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Paradoxes at The Heart of Protein Transition

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Abstract

Research highlights that while alternative proteins hold significant promise for reducing the environmental burden of food systems, their widespread adoption is entangled in a web of structural, nutritional, commercial, and societal paradoxes. The literature collectively points to a fundamental tension: the protein transition is being pursued through substitution rather than reduction, processing rather than simplification, and market expansion rather than systemic reform. This study, therefore, aims to synthesize and rephrase the key evidence across paradoxes at the heart of protein transition through a comprehensive literature survey based on the Fermi Paradox. Overall, the findings suggest that core paradoxes of the protein transition explain why alternative proteins often maintain, rather than disrupt existing systems; but achieving a meaningful and equitable protein transition requires systemic reform that goes beyond ingredient substitution to address overconsumption, processing trade-offs, and governance gaps.

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Introduction

Ever since the International Conference on Nutrition and the Plan of Action on Nutrition (ICN) in 1992 convened by the UN Food and Agriculture Organization (FAO) and World Health Organization (WHO), government policies across the world have been increasingly directed toward addressing the broader and more complex consequences of nutritional frameworks. This shift has encompassed promoting the health and well-being of aging populations, as well as expanding the focus on evolving disease patterns to cover all demographic groups. Furthermore, the UN Sustainable Development Goals (SDG) set an ambitious target of eliminating hunger and ensuring comprehensive food and nutrition security by the year 2030. The 1950s marked a pivotal turning point, initiating a profound transformation of global food systems and societal structures. This era laid the groundwork for the rapid acceleration of mass production and overconsumption within food and nutrition systems, trends that became especially pronounced from the 1970s onward across the globe (Tekiner, 2020). The overall quality and composition of human diets are shaped by a complex web of interconnected elements, including individuals, institutions, environments, infrastructure, and the full spectrum of food-related activities such as production, processing, distribution, marketing, sales, preparation, and consumption. Each of these elements is deeply intertwined with health outcomes, environmental conditions, cultural values, political structures, and economic systems (Fanzo et al., 2020). These multifaceted challenges underscore the fact that nutrition and health are deeply interrelated and inherently complex, making policy development in this domain exceptionally delicate and demanding (Tekiner et al., 2023). The overarching long-term objective of food sustainability is to ensure sufficient food production to support and sustain the growing global population. The fundamental prerequisites for achieving a sustainable food system include fertile agricultural land, adequate water resources, access to fertilizers, a stable and predictable climate, and reliable energy sources. Nevertheless, as the world's population continues to expand, the volume of food required in the future will no longer be determined solely by these foundational factors but will increasingly depend on the collective choices made by humanity (Morawicki & Díaz González, 2018).

Protein has emerged as a major health and wellness megatrend in recent years. Once largely associated with bodybuilders and athletes, high-protein diets have now been widely embraced by the general population and are increasingly viewed as a cornerstone of healthy living. Among its many benefits, protein supports muscle growth, enhances bone density, and

promotes satiety, which may play a role in effective weight management (Strategic Allies, 2026). The production of adequate protein supplies remains one of the most pressing challenges facing global food systems (Rahman et al., 2023). According to a recent study, the current dominance of meat and seafood as primary protein sources is expected to decline significantly over the coming decades, with various alternative protein sources stepping in to bridge the gap (Wood et al., 2026). While overall global protein consumption is projected to double over the next 40 years — rising from 473 Mt to 944 Mt by 2054 — alternative proteins are anticipated to grow at a far more rapid pace of approximately 9% per year, positioning them to become the predominant source of protein in the human diet by the middle of this century (UN Decade of Action on Nutrition, 2016; Bio Based Press, 2026).

Nevertheless, the protein transition is not without its contradictions. The first paradox lies in the prevailing focus on replacing animal-based proteins with alternative sources, rather than addressing the need to reduce overall protein consumption. The second centers on the pursuit of novel protein sources as a solution, while largely overlooking the deeper issues of overconsumption and overproduction. The third paradox concerns the ongoing exportation of animal proteins from Europe, a practice that continues to be justified through narratives of food security, economic efficiency, and comparative advantage. These dominant narratives shape public discourse, legitimizing existing production and consumption patterns while simultaneously influencing perceptions, decisions, and policies that will determine the future trajectory of our food systems. In light of the significant role that stakeholder narratives play in driving — or hindering — this transition, a holistic and systemic approach is essential. Rather than relying on isolated or short-term fixes, coherent and far-reaching strategies are needed to meaningfully advance the protein transition (Teh, 2023; Duluins & Baret, 2024a). The literature collectively points to a fundamental tension: the protein transition is being pursued through substitution rather than reduction, processing rather than simplification, and market expansion rather than systemic reform. This study, therefore, aims to review synthesizes and rephrases the key evidence across paradoxes at the heart of protein transition through a comprehensive literature survey based on the Fermi Paradox.

