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Plant-based Meat Design Cycle:
Background for driving plant-based meat innovation
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Introduction

The Good Food Institute (GFI) defines plant-based meat as a food product that directly replaces animal meat, including poultry and seafood, and that is marketed as a meat substitute. Plant-based meats are structured plant- or fungus-derived products designed to replace animal-based meat either as a stand-alone product or within recipes.[1] Products such as seitan, which are traditional foods in some cultures, are also included as plant-based meat because they are a central component of many meat analogues and are marketed as such. Similarly, veggie burgers, which often do not simulate meat (e.g., black bean burgers), are included in this definition because they serve as a direct replacement for a beef, chicken, or fish patty.

While products such as plant protein isolates, concentrates, and textured vegetable protein (TVP) are used to make plant-based meat, such ingredients should not be confused with plant-based meat itself, which is the final consumer product designed to replace meat directly. TVP is extruded (or otherwise textured by kneading or mixing) protein in the form of small chunks or shreds and is not typically seasoned or prepared for direct consumption. Converting plant protein ingredients into plant-based meat usually requires processing in an extruder or forming machine, with additional formulation and flavoring to create an appetizing ready-to-eat plant-based meat product. Optimal proteins for plant-based meat applications are those that can be structured or molecularly organized in such a way that the final product recapitulates the mouthfeel of meat. From the perspective of food science functionality, this means gelling and crosslinking capacity for structuring and high water-holding and fat-holding capacity for juiciness.

Motivation for pursuing plant-based meat

In recent years, multiple start-ups as well as major meat companies have pursued involvement in the plant-based meat industry.[2,3] In part, investments and entrepreneurship in plant-based meat innovation are motivated by the threat of global climate change, which has been significantly propelled by the substantial growth of the animal agriculture industry from the 1950s to today.[4,5] Furthermore, the World Resources Institute estimates we will need 70% more food to meet global demand in 2050, compared to 2006, and

[1] Note that 'meat' is a term used to describe the flesh of an animal, but also the solid portion of foods, such as the flesh of a coconut or the flesh of a fruit. Similarly, the term is used to describe the solid, flesh of a structured food from plant-material.
[2] Tyson Foods, a Meat Leader, Invests in Alternatives Proteins, New York Times, Oct. 2016
[3] Maple Leaf Foods to Acquire Lightlife Foods, 2017 (press release)
[4] Saving the Planet: The Market for Sustainable Meat Alternatives
[5] Tackling Climate Change Through Livestock, FAO

closing this 70% food gap will require dietary shifts away from consumption of animal-based proteins.[6] Likewise, from a public health perspective, the rise of antibiotic resistant bacteria in farm animals, which spread to humans through contact and food consumption, is a major concern, and the worldwide pandemic of bird flu and the spread of zoonotic diseases pose a constant threat on local and global populations.[7,8,9] Finally, public concern is rising that the majority of the roughly 9 billion land animals raised for food each year in the U.S. have few or no protections from cruelty and routinely suffer abuse that would be illegal if committed against companion animals.[10]

For all of these reasons, there is an urgent need to accelerate growth of the plant-based meat industry. Yet an even more practical reason to improve and expand plant-based meat offerings is born out of the results of behavioral economics. Studies continue to identify taste, price, and convenience as the primary factors influencing consumer purchasing decisions, despite emergent factors (such as 'evolving value drivers' of sustainability, social impact, and health/wellness) being increasingly self-reported as influencers of consumer choice.[11,12,13,14] Thus, developing plant-based meat with superior taste, price, and convenience will ultimately drive consumers to make the healthy, humane, and sustainable choice the default choice in their food selection and purchasing decisions.

