NEXT-GENERATION MEAT ANALOGUES: SCIENCE AND SUSTAINABILITY

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ABSTRACT

Amid growing concerns over the health, environmental, and ethical implications of conventional meat consumption, plant-based meat analogues are emerging as compelling alternatives. Designed to replicate the taste, texture, and nutritional value of animal meat, these products draw on proteins from sources like soy, peas, mung beans, oats, and others. Cutting-edge technologies including extrusion, 3D printing, and scaffold-based structuring enable manufacturers to create increasingly lifelike meat substitutes. Beyond reducing the risk of foodborne illnesses and chronic diseases such as heart disease, plant-based meats also offer significant environmental advantages. Ingredients like functional fats and umami-rich flavor compounds help bridge the sensory gap between plant and animal products. Still, challenges remain: nutrient shortfalls, allergen concerns, and cultural resistance all present hurdles to broader acceptance. Nevertheless, with continued innovation and rising public awareness, meat analogues have the potential to become central to healthier diets and a more sustainable global food system.

INTRODUCTION

Traditional meat has long been a primary protein source, but it comes with serious health and environmental costs. Foodborne pathogens like *Salmonella*, *E. coli*, *Listeria*, and *Campylobacter* frequently contaminate meat during slaughter, processing, or storage especially when hygiene lapses leading to millions of illnesses worldwide each year (Habib *et al.,* 2021). Beyond contamination, regular consumption of red and processed meats is linked to chronic diseases such as heart disease, obesity, inflammation, and colorectal cancer. These risks are associated with high saturated fat content, calorie density, and carcinogens like heterocyclic amines (HCAs), polycyclic aromatic hydrocarbons (PAHs), and nitrites formed during cooking or added during processing (Papier *et al.,* 2023).

The consequences extend to the planet. Livestock farming fuels deforestation, biodiversity loss, greenhouse gas emissions, and nutrient cycle disruption. It also drives extensive antibiotic use set to account for nearly two-thirds of global usage worsening the threat of antimicrobial resistance (Igbinosa, 2023). Ethical concerns around animal welfare further underscore the urgency for change.

In this context, alternative proteins like cultured meat and plant-based substitutes are emerging as viable solutions. Once considered niche, these innovations are now central to efforts addressing the intertwined issues of health, sustainability, and ethics (Crudup, 2025).

NUTRITIONAL CHARACTERISTICS OF PLANT-BASED MEAT ANALOGUES

Plant-based meat alternatives (PBMAs) are rapidly gaining popularity, not only for their environmental benefits but also for their advancing nutritional profiles. Core to most PBMAs are plant-derived proteins like soy, wheat gluten, and pea protein. Soy remains a top choice for its complete amino acid profile, affordability, and meat-like texture when hydrated (Singh *et al.,* 2021). Pea protein, while occasionally associated with digestive concerns or purine sensitivity, is nutritionally solid and widely used (Lu *et al.,* 2020).

To enhance both texture and nutrition, some formulations include small amounts of animal-based proteins such as egg white or whey. Fat sources like coconut, canola, flaxseed, and sunflower oils add both desirable mouthfeel and healthy omega-3 and omega-6 fatty acids. Flavor development focuses on umami-rich ingredients such as yeast extract, miso, mushrooms, and spices alongside Maillard reaction compounds to achieve meat-like taste and aroma (Kaczmarska *et al.,* 2021). Beyond common sources, new plant proteins are expanding PBMA options. Mung beans, rich in leucine and arginine, offer high protein content (20-27%) and excellent binding properties for extrusion (Jang *et al.,* 2024). Pumpkin seed protein (31.5-51%) offers good solubility and hydration, though visual consistency remains a challenge. Rice protein, often paired with soy, provides better amino acid quality than wheat or corn despite lower protein content (Usman & Xu, 2024).

Oat protein, naturally gluten-free and rich in lysine, enhances moisture and texture, especially when combined with pea protein (Zhang *et al.,* 2024). Fungal proteins like mycoprotein and edible mushrooms add fiber and micronutrients, while oilseed proteins from rapeseed and canola supply emulsifying agents like cruciferin and napin (Wanasundara *et al.,* 2016).

This growing diversity of ingredients is bringing PBMAs closer to replicating not only the sensory qualities of meat but also its nutritional complexity.

PRODUCTION METHODOLOGY FOR PLANT-BASED MEAT ANALOGUES

The creation of plant-based meat analogues begins with the careful selection and cultivation of protein-rich crops such as soy, pea, wheat, and mung bean. These crops are chosen not only for their nutritional value but also for their functional qualities and adaptability to various agricultural settings. Once harvested, the proteins are extracted and refined into concentrates or isolates, forming the base for plant-based meats (Newton & Blaustein-Rejto, 2021).