Paradoxes at the Heart of Protein Transition

In 1950, during an informal lunchtime discussion about extraterrestrial life, the renowned physicist Enrico Fermi posed a deceptively simple yet profoundly thought-provoking question to his colleagues — Edward Teller, Emil Konopinski, and Herbert York: *"Don't you ever wonder where everybody is?"* (DeVito, 2014). The paradox embedded in this question arises from a striking contradiction: while the scientific community broadly accepts the likelihood that technologically advanced civilizations exist elsewhere in the Milky Way galaxy, more than six decades of systematic searching have yielded no evidence of their existence whatsoever. Over the years, numerous proposed "solutions" to this paradox have been put forward (DeVito, 2019). One particularly relevant explanation suggests that technology can foster a form of *"fake fitness"* — generating psychological signals associated with survival, such as the ready availability of food, without ensuring genuine long-term nutritional sustainability (Miller, 2007). True civilizational survival, therefore, demands a fundamental shift away from short-term resource exploitation toward responsible environmental stewardship, integrating sustainable practices with population management in order to avert ecological — and ultimately civilizational — collapse (Miller, 2023). Taken together, the Fermi Paradox implies that the capacity to build sustainable food systems, regulate population growth, and safeguard the biosphere represents a critical threshold that any technologically advanced civilization must overcome. Should this threshold rarely be crossed, it would account for the prevailing silence of the galaxy (Baum, 2009) — lending considerable weight to what has been termed the *"sustainability solution"* to the Fermi Paradox (Mullan & Haqq-Misra, 2019). Through this lens, the protein transition itself can be reframed as a Fermi-like paradox: where, precisely, is the long-promised shift away from animal-based protein consumption, given that global meat production continues to rise at a significant rate? And what are the underlying forces that perpetuate this contradiction? At the political level, the protein transition — as a component of broader shifts toward sustainable food systems — is actively supported by a range of national and international initiatives, including the Farm to Fork Strategy (European Green Deal), Canada's food policy, Brazil's National Plan for Agroecology and Organic Production, China's Healthy China 2030 Plan, and the UN SDG (FAO, 2018; Guthman et al., 2022). From a private sector perspective, the protein transition has become a focal point for growing investment activity, attracting not only conventional capital but also speculative finance — including high-risk trading — while simultaneously fostering innovation and the emergence of new product offerings (Duluins et al., 2022). Core paradoxes of the protein transition explain why alternative proteins often maintain, rather than disrupt existing systems. Yet despite considerable scientific and commercial interest, the transition is progressing unevenly, and a number of deep-seated paradoxes continue to constrain its pace and scope (Duluins & Baret, 2024a).

Substitution vs. Reduction

"*Cars replaced horses, petroleum replaced whales, tractors replaced oxen, telecommunications replaced carrier pigeons … Wherever we look, humans have consistently built technologies that surpass their animal predecessors. Food may be next*." — Agfunder, venture capital firm, in an investor pitch for their "New Carnivore" Alternative Protein Fund (Leclerc, 2019; Dickson & Clay, 2024). This perspective encapsulates a prevailing narrative within the alternative protein sector — one that frames the future of food as a technological substitution problem rather than a systemic consumption challenge. Indeed, the dominant discourse surrounding the protein transition tends to center on replacing animal-derived products with alternative protein sources, while largely sidestepping the more pressing and

sustainability-critical issue of reducing overall protein intake. The protein transition has been widely positioned as a meaningful strategy for combating climate change, premised on the idea of shifting dietary patterns away from animal proteins and toward plant-based alternatives. However, this transition is far from straightforward. The comparatively lower nutritional quality of plant proteins relative to their animal-based counterparts presents a significant barrier to their widespread dietary adoption, constraining the extent to which they can realistically substitute for conventional protein sources (Duque-Estrada & Petersen, 2023). However, precise scientific indicators like PDCAAS (Protein Digestibility-Corrected Amino Acid Score) or DIAAS (Digestible Indispensable Amino Acid Score) reveals that certain plant sources such as soy, rapeseed, spirulina, chickpeas, peas, faba beans, and mung bean match or exceed the nutritional quality of animal proteins (Matthews et al., 2025). Rather than confronting the root issue of overconsumption — particularly acute in high-income countries — the food industry has largely opted for a substitution-oriented approach, swapping one protein source for another without meaningfully challenging existing consumption volumes or patterns (Duluins & Baret, 2024a). In doing so, it risks perpetuating the very structural imbalances that underlie the sustainability crisis it purports to address. Perhaps the most structurally important finding across the literature is that the protein transition, as currently conceived, is oriented towards substitution rather than reduction –and this fundamental framing limits its transformative potential.