History and State of the Plant-based Meat Industry

Plant-based meat is not a modern development. Various forms of plant-based meat have been made for centuries, with early forms predating modern food processing techniques like extrusion by nearly a millennium. Early mentions of plant-based meat from 965 CE China refer to tofu as "mock lamb chops." Seitan, comprised of structured wheat protein, was first recorded around 1300 CE. By 1852, items explicitly analogous to animal-based meat products — such as sausages made from plant proteins — had begun to appear. The prevalence and variety of plant-based meat has steadily increased since that time, culminating in the explosion of innovation the sector has experienced during the last decade.[15]

Current leaders in the plant-based meat industry have invested years of innovation to develop high-quality plant-based chicken, beef, and fish products. Recent launches of innovative products demonstrate remarkable advances in flavoring, formulation, and novel ingredient incorporation. Yet, if alternative proteins are to comprise one-third or more of the market share within the coming decades as predicted by Lux Research, there remains tremendous need for the development of affordable and appetizing

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[6] Shifting Diets for a Sustainable Food Future
[7] CDC: Antibiotic Resistance and Food Safety
[8] IOE World Animal Health Database: Weekly Diseases information
[9] OIE World Animal Health Database: Zoonotics Diseases report
[10] Humane Society of the United States: Protect Farm Animals
[11] Importance of taste, nutrition, cost and convenience in relation to diet quality: Evidence of nutrition resilience among US adults using National Health and Nutrition Examination Survey (NHANES) 2007–2010
[12] Analysis of Snack Food Purchasing and Consumption Behavior
[13] Healthy and environmentally sustainable food choices: Consumer responses to point-of-purchase actions
[14] Capitalizing on the shifting consumer food value equation
[15] History of Meat Alternatives, Soy Info Center

plant-based meat products.[16] This innovation and subsequent growth of the plant-based meat industry will only be realized through a concerted and collaborative effort to direct resources to this area. To that end, the Plant-based Meat Design Cycle is proposed to help focus efforts for coordinated impact in this industry.

The Plant-based Meat Design Cycle

The development of plant-based meat products, and the systems by which we deliver them to consumers, involves multiple steps and multidisciplinary efforts including plant protein source selection to product design to coordinated distribution. These steps can be integrated within the design cycle depicted in Figure 1. This design cycle is proposed as an overarching structure for an in-depth analysis of opportunities for research and commercialization within each step of the plant-based meat production process.

The plant-based meat design cycle emerged from a collaboration between GFI and the UC Berkeley Sutardja Center for Entrepreneurship and Technology (SCET) to address a need for a conceptual framework in the newly launched undergraduate course at UC Berkeley, the Challenge Lab on Plant-based Meat. This design cycle was further refined through literature searches and discussions with professionals in the plant protein industries. Moving forward, this design cycle is a starting point for collaborative discussions on intent, progress, innovation, impact, research, and development. To that end, this document briefly outlines ideas encompassed in each of the seven design cycle steps (grouped into three sections on protein sources, product development, and supply/demand) to help inform deeper discussions within the industry, define specific challenges, and propose options for solutions.

