern non-thermal technologies like HPP.	Energy intake rate (mean): Unprocessed: 36 kcal/min; Processed: 54 kcal/min; UPF: 69 kcal/min; UPF meal postprandial thermogenesis is lower than whole food isocalories and decreased total daily energy expenditure. Energy Efficiency: Not in the context of processing, but metabolic energy shows the efficiency of UPF in energy storage and leads to obesity.	[20]
This research evaluates the health risks associated with ultra-processed meat products, especially on gut health and digestibility.	Over-processing reduces digestibility and promotes formation of harmful substances (acrylamide, AGEs, PAHs).	Moderate processing (e.g., HPP) is preferable for health and efficiency but scaling it in the meat sector is limited by cost.	[21]
This review article aiming to analyze how ultra-processing affects the quality of aquatic proteins.	Non-thermal methods such as HPP improve protein functionality (solubility, texture), while thermal processing induces oxidation.	HPP is energy-efficient but industrial application in seafood is limited by cost and raw material variability.	[22]
This research reviews the health and safety challenges in ultra-processed plant-	These analogs often contain excessive NaCl, experience lipid/protein oxidation, and require reformulation.	HPP is proposed as a cleaner alternative but has limited commercial use due to	[23]

based meat analogs and propose improvement strategies.		equipment costs and lack of industry adaptation.	
research looks at the cardiovascular health risks of ultra-processed plant-based meat products.	High sodium and additives negate potential health benefits of plant-based meats.	HPP is mentioned as a non-thermal alternative, but its adoption remains low in this sector due to high setup costs.	[24]
This research evaluates the role of food processing and critique the NOVA classification system.	Non-thermal technologies like HPP can improve safety and nutrition without compromising energy use.	High efficiency; constraints include capital cost and knowledge gaps in small industries.	[25]
This research assessed the association of UPF with metabolic syndrome and thermogenesis.	High UPF intake (≥5 servings/day) increased the risk of inflammatory bowel disease by 82% (HR = 1.82). Processed meats, salty snacks, and sweetened drinks had the strongest association.	Though not processing-focused, results highlight the need for healthier, lower-impact food technologies like HPP.	[26]

3. Result and Disscussion

3.1. Energy Efficiency Challenges in HPP for Ultra-Processed Meat

The 21st century has witnessed an unprecedented expansion of the UPF sector, with meat products like sausages, nuggets, and reconstituted hams becoming dietary staples globally. These products now contribute >50% of caloric intake in high-income nations and show 5-10% annual market growth in middle-income countries, driven by demands for convenience, shelf stability, and hyper-palatability [3]. Yet this ubiquity comes with significant trade-offs: conventional thermal processing compromises nutritional integrity, accelerates quality degradation, and fails to eliminate persistent pathogens like *Listeria* and *Salmonella*, implicated in 15% of U.S. foodborne illnesses [27]. Amid mounting epidemiological evidence linking UPF-heavy diets to obesity, cardiovascular disease, and metabolic disorders 112, the meat industry faces intensified pressure to reconcile safety with sensory and nutritional quality [1][3].

HPP has emerged as a transformative non-thermal technology addressing these dual imperatives. By applying 400–600 MPa of isostatic pressure via water-mediated systems, HPP achieves microbial inactivation while preserving heat-sensitive nutrients and organoleptic properties critical for maintaining the textural and flavor profiles consumers expect from ultra-processed meats [27][29]. Unlike chemical preservatives or high-temperature treatments, HPP leverages physics rather than chemistry to meet safety standards, aligning with clean-label trends. Its adoption represents a technological pivot toward "safety-by-design" in industrial food systems, responding to 21st-century demands for minimally processed, additive-free options. However, this innovation exists within a paradox: while HPP enhances product safety and quality, its high energy intensity (2.5–3.2 kWh/kg) and batch-processing constraints create sustainability and scalability challenges that threaten widespread implementation [29]. As the industry balances consumer health priorities against operational viability and planetary boundaries, HPP stands as both a beacon of technological progress and a test case for the sector's capacity for eco-innovation.

The adoption of HPP in ultra-processed meat production faces significant energy efficiency barriers despite its advantages in preserving nutritional quality and extending shelf life. Operating at 400–600 MPa, HPP consumes 2.5–3.2 kWh/kg of energy up to 26 times more than thermal pasteurization due to the massive electrical demand of hydraulic systems and adiabatic heat management [30][31]. This inefficiency stems from fundamental thermodynamic constraints: only 12–15% of electrical input converts to effective pressure work, with losses occurring through mechanical friction and residual heat dissipation during batch cycling [31]. The batch-based design of HPP systems exacerbates energy waste, as 3–7 minute processing cycles include decompression and reloading phases where 40% of energy dissipates as unused heat [32].Product matrix variations further complicate efficiency. High-fat emulsions (e.g., sausages, nuggets) require 50–100 MPa higher pressure than whole meats due to lipid-mediated protective effects on microbes, directly increasing energy demand. Similarly, water-rich formulations suppress adiabatic heating, necessitating longer processing times [31]. These technical hurdles intersect with economic and environmental repercussions: energy expenses reach $0.18–0.25/kg, elevating production costs by 15–30% compared to thermal alternatives. Consequently, carbon footprints expand to 1.8–2.3 kg CO_2/kg of product over 10 times higher than conventional methods undermining sustainability goals [30][33].