Processing

While consumers increasingly seek healthier dietary alternatives, plant-based food products frequently demand extensive processing — including protein refining and the incorporation of binding agents — in order to replicate the taste, texture, and visual appeal of conventional meat. This often results in their classification as "ultra-processed" foods, a designation that sits in uncomfortable tension with the health-conscious motivations driving their consumption. Compounding this challenge, many of the processing techniques routinely employed by the food industry carry their own environmental costs, prompting a growing preference for less purified plant protein ingredients that require fewer processing steps and lower inputs of water and energy (Kashyap et al., 2019; Sarathy et al., 2025)). In practice, protein quality is enhanced through processing and cooking methods that reduce antinutrients, denature proteins, and decrease food particle size and structure. Conversely, exposure to prolonged storage, heat sterilization, and high surface temperatures has been shown to diminish protein quality (Xiao et al., 2023; Matthews et al., 2025). Therein, however, lies a fundamental sustainability paradox: the environmental appeal of reduced processing does not come without cost, as it consistently yields lower protein nutritional quality than that achieved through more extensive processing and purification of protein ingredients. As with most complex trade-offs, however, the answer lies not at either extreme but in striking an appropriate balance. Food processing, though indispensable, is known to exert both positive and negative effects on the nutritional quality of proteins — and navigating this duality remains a central challenge for the industry (Duque-Estrada & Petersen, 2023). Beyond processing considerations, the scalability and environmental footprint of various protein extraction routes at both pilot and industrial scales must be rigorously evaluated before commercial viability can be fully determined. Future research should therefore incorporate quantitative life cycle assessments and energy efficiency analyses to provide a definitive appraisal of the sustainability credentials of emerging extraction technologies relative to conventional methods (Zenasni et al., 2026). Furthermore, continued investigation into alternative extraction approaches is warranted, with a particular focus on obtaining native, unmodified proteins that retain high antioxidant activity (Mehdizadehtapeh et al., 2026).

Sustainability-Nutrition Trade-off: A Central Dilemma

The global food system has undergone a profound transformation, producing processed, affordable, and aggressively marketed food products at an unprecedented scale. Consequently, dietary behaviors across the world are shifting away from scarce, fresh, and minimally processed plant-based foods toward highly processed alternatives characterized by elevated levels of sugar, fat, and animal-derived ingredients. This phenomenon, widely referred to as the "nutrition transition," is reshaping global food demand and driving a significant shift in public health challenges — moving away from conditions rooted in undernutrition toward a growing burden of diseases and disorders associated with overconsumption. The implications of this transition for public health and policy are substantial and far-reaching. In recognition of this, international bodies, governmental institutions, and non-governmental organizations alike have called for the integration of nutrition transition impacts and corresponding responsive measures into the fabric of public policy frameworks (Tekiner, 2020; Tekiner et al., 2023). This broader dietary shift further complicates efforts to promote plant-based protein alternatives. Enhancing the digestibility and sensory appeal of plant-based proteins — qualities essential for broader consumer acceptance — typically necessitates processing interventions such as protein isolation. However, these very processes can inadvertently compromise nutritional quality, most notably through protein oxidation and the degradation or loss of essential amino acids. The result is yet another layer of tension within the protein transition: the pursuit of palatability and accessibility may come at a measurable cost to the nutritional integrity of the very foods being promoted as healthier alternatives (Willett et al., 2019).

Market Growth vs. Profitability

The market dynamics of the alternative protein sector reflect a systemic tension. Stake-holder research documents a boom-and-bust cycle driven by speculative investment, underscoring that scaling, affordability, and policy coherence are prerequisites for a stable and sustained transition (Wood et al., 2026). Despite

attracting considerable investment and witnessing notable growth in consumer demand, the alternative protein sector continues to face persistent challenges in achieving profitability and reaching price parity with conventional meat products. The economic viability of these emerging industries remains a significant barrier to their mainstream adoption and long-term commercial sustainability. In parallel, regions such as Europe have increasingly championed the goal of protein self-sufficiency, framing it as a strategic imperative to reduce dependence on imported feed inputs — most notably soy. However, rather than serving as a catalyst for a genuine transition away from livestock-based food systems, this narrative is frequently leveraged to justify the maintenance of existing livestock production levels. In effect, the rhetoric of self-sufficiency becomes a means of preserving the status quo, rather than enabling the structural transformation that a meaningful protein transition would demand (Duluins & Baret, 2024b).