[16] Alternative Proteins to Claim a Third of the Market by 2054, Lux Research

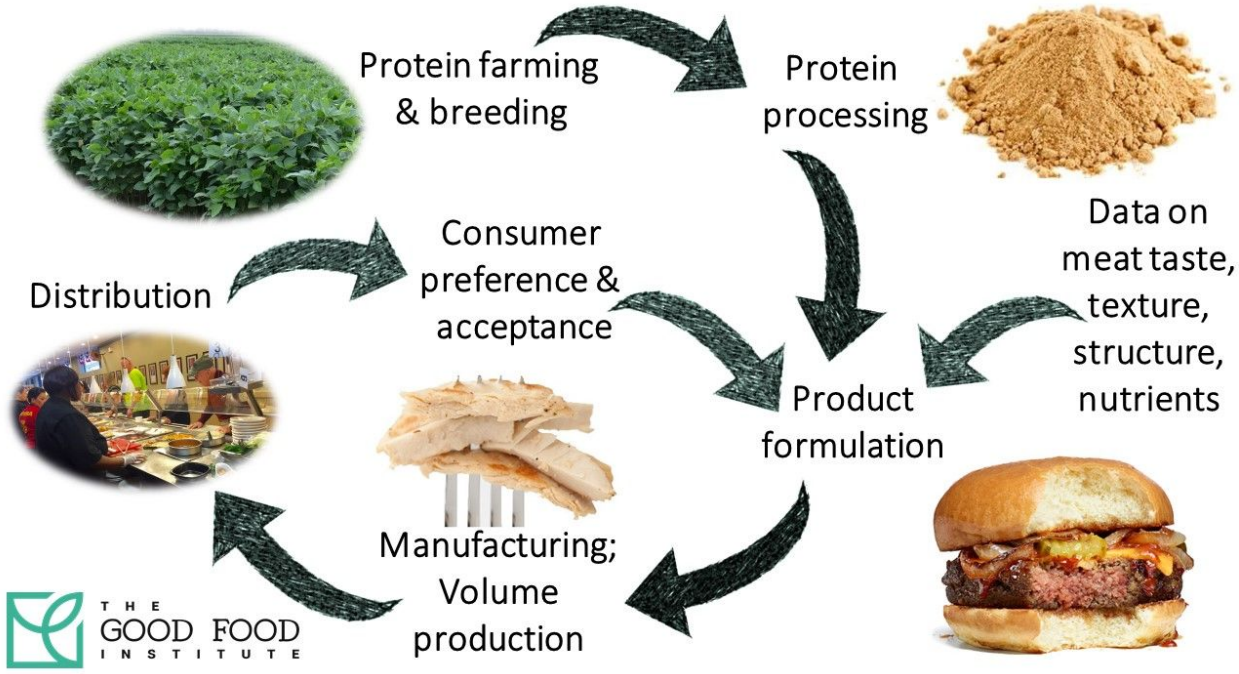

Figure 1. The plant-based meat design cycle.

Section 1: Protein Sources

Plant-based protein serves as the primary raw material for plant-based meat; optimizing this raw material allows for less costly, time-consuming, and complex downstream processing to achieve the desired end product. The more precisely tailored the raw plant protein can be for plant-based meat as the intended end application, the less effort must be expended to achieve the desired functional and sensory aspects through subsequent steps in the process such as flavoring, formulation, or mechanical production.

The primary starting material for the plant-based meat production process is typically plant protein concentrate (a designation comprising 60-70% protein) and/or plant protein isolate (comprising at least 90% protein).[17] These proteins form the major ingredient of the end product, with other components such as lipids, starch, and flavoring agents comprising small fractions. Opportunities for expanding the availability and suitability of protein sources as well as opportunities to improve the isolation and processing of these proteins for plant-based meat applications are discussed herein.

Protein Farming and Sourcing

At present, the protein sources *predominantly* used in plant-based meat are commodity crops whose selective breeding, growing, harvesting, and processing considerations have been optimized for co-products other than the protein fraction. For example, soy has been primarily optimized as an oilseed

[17] Soy protein products: processing and use

crop, and crops like pea and potato — both of which are gaining traction for use in plant-based meat — have historically been bred and grown with an eye towards starch production. There are no plant strains or cultivars bred or grown primarily for making plant-based meat and thus whose composition and protein profile has been optimized for such an application.

Furthermore, the current availability of plant protein concentrates and isolates is limited in terms of species diversity. In a survey of plant proteins by GFI (flours, concentrates, and isolates) available from global ingredient suppliers, over 80% of the product offerings are derived from soy. The vast majority of plant proteins have only been sparsely explored for their suitability in plant-based meat applications, and in some cases the raw materials are less available for R&D and product development.

When novel proteins *are* available, their supply (in terms of volume and/or the number of unique suppliers) may be too limited to be attractive as a primary ingredient for a new line of plant-based meat products. In addition, the lower volume of production and the relative lack of concerted strain optimization with respect to commodity crops contribute to higher prices per pound for less common plant proteins, further disincentivizing their utilization in plant-based meat products — especially for plant-based meats that are intended to appeal to mainstream consumers rather than niche segments that are willing to pay a premium.