Next, these proteins undergo texturization processes that replicate the fibrous structure of animal meat. The texturized proteins are then combined with plant-based fats, flavor enhancers, binders, and micronutrients to enhance taste, mouthfeel, and nutritional value. The final products such as burgers and sausages are distributed through retail, foodservice, and online markets, becoming part of mainstream food culture.

Replicating meat’s texture and juiciness remains a key challenge. High-moisture extrusion is widely used for its ability to align plant proteins into meat-like fibers. Emerging technologies like shear cell processing, wet and electrospinning, 3D printing, scaffold-based structuring, and bottom-up tissue engineering are also being explored to better imitate the anisotropic texture of muscle (Singh & Sit, 2022). Each method offers unique advantages in simulating the structure and sensory experience of traditional meat.

ADVANCED STRUCTURING TECHNOLOGIES IN PLANT-BASED MEAT PRODUCTION

Extrusion is the backbone of plant-based meat structuring. By forcing protein mixtures through an extruder under heat, pressure, and shear, the proteins realign into fibrous textures that mimic muscle tissue. High-moisture extrusion is ideal for juicy, tender products like plant-based chicken and beef, while low-moisture extrusion produces shelf-stable textured vegetable protein (TVP) for rehydration during cooking.

Shear cell technology offers an alternative. In a sealed, temperature-controlled chamber, protein blends are subjected to uniform shear forces, aligning them into thick, layered textures suitable for products resembling pulled pork or steak. This method enhances moisture retention and preserves nutritional quality with minimal high-heat exposure.

At the forefront of innovation is 3D food printing, which builds products layer by layer for intricate texture and structural precision. It allows customization in both form and nutrition, supporting applications from premium items to personalized diets.

Techniques like wet spinning and electrospinning borrowed from textile and biomedical fields further refine texture. Wet spinning uses a coagulation bath to form protein fibers, while electrospinning creates ultra-fine nanofibers under electric fields, replicating the fine structure of muscle tissue.

Scaffold-based structuring, inspired by tissue engineering, guides proteins or cultured cells along edible frameworks to form anisotropic, layered architectures. This method enables complex structuring that traditional approaches struggle to achieve.

Bottom-up assembly takes a modular approach, constructing complex textures from smaller protein elements like fibers or strands. This allows for greater precision in replicating meat's alignment, moisture levels, and bite.

Together, these technologies blend food science and biomimicry to enhance the realism, nutrition, and sustainability of plant-based meats shaping the next generation of alternative proteins.

FUTURE PROSPECTS

The growing popularity of meat analogues reflects a convergence of food science, engineering, and biomimicry aimed at creating sustainable, ethical, and health-conscious alternatives to conventional meat. Whether sourced from plants, fungi like mycoprotein, or even insects, these proteins offer significant environmental advantages: lower greenhouse gas emissions, reduced land and water use, and fewer animal welfare concerns. They also promote dietary diversity and may contribute to improved public health in the long run.

However, challenges remain. Nutritional shortcomings particularly in vitamin B12, iron, and zinc often require fortification. Consumer concerns around allergens and additives, especially in soy or gluten-based products, are driving demand for clean-label formulations and greater transparency. Taste and texture also remain barriers; many consumers are still hesitant to replace traditional meats due to cultural preferences and sensory expectations. Addressing this may require localized innovation and broader public education.

Regulatory inconsistencies and resistance from traditional meat industries further complicate adoption. For meat analogues to move from niche to norm, progress will depend not only on technological innovation but also on clearer regulations, cross-sector collaboration, and active consumer engagement.

If these hurdles are overcome, meat analogues could become a central pillar of climate-resilient, sustainable food systems that meet global environmental goals while supporting everyday nutrition.

CONCLUSION

Meat analogues occupy a pivotal role at the intersection of innovation and urgent global needs, presenting a compelling alternative to conventional meat amid rising concerns over health, sustainability, and ethics. Their ability to lower environmental footprints and contribute to more diverse, balanced diets is clear but so are the challenges. Sensory replication, nutritional completeness, consumer trust, and regulatory clarity all remain critical hurdles. Advancing this field will require more than innovation alone. Strategic research, technological refinement, and coordinated action across industry, policy, and public spheres are essential. If these elements come together, meat analogues could evolve from niche alternatives into mainstream staples redefining global protein consumption in a way that's both sustainable and widely embraced.

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