Addition, Not Replacement

Contrary to the assumption that alternative proteins displace animal-based products, emerging research suggests that they frequently function as additions to the total protein market rather than substitutes within it. Rather than contracting the environmental footprint of meat consumption, the proliferation of alternative proteins appears to be expanding overall protein consumption. As these products become increasingly efficient and cost-effective to produce, total protein intake rises accordingly — with alternative proteins acting not as replacements for meat, but as supplementary additions layered onto already protein-rich diets (Duluins & Baret, 2024b). The nutritional equivalency of alternative proteins to their animal-based counterparts also remains a subject of considerable scrutiny. Plant proteins are widely criticized for their comparatively lower anabolic effect per gram than animal proteins, a limitation closely tied to their reduced content of essential amino acids (EAAs), due to three primary variables: (1) digestibility (reduced by 10-20% due to cellular structures and intrinsic fiber matrices), (2) leucine content (contains typically <10% leucine, whereas animal sources contain >10%), and (3) limiting amino acids (often deficient in specific EAAs like methionine or lysine) (Hertzler et al., 2020; Morgan et al., 2024). This nutritional shortfall can, to varying degrees, be compensated through strategies such as increased intake volumes, the formulation of complementary protein blends, and targeted fortification with deficient amino acids. Furthermore, assessments of protein solubility have revealed significant research gaps concerning their digestibility and overall nutritional value — particularly with respect to the influence of extraction processes on these properties (Mehdizadehtapeh et al., 2026). These gaps underscore the need for more rigorous and systematic investigation into the functional and nutritional performance of alternative proteins before they can be confidently positioned as nutritionally adequate alternatives to animal-derived sources.

Health and Environmental Perception

Alternative protein brands frequently employ environmental messaging to project an image of sustainability and cleanliness, yet this narrative often obscures the complex and resource-intensive industrial processes — encompassing cultivation, transportation, and extraction — that underpin their production (Amato et al., 2023; Daou et al., 2025; Kaur et al., 2025). These inherent contradictions have not gone unnoticed by consumers. A growing segment of the population has begun to reject highly processed alternatives in favor of whole, minimally processed foods, a shift that has contributed to declining sales for several prominent players within the alternative protein industry (De Castro Carvalho et al., 2025). Within this landscape, plant-based biomasses hold considerable promise as diversified protein sources capable of offering satisfactory levels of safety and nutritional quality. Nevertheless, realizing this potential will require sustained efforts toward safety standardization and nutritional consistency, ensuring their viable and sustainable integration as health-promoting food ingredients (Mehdizadehtapeh et al., 2026). Experts at the Good Food Institute (GFI) and Foodsteps caution against the overly simplistic assumption that a lengthy ingredients list is inherently indicative of an unhealthy product. This nuance, however, remains a source of considerable confusion among consumers. Academic research has increasingly highlighted an emerging tension between the perceived health benefits and the sustainability credentials of plant-based alternatives. As noted in a 2022 study conducted across Norway and France and published in the journal *Appetite*, consumers *"face much incertitude when it comes to replacing meat"* (Burrows, 2024). This uncertainty is further corroborated by a more recent survey of 1,000 UK consumers, conducted by Bryant Research in collaboration with ProVeg International and Plant Futures, which found that 49% of respondents expressed concern that plant-based options are either insufficiently natural or excessively processed. Notably, health benefits emerged as the primary motivation for choosing meat alternatives, cited by 39% of participants — a finding that underscores the critical importance of plant-based proteins demonstrating clear and credible health advantages. As the researchers observed, *"while nutritional concerns, and related concerns about the healthiness of processed foods, are held by some, healthiness is also regarded as a benefit of plant-based meats by those who consume them."* Consequently, concerted efforts must be directed toward deconstructing the entrenched narrative that processed foods are inherently unhealthy, while actively promoting the evidence-based benefits of plant-based meat alternatives — including reduced caloric density, lower saturated fat content, reduced cholesterol levels, and increased dietary fiber (Burrows, 2024).

Conclusion

The pursuit of sustainable protein systems reveals a fundamental tension that may be framed as a sustainability paradox: while reduced processing is environmentally advantageous, it frequently compromises protein nutritional quality relative to more extensively processed and purified protein ingredients. This paradox is further compounded by a second, equally critical contradiction — the protein quality

paradox — whereby the processing methods most effective at enhancing nutritional value are often those with the greatest environmental footprint. Together, these paradoxes present significant challenges and opportunities across multiple domains. For future research, they underscore the urgent need for innovative processing technologies that reconcile environmental sustainability with nutritional adequacy. For industry development, they signal the importance of investing in scalable, low-impact processing solutions capable of delivering both ecological and nutritional value. For policy formulation, they highlight the necessity of developing integrated regulatory frameworks that do not treat environmental and nutritional objectives as mutually exclusive, but rather as complementary pillars of a truly sustainable food system.

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