Protein Processing

As noted, most of the crops currently used for plant-based meat are grown primarily for other products (starch, oil, etc.), so the fractionation process may not be optimized around the protein component. For some proteins, the quality of this fraction can vary considerably. Yet, plant-based meat, especially when produced through extrusion, is particularly sensitive to batch-to-batch inconsistency in the composition of raw materials.

Protein fractions are typically processed into protein concentrates or isolates. These can be further processed to select for specific sets of desirable functional attributes. For example, soy protein isolates that exhibit greater solubility may be better suited for use in high-protein beverages to avoid a gritty or chalky taste, whereas plant-based meat applications may benefit from isolates that exhibit higher gelling and crosslinking capacity. However, this range of protein preparations with strictly defined functional parameters is not typically available for crops beyond soy and wheat. Some suppliers are beginning to branch into multiple product lines for protein concentrates and isolates for crops like pea, but these do not yet capture the diversity of options available for the traditional commodity crops.

While protein serves as the base ingredient for plant-based meat, fats and starch are also required. These may come from the same plant source as the protein ingredient, but they are sold as separate fractions that are recombined during plant-based meat production, contributing time and cost to the production process.[18] This system of fractionation and reconstitution of the various plant components (protein and starch, most notably) helps with consistency and reproducibility of the ratios within the final formulation and

[18] Concepts for further sustainable production of foods

allows the raw materials to be stored as shelf-stable dry fractions. While these processes are effective for creating stock ingredients for a wide variety of applications, this focus on purity of ingredients causes considerable energy losses in the overall process for plant-based meat production.[19]

Energy expenditures in this process may render plant-based meat nearly as energy-intensive as conventional animal meat, jeopardizing the sustainability claims of plant-based meat.[20] Further, underutilized proteins from pulses, lentils, and other novel plant protein sources may require unique methods of milling to support fractionation, many of which have only been recently developed or have yet to be studied.[21] Water consumption is also a major resource concern for producing plant protein concentrates,[22,23] and efforts to implement dry fractionation[24] are already being developed to support sustainable systems for producing plant-based products.

A number of studies have found that hydrolysis and other forms of enzymatic functionalization can produce variable results depending on the protein source because the effects of enzymatic treatment are specific to the protein sequence of each plant's dominant storage proteins.[25] However, a comprehensive data set on protein characterization and functionalization does not currently exist.

Section 2: Product Development

Although product development is broadly defined as all steps necessary to bring new products to market, with respect to plant-based meat the process more specifically includes the biomimicry of meat, materials selection, and manufacturing feasibility, as well as feedback on consumer acceptance issues.[26] Hence, product development of plant-based meat constitutes the bulk of our design cycle because information must continually be updated as consumer preferences, production conditions, and supply chains change.

Data Analysis on Meat Texture, Taste, Structure, and Nutrients

Animal-based meat is comprised of a complex organization of tissues that contribute to the taste, nutrient composition, texture, and structure of meat and processed meat products.[27] Replicating these products with plants has been difficult, and knowledge about meat has played a small role in the production of replacements for animal-based meats. Some compositional and structural studies of meat have been conducted, but with the intention of creating better animal-based meat rather than identifying attributes

[19] Concepts for further sustainable production of foods
[20] Exergy analysis: A tool to study the sustainability of food supply chains
[21] Method Development to Increase Protein Enrichment During Dry Fractionation of Starch-Rich Legumes
[22] FAO Technology of Production of Edible Flours and Protein Products from Soybeans: Chapter 5: Soybean Protein Concentrate
[23] FAO Technology of Production of Edible Flours and Protein Products from Soybeans: Chapter 6: Isolated Soybean Protein
[24] The potential of dry fractionation processes for sustainable plant protein production
[25] Relevance of the Functional Properties of Enzymatic Plant Protein Hydrolysates in Food Systems
[26] Business Dictionary: Product Development
[27] How Muscle Structure and Composition Influence Meat and Flesh Quality

that may be mimicked with plant-derived components.[28,29,30] This is changing as companies, such as Beyond Meat and Impossible Foods, are implementing more sophisticated analyses to understand meat at a molecular level.