Recent advances target multi-faceted solutions. Process optimization reduces energy intensity by 22% through pressure-time parameter adjustments (e.g., 550 MPa for 3 minutes instead of 400 MPa for 7 minutes) while maintaining pathogen inactivation [31]. Heat recovery systems, such as regenerative coolers, repurpose adiabatic heat for preheating subsequent batches, slashing cooling loads by 30% [32]. Digitalization enables real-time monitoring via cloud-based platforms, identifying energy waste in compressors, pumps, or idle equipment. Siemens' SIMATIC Energy Suite, for example, has cut energy use by 45% in food facilities through predictive analytics [34][35]. Renewable energy integration mitigates grid dependence. Solar-powered HPP units demonstrated in Spanish pilot plants lower operational emissions by 40% with a 5-year payback period [32]. Emerging semi-continuous systems with dual-pressure vessels automate product transfer, reducing idle time by 50% and boosting throughput efficiency by 35% [31]. Nevertheless, high capital costs ($2.5 million/unit) and unresolved technical trade-offs hinder scalability, especially for small-scale processors [30][32]. The energy and environmental performance of HPP compared to other technologies is shown in Table 2.

Table 2. Energy and Environmental Performance of Meat Preservation Technologies

Technology	**Energy Use (kWh/kg)**	**CO_2 Emissions (kg CO_2 /kg)**	**Nutrient Loss (%)**	**Key Advantages**	**Limitations**	**Ref.**
Conventional Thermal	0.10 - 0.15	0.15 - 0.25	15–30	Low equipment cost; Wide applicability	High nutrient degradation; Slow processing	[36][37]
High-Pressure Processing	2.5 – 3.2	1.8 – 2.3	< 5	Minimal nutrient loss; No chemicals	High capital cost ($2.5M/unit); Batch-only	[37][38]
Ohmic Heating	0.15 - 0.30	0.10 - 0.15	5–10	40–70% energy savings; Renewable-compatible	Limited to pumpable products; non-uniform heating	[39]
Flash Joule Heating	0.05	0.02 - 0.05	< 3 (surface only)	Microsecond processing; No cold chain needed	Surface treatment only; Carbonization risk	[40]

Pulsed Light	0.02 - 0.05	0.03 - 0.06	< 2	Seconds-scale treatment; No waste water	Shadowing effects; Opaque products	[38]
Cold Plasma	0.04 - 0.08	0.05 - 0.10	< 3	Chemical-free; Room-temperature operation	Scalability challenges; Gas dependency	[38][41]

Five persistent challenges dominate current research, beginning with energy recovery limitations where adiabatic heat generated during compression remains underutilized due to significant temperature mismatches between compression and decompression phases, preventing efficient thermal recycling [31]. Concurrently, scale-up barriers pose formidable obstacles, as batch vessel volume exhibits nonlinear expansion under high pressure, escalating energy intensity, while vessels exceeding 500 liters suffer from inconsistent heat distribution that compromises process uniformity [32]. The integration of renewable energy faces economic headwinds, as solar/HPP hybrid systems require $1.2–1.8 million in ancillary infrastructure, eroding short-term savings despite long-term sustainability benefits [32]. Additionally, product-quality trade-offs emerge when energy-saving protocols such as reduced pressure coupled with extended processing times alter the microstructure of emulsified meats, leading to textural defects in products like sausages and patties [31]. Finally, the absence of digital twins impedes progress, as underdeveloped real-time simulation models fail to predict energy consumption accurately across diverse meat matrices, hindering dynamic optimization [34]. These interconnected challenges collectively constrain industrial adoption, demanding coordinated solutions that bridge thermodynamics, materials engineering, and digital innovation.

Recent studies propose paradigm shifts. Pulsed HPP applying pressure in oscillating waves reduces net energy by 18% while enhancing microbial inactivation in cured meats [42]. Biomechanical synergies using plant-derived antimicrobials (e.g., rosemary extract) lower required pressure levels by 150 MPa, directly cutting energy use [43]. However, industrial adoption remains sluggish; only 18% of large meat processors employ HPP due to unresolved techno-economic constraints [30][31].

3.2. Scalability Challenges in HPP for Ultra-Processed Meat Products

The widespread application of HPP in the ultra-processed meat industry has encountered substantial obstacles, especially regarding scalability. Scalability in the context of the food industry refers to the ability of a technology or process to be efficiently improved to increase greater production volumes without sacrificing product quality, profitability and operational efficiency. These challenges manifest themselves in both technical and economic dimensions:

