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Future protein foods: plant versus animal sources, nutrient release rates, and gateway products

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A Viewpoint on the Frontiers in Science Lead Article
Hybrid alternative protein-based foods: designing a healthier and more sustainable food supply

Key points

- Achieving a sustainable balance of animal, plant, and alternative protein sources is complex and will continue to evolve with technological innovation.
- The nutritional benefits of protein foods depend not only on composition but also on nutrient release rates—an area where some animal-sourced foods retain advantages over current alternatives.
- Plant-based analogues of animal foods should serve as "gateway" products, guiding consumers toward the culinary richness, sustainability, and nutritional value of whole legume foods.

Protein is an essential component of human diets and can be obtained from diverse sources, mostly of animal or plant origin. As described by Kaplan and McClements (1), alternatives to livestock production for protein foods are being sought with the aim of reducing greenhouse gas emissions and environmental degradation, while positively impacting human health and animal welfare. The dominant trend in these efforts is to produce non-animal-sourced analogues of meat- and dairy-based foods, using either single-sourced or hybrid combinations of protein types. Here, three perspectives on these developments are discussed: (i) the diversity of animal protein sources and potential future changes in their environmental impact; (ii) the oversimplification of protein or amino acid content as a marker of nutritional value, which ignores nutrient delivery rates; and (iii) the potential for current animal food analogue products to serve as "gateways" to the rich cuisine and high nutritional value of whole legume foods.

Diverse and changing environmental impacts of animal vs plant protein foods

Many analyses of the comparative environmental impact of animal and plant protein sources have shown that, overall, animal sources create more environmental damage (e.g., greenhouse gas emissions and land degradation) than plant sources. However, there is a wide range of calculated environmental impacts for animal protein, primarily depending on whether the production animals are ruminants or monogastrics (2, 3). A secondary factor is the efficiency with which production animals convert feed (largely of plant origin) into muscle mass, with poultry being the most efficient. For example, chicken meat and eggs have environmental impacts per gram of protein that are comparable to legumes (less land and water use but a higher carbon footprint) (2), the primary source of protein-rich plant foods. The central socioeconomic role of meat in society (4) also needs to be recognized and addressed in any shift toward a more plant-based diet.

A major reason for the high environmental impact of ruminant animals such as cattle, sheep, and goats is that their rumen microbiota produce methane, a potent greenhouse gas, which is emitted into the atmosphere. Monogastric animals, on the other hand, produce much less methane. However, methane production is not inevitable with ruminant animals, as shown in recent studies of feed additives designed to reduce methane emissions. These trials showed very little impact on animal growth while nearly eliminating methane production in small-scale studies (5, 6). If these preliminary results can be replicated on a large scale, future ruminant production may involve much lower methane emissions. While many practical hurdles remain before effective methane elimination from ruminants is a reality, this demonstrates that the environmental impact of protein sources is not fixed and needs to be reevaluated as new technologies emerge.

Recent food product innovations seeking to mimic the eating experience of meat products are primarily based on legume proteins (e.g., from pea or soybean). Although legumes as crops have modest environmental impacts, their recent use in meat analogues typically involves protein-rich extracts obtained through wet chemical or dry milling fractionation processes, both of which have environmental impacts. As legumes contain only 20–30% protein, fractionation produces large quantities of carbohydrate-rich co-products, which must be utilized for economic sustainability. Ironically, many of these co-products are currently used in animal feed.

Approaches to determine the best use of finite planetary resources for future food production are complex and contested. However, approaches that treat animal and plant proteins as binary alternatives risk making overly simplistic recommendations regarding environmental impacts.

Nutritional value of protein foods depends on nutrient release rates as well as composition

The nutritional value of foods is currently assessed by their chemical composition and caloric energy content alone, as presented on nutrition labels. However, this overlooks the profound effects of digestion rates, which determine both the timing and location of nutrient release and absorption in the digestive tract (7). Protein digestion rates are influenced by the microstructure of foods: soluble proteins are usually digested rapidly, while condensed or insoluble proteins are digested more slowly. A textbook example of this is milk, which contains casein proteins that coagulate in the acidic environment of the stomach, leading to prolonged gastric residence and slow proteolytic breakdown (digestion) in the small intestine. In contrast, the minor whey protein component remains soluble, passes quickly through the stomach, and is digested efficiently in the small intestine. Thus, milk provides sustained nourishment through a combination of rapid and slow protein digestion (8). Plant-based milk alternatives do not replicate these functional benefits.

Animal muscle fibers in meat are another example of condensed proteins that can slow digestion and offer a desirable prolonged release of amino acid nutrients. Digestion rates vary depending on the animal source and preparation method, and more *in vivo* research is needed to compare nutritional outcomes reliably. If protein digestion in the small intestine is too slow, undigested protein may reach the large intestine, where it can serve as an energy source and/or amino acid substrate for the resident microbiota. A lot more research is needed to understand how common this is (7) and how it affects gut microbiota. The consequences depend on dietary context: in the absence of carbohydrates, gut microbes may ferment protein into potentially harmful compounds associated with colon cancer risk. However, with sufficient carbohydrates, microbes can use protein-derived amino acids for beneficial growth. This underscores the need to evaluate foods within the context of whole meals and not in isolation.

Legume foods are considered highly nutritious based on large-scale epidemiological studies and healthy eating guidelines. This is due to their combination of protein, starch, fiber, and lipid content. However, the plant tissue structure can also play a major role in determining nutritional value: legume nutrients are enclosed in ~0.1mm cotyledonary cells and, therefore, are effectively encapsulated by cell walls. If food processing and chewing do not break these cells, nutrient digestion and release are substantially delayed, as digestive enzymes are impeded by the cell walls. A recent study comparing intact versus broken-cell chickpea foods showed dramatic differences in nutrient release rates and hormonal responses despite having identical chemical compositions (9). As legume proteins used in meat analogues are extracted after breaking of the cell walls, this nutritional benefit is not retained, unlike in whole legume foods.

Meat and dairy analogues as "gateway" products to whole legume foods

As discussed above, both environmental and nutritional arguments for replacing animal protein with legume-based analogues warrant further scrutiny. It is also important to ask why current innovation focuses on mimicking animal-based products. A shift toward legume protein would be more compelling from both environmental and nutritional perspectives if legumes were consumed in their whole form rather than as protein-rich fractions formulated into what are now classified as ultra-processed foods.

The rationale for focusing on meat and dairy analogues is that consumers are familiar with these types of products and may be reluctant to adopt foods that differ from their current diets. However, dietary habits often evolve through the introduction of "gateway" products that pave the way for more diverse culinary experiences. These gateways vary across age groups and cultures. In Western contexts, examples include the introduction of noodle dishes via instant pot noodles (popularized alongside domestic microwave ovens) or of raw fish via sushi rolls. The author's own experience was an introduction to pasta through spaghetti hoops in tomato sauce, familiar as an analogue to baked beans in tomato sauce.

These examples illustrate three points. First, human food preferences can change markedly over time, often facilitated by gateway products. Second, while some gateway products persist, they are often surpassed in impact by the foods they introduce. Third, many global cuisines feature legumes as central ingredients, though not all have achieved widespread adoption. In this context, and from both environmental and nutritional perspectives, it is to be hoped that today's wave of meat and dairy analogues based on extracted legume proteins will lead to a renewed and enhanced embrace of the rich culinary traditions and product innovation opportunities of whole legume foods.

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