Additionally, not all plant-based meats are produced with the goal of precisely mimicking animal meat texture, taste, structure, and nutrition. Some products designed to be used in place of meat seek only to replicate the purpose of meat rather than necessarily recapitulating the precise texture, flavor, and nutritional characteristics of the meat itself. Plant-based meat should be designed to replicate meat in ways that matter most to consumers and that will encourage widespread adoption of such products.[31] Consumers have many sensory associations with meat, and plant-based meat should aim to replicate them.

Formulation and Protein Selection

For reasons of limited supply and lack of basic research, only a few species of plant proteins are available for formulating plant-based meat, although this is changing rapidly. Currently only soy and wheat are used broadly for both TVP and plant-based meats, but pea protein is quickly becoming a major player. However, the rich diversity of the plant kingdom has yet to be explored to capitalize on the breadth of tastes, textures, and structures achievable from novel plant proteins. Further, due to the lack of information on animal-based meat in the context of replacements (see previous section), plant-based meats that have been designed to replicate the macroscopic aspects of animal meat (shaped into a burger patty, for instance) have historically fallen short of consumers' expectations regarding many of the ways that consumers conceptualize meat (for example, as a good source of iron) and experience meat (for example, grilling aroma, juiciness, etc.).[32]

Product development of new plant-based meats is also stymied by the lack of ideal analytical tools for predictive protein selection. Currently, product designers are limited to micro-viscoamylographs, the Rapid Visco Analyser (RVA), texture analyzers, and/or some combinations of these tools to predict the structuring performance of new proteins or combinations of proteins.[33,34,35] This methodology is reported as slow and provides limited predictive value for plant protein structuring. Hence, plant-based meat product development can be costly and often depends predominantly on iteration, informed guesswork, designer experience, and running the product through an extruder to understand product performance, thereby expending considerable time and resources. Additionally, since plant proteins — like any

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[28] Characterization of the key aroma compounds in beef extract using aroma extract dilution analysis
[29] Significant influence of particular unsaturated fatty acids and pH on the volatile compounds in meat-like model systems
[30] Flavour formation in meat and meat products: a review
[31] Sensory aspects of consumer choices for meat and meat products
[32] Replacement of meat by meat substitutes. A survey on person- and product-related factors in consumer acceptance
[33] Brabender analytical tools: Micro Visco-Amylo-Graph
[34] Perten Instruments analytical tool: Rapid Visco Analyser
[35] TA Instrument analytical tools

biological material grown in an open environment — are inherently variable (see next section), the lack of predictive analytic tools resigns the industry to long lead times for adjusting formulations in response to new batches or lots of raw materials, adding cost and creating production delays even for established products.

Manufacturing

There are two commonly used methods of creating textured proteins: low moisture extrusion cooking (LMEC)[36] and high moisture extrusion cooking (HMEC).[37] More recently, researchers at Wageningen University in the Netherlands have demonstrated a pilot-scale shear cell method of fibrous plant-based meat formation. Research on this method of production shows it to use less energy and gentler (atmospheric rather than high pressure) protein structuring than extrusion. The shear cell technology is currently in the development stage.[38] Developing innovative technology for novel manufacturing methods is useful because extrusion methods for creating plant-based meats may be energy intensive and the high capital cost of extrusion equipment (upwards of $1M for each machine) can also be a barrier for use by start-up plant-based meat companies.[39]

Extruders apply shear stress to proteins to align, or "structure," them to produce a fibrous, meat-like texture. However, there are limitations to extrusion for manufacturing plant-based meat, including: (1) interference of shear force generation by inclusion of fats in the material being extruded; and (2) differential breakdown of amino acids due to the intense temperatures and pressures generated within the extruder, resulting in a loss of nutritional quality of the final product.[40]