3.2.1. Technical Constraints of Scalability

The technical aspects of the current HPP system pose a great scalability challenge, the technical aspect is in the form of production process limitations due to the process used Batch based [44]. This severely limits the production throughput in the form of the number of products that are successfully produced in a given time frame, which is very important in the processing of large-scale Ultra-Processed meat products. The processing cycles that are generally 3-7 minutes including downtime for loading, unloading, and decompression have a significant impact on daily troughput, especially when compared to the continuous processes that are prevalent in other high-volume food sectors where there is no downtime [6]. Manual or semi-automatic filling processes also further extend cycle times and increase labor costs [13]. The study by Bolumar *et al*. [6] specifically highlights that cycle speed and vessel volume are the main factors inhibiting production efficiency when HPP is applied to meat products on a large scale. For example, a study on breast milk donors by Medina-Meza *et al*. [45] showed that although HPP is effective in maintaining product quality, due to the limited testing scale (3 mL per cycle) it is not representative of large-scale industrial needs, which confirms vessel capacity and throughput constraints. The limited size of pressure vessels is also another technical obstacle. Industrial units often do not exceed 500 liters, so to achieve high production capacity more than one unit of HPP is required. This is in addition to increasing the cost of capital investment exponentially because there are additional costs for special installations, an increase in factory area and the addition of skilled labor, in addition to increasing operational complexity [46]. In addition, studies by Lin and Fernandez-Fraguas [47] show that to achieve the maximum effect of the functional properties of food ingredients such as peanut flour very high pressures (>600 MPa) are required, which increases equipment costs and limits the scalability of the industry. Similarly, in raw meat-based pet food processing, the large surface area of the minced meat reduces the effectiveness of HPP, thus requiring higher pressures and complicating large-scale implementation due to strict regulations [48].

3.2.2. Economic Constraints of Scalability

The economic aspect is also a challenge in implementing scalability in HPP for Ultra-Processed meat products. The economic aspect in the form of initial capital investment for HPP units at the industrial level is very high [49]. This cost is based on a sophisticated design and strong materials to withstand extreme pressures. This high initial cost is a barrier for some industries to implement this system. As a result, the Return on Investment (ROI) calculation for HPP often seems less attractive than conventional processing methods, especially for manufacturers aiming for mass production with tight profit margins. Although HPP offers advantages in product safety and shelf life, a study by Marco [49] discusses the cost analysis of HPP in a wide range of food applications, the high initial capital cost being a barrier that prolongs the return on capital, making the technology less attractive. This calculation is also complicated by high operational costs, which go beyond direct energy consumption. Many producers consider HPP to be less competitive than other large-scale processing methods, as producers take into account the cost efficiency per unit for mass production [49]; [12]. Although the benefits of HPP are proven, many manufacturers are reluctant to implement them. This reluctance is reinforced by Knorr and Augustin [50] that although the efficiency of HPP is high, the initial capital cost is an obstacle to its implementation.

3.3. Alternative Non-thermal Technologies as a Future Trend

Beyond high-pressure processing (HPP), several alternative technologies offer energy-efficient and sustainable potential. Combined Heat and Power (CHP) systems from livestock waste can achieve up to 80% energy efficiency [51]. Microwave irradiation has also shown to improve lipid extraction in microalgae by 31% compared to conventional heating, with lower energy use and cost [52]. Meanwhile, bioethanol production from rice straw via Separate Hydrolysis and Fermentation (SHF) reached yields up to 80.9%, highlighting the role of agro-waste valorization [53]. In addition, a study by Bahlawan *et al*. [54] demonstrated that fermentation and fortification of sorghum flour using *R. oligosporus* and soybean increased protein to 9.09% while reducing antinutritional tannins by 86.9%. It may serve as a viable base for ultra-processed meat analogs, offering improved nutritional attributes without relying on energy-intensive preservation technologies.

4. Conclusion

High-Pressure Processing (HPP) offers a compelling non-thermal alternative to conventional meat preservation by maintaining microbiological safety, nutritional value, and sensory attributes. However, this review reveals that HPP's industrial scalability and energy efficiency remain critical bottlenecks that limit widespread adoption particularly in the context of ultra-processed meat products. With energy demands reaching 2.5–3.2 kWh/kg and capital investments up to USD 2.5 million per unit, only a fraction of large-scale processors have integrated HPP into their production systems. These constraints underscore a broader challenge: the tension between high-performance food safety technologies and the need for economically viable, sustainable production methods. Beyond the technical details, the challenges of HPP reflect a deeper systemic issue in the global food industry: how to reconcile growing demand for clean-label, minimally processed, yet safe and scalable food products. The insights from this review are not only relevant to meat preservation but also generalizable to other sectors confronting similar trade-offs between innovation and implementation cost such as plant-based analogs, seafood, or dairy. Future directions should not focus solely on hardware optimization but embrace integrated solutions, such as semi-continuous systems, digital twin simulations, renewable energy sourcing, and shared processing infrastructures. These approaches offer a pathway to balance operational efficiency with environmental and economic sustainability. Equally important is the role of interdisciplinary collaboration bringing together process engineers, materials scientists, data analysts, and policymakers to drive holistic innovation. In conclusion, HPP stands at a crossroads between promise and practicality. Its evolution from niche innovation to mainstream processing solution will depend not only on overcoming technical and financial hurdles, but also on how effectively industry and academia can align technological capability with systemic feasibility. This review contributes to that alignment by clarifying the scope of current limitations and mapping out strategies that could support the broader transformation toward sustainable, high-quality food systems.

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