Further, extrusion processing can be impacted by control issues as a result of variation in extruder parameter control or machine-to-machine operational variation across manufacturers, as well as in variable ingredient quality as discussed above. Without careful control of these parameters, product quality and characteristics can range widely.[41,42]

In other industries including the meat industry, development of manufacturing processes and adaptation to changes in manufacturing systems are assisted by modeling to understand and control parameters prior to implementation or in post-mortem analysis of failures.[43] Unfortunately, limited modeling research has been developed for protein extrusion purposes, except early work to identify mass transfer properties and protein characterization modeling and more recent work on twin screw extrusion transport as it applies to

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[36] Die design and dough expansion in low moisture extrusion-cooking process
[37] High moisture extrusion cooking of pea protein isolates: Raw material characteristics, extruder responses, and texture properties
[38] Production of structured soy-based meat analogues using simple shear and heat in a Couette Cell
[39] Effects of the specific mechanical energy on the physicochemical properties of texturized soy protein during high-moisture extrusion cooking
[40] The influence of extrusion on loss of and racemization of amino acids
[41] Extrusion Process Parameters, Sensory Characteristics, and Structural Properties of a High Moisture Soy Protein Meat Analog
[42] Influence of process and product variables on extrusion energy and pressure requirements
[43] Computer simulation model of swine production systems: I. Modeling the growth of young pigs

starch mixing.[44,45,46] Based on information from extrusion experts, most production processes are done by informed trial and error with new (or variable) materials, complex extruder parameters, and a trained, adaptive operator in order to achieve quality production. This manufacturing system is sensitive to minor (or major) upsets and requires the presence of skilled operators. Thus, production parameters may fail to translate well to other extrusion systems - either at larger scale or made by different manufacturers - thereby raising the cost of the product overall and limiting attempts to use co-manufacturing facilities to increase production capacity.

Plant-based meat is also made using pre-extruded TVP, which is typically produced via low-moisture extrusion at milling companies.[47] TVP can contribute to the fibrous structure and microstructure of plant-based meat from small particles that are wetted and combined with a binder for making formed plant-based meat. Since some extrusion is done at a centralized facility rather than at the plant-based meat factory, it may be cost effective for companies to use TVP due to lower capital costs. Many plant-based meat companies, including Impossible Foods, Hungry Planet, and LightLife make ground meat and formed products using TVP.

Section 3: Supply and Demand

Distribution and Supply

Plant-based meat manufacturers must navigate the complex food distribution industry to be successful. Manufacturers should formulate, manufacture, and distribute their products in a way that meets the expectations of not only the consumer, but the entire distribution chain, including redistributors, distributors, and retailers or foodservice establishments. For example, foodservice customers expect bulk packaging, whereas retail products must be packaged and labeled for individual sale. Quick-service restaurants have different standards for product quality and price than fine dining restaurants, and the costs of slotting fees that manufacturers often must pay for placement of their products on grocery store shelves must be incorporated into final prices. In order to find the right product-market fit, manufacturers should consider these expectations during every step of the plant-based meat design cycle and make adjustments to the product or the distribution strategy as appropriate.

One example of the challenges that plant-based meat manufacturers face is that distributors usually prefer not to stock products in less-than-truckload quantities. Thus, manufacturers with limited production capacity or sales volume often struggle with getting their products to distributors. Fortunately, manufacturers have the option to use redistributors, such as Dot Foods, that consolidate less-than-truckload quantities from multiple manufacturers into truckload quantities to be delivered to distributors.[48] Another challenge that plant-based meat manufacturers might face is that distributors often have case minimums (i.e., a minimum number of cases that must be sold each week) for the distributor to

[44] Flow rate and heat transfer modelling in extrusion cooking of soy protein
[45] Effect of Specific Mechanical Energy on Properties of Extruded Protein-Starch Mixtures
[46] Analysis of the dispersive mixing efficiency in a twin-screw extrusion processing of starch based matrix
[47] Expanded textured protein product and method for making same, US 4418086 A
[48] Dot Foods

continue stocking the product. Manufacturers can utilize certain strategies to meet case minimums, such as focusing sales efforts on retailers and foodservice establishments (the distributor's customers), including group purchasing organizations, foodservice management companies, and other organizations with significant purchasing power. Manufacturers might also consider hiring a broker who develops and maintains relationships with customers to complement in-house sales efforts.

Other challenges can even be particular to different subsets of foodservice, such as K-12 school foodservice, which necessitates compliance with nutritional and quality assurance requirements, and often involves low profit margins.[49] Further, supply of plant-based meat products must be scaled rapidly to attract and maintain retail and foodservice customers and to address the unmet demand. Lower costs should be achieved to promote sales to particularly cost-sensitive markets, such as K-12 school foodservice. A focus should be placed on offering products from companies that meet these foodservice needs from the perspective of volume, storage, cooking time, preparation, convenience, and distribution limitations.

Consumer Acceptance

Consumers are increasingly eating plant-based meat, but overall consumption is still limited. Most consumers have little access to and/or familiarity with alternatives to animal-based meat due to availability and price constraints and because consumers rarely encounter plant-based meat at the most popular restaurants or cafeterias. Yet, Mintel reports that consumers are looking for healthier alternatives to animal-based meat to address concerns about consuming cholesterol and saturated fat, and the desire for weight loss. Consumers also report uncertainty about how to prepare alternatives and have concerns about sodium levels and too much processing.[50] However, in general, academic research and data on consumer preferences for plant-based meat are somewhat limited, and may thereby fail to inform the broader trajectory for plant-based meat product development. For example, according to recent research, more concern should be paid to consumer evaluations of meals that include meat substitutes, rather than just testing consumer reactions to meat substitutes as stand-alone products.[51] Further, the desire for sustained replacement of animal-based meat is impacted by boredom with current products, and there are often cultural barriers impacting consumer choices as well.[52, 53]

To support consumer acceptance, it is recommended that we guide product design and marketing strategy using needs assessments of consumers and institutions from a holistic perspective of taste, performance in popular recipes, cooking ease, nutrition, and much more to address and incorporate the complex reasons that consumers may or may not choose alternatives to animal-based meat.

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[49] Rigged: Supermarket Shelves for Sale
[50] US The Protein Report: Meat Alternatives market report
[51] Consumer acceptance and appropriateness of meat substitutes in a meal context
[52] Are meat substitutes liked better over time? A repeated in-home use test with meat substitutes or meat in meals
[53] Analysis of Consumer Behavior Towards Plant -Based Meat and Dairy Alternatives Market in Sweden

Conclusion

Plant-based meat in various forms has been a part of the human diet for millennia and plant-based meat sourcing, design, production, and distribution has deep historical roots. Yet, recently there has been an urgent push to improve the quality, production capacity, and accessibility of more sustainable alternatives to animal-based meat. Efforts to date have been considerable, and the improvement in the quality and access of these products in recent years is a testament to this deliberate effort. Yet population growth and intensifying strains on natural resources are exhibiting mounting pressures on the food system. A concerted effort is needed to accelerate progress towards addressing the challenges the plant-based meat industry faces to efficiently and effectively move us from our current state in each step of the design cycle to our targeted goals.

This analysis of the current state of the plant-based meat design cycle is intended to nucleate the discussion around plant-based meat industry growth. As a multi-disciplinary and socially complex issue, development of replacements for animal-based meat will always be an evolving and at times contradictory area of consideration. The design cycle conceptualization attempts to bring structure, linearity, and clarity to help explore solutions.

Moving forward, further discussion will provide perspective on the proposed strategies as the industry evolves. New proteins, processing methods, companies, and consumers will change the landscape in ways we cannot yet anticipate, but that will provide additional opportunities for the proliferation of plant-based meat. Remaining open to new collaborations, partnerships, and novel outcomes may lead to solutions not yet conceived, and our willingness to consider both mundane and novel solutions to the challenges presented herein will undoubtedly benefit our entire food system.