THE GOOD FOOD INSTITUTE

PLANT-BASED MEAT MIND MAPS:

AN EXPLORATION OF OPTIONS, IDEAS, AND INDUSTRY

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GFI is a 501(c)(3) nonprofit working to create a healthy, humane, and sustainable food supply. GFI is committed to democratizing scientific information that will help move our food system away from factory farming and toward better alternatives.

I. AN INTRODUCTION TO MIND MAPS: CONCEPTUALIZING GROWTH OPPORTUNITIES

A mind map provides a visual representation of critical technologies in an emerging industry to identify gaps in research and development as well as opportunities for strategic industry partnerships. This paper presents established, emerging, and speculative opportunities for plant-based meat sourcing, creation, processing, and distribution through two schematics: the plant-based meat product mind map, which surveys the types of meat analogues that have the potential to replace meat; and the plant-based meat technology mind map, which outlines areas of research and innovation that will accelerate the sector's ability to compete for market share of the meat industry.

The end goal of producing more and better plant-based meat products is to decrease consumption of animal meat products at all levels of quality and price, from steaks to processed meat. Therefore, some of the opportunities and recommendations presented here may apply to only certain types of products or manufacturing methods. For replacement to be successful, in addition to the scientific and technological opportunities discussed below, we must consider the nutritional profiles of various types of plant-based meat and their comparability to the animal products they are designed to replace. Moreover, as it advances, the industry should be transparent regarding its natural resource consumption and other environmental impacts. Though beyond the scope of this introductory paper, The Good Food Institute plans to conduct in-depth analyses of research and innovation opportunities regarding the nutritional qualities of plant-based meat and the environmental significance of its production.

II. THE CASE FOR PURSUING PLANT-BASED MEAT RESEARCH AND DEVELOPMENT

It is now widely recognized that industrialized animal agriculture takes a significant toll on our environment, sustainability, human health, and animal welfare. Additionally, the possibility that antibiotics will become useless for treating human infections due to their overuse in farm animals or that a zoonotic disease outbreak could kill tens of millions of people is a very real threat.

Nevertheless, decades of work by the health, environmental, and animal protection communities to convince people to consume less meat have not put a dent in meat consumption. In fact, meat consumption in the developed world continues to rise, and meat consumption in the developing world is growing rapidly. According to the United Nations, global meat production is projected to increase by nearly 360 million tons by 2050.

Despite rising awareness of the global impacts of our dietary choices, consumers continue to base their purchasing decisions on price, taste, and convenience. Plant-based meat still accounts for only a small percentage of the meat market. While plant-based milk commands more than 9 percent of total milk sales, plant-based meat commands less than one-quarter of 1 percent of meat sales in the U.S. Because the industry is so small, major players have not meaningfully entered, and most of the potential innovation remains unexplored. Merely bringing plant-based meat to 10 percent of the market share would create a $20 billion market in the U.S. alone, and it would have a significant positive impact on our climate, food sustainability, and global health.

That said, the wide-ranging uses of meat present a challenge for understanding where to focus research, development, and manufacturing innovations to create meat replacements. A schematic overview of the opportunities in this market—from both product and technology perspectives—can provide direction for research in food science programs, emergent or established plant-based meat companies, and the food industry as a whole. To this end, GFI has produced two industry mind maps to establish focus areas and provide insight into targeted research and innovation that may advance the industry via product development, production processes, and agricultural research.

III. PLANT-BASED MEAT PRODUCT MIND MAP

Several different animal species are bred, raised, and killed for meat, and each species is used to produce many different types of meat. While some meat is sold relatively unprocessed, a significant amount of meat is ground, minced, or processed in other ways. To effectively compete with animal-based meat products, the plant-based meat industry must expand and innovate to develop a variety of replacements that are as appetizing and affordable as conventionally produced animal meat. Fortunately, opportunities for innovation in the plant-based meat industry are even more vast than for the conventional meat industry. The conventional meat industry is inherently constrained by limitations in the diversity, anatomy, and physiology of the animals it uses, whereas plant-based meat companies can innovate beyond mere replication of the limited types of animal meat currently manufactured. In the following section, we outline categories of meat replacements that represent areas for plant-based meat product innovation that align with this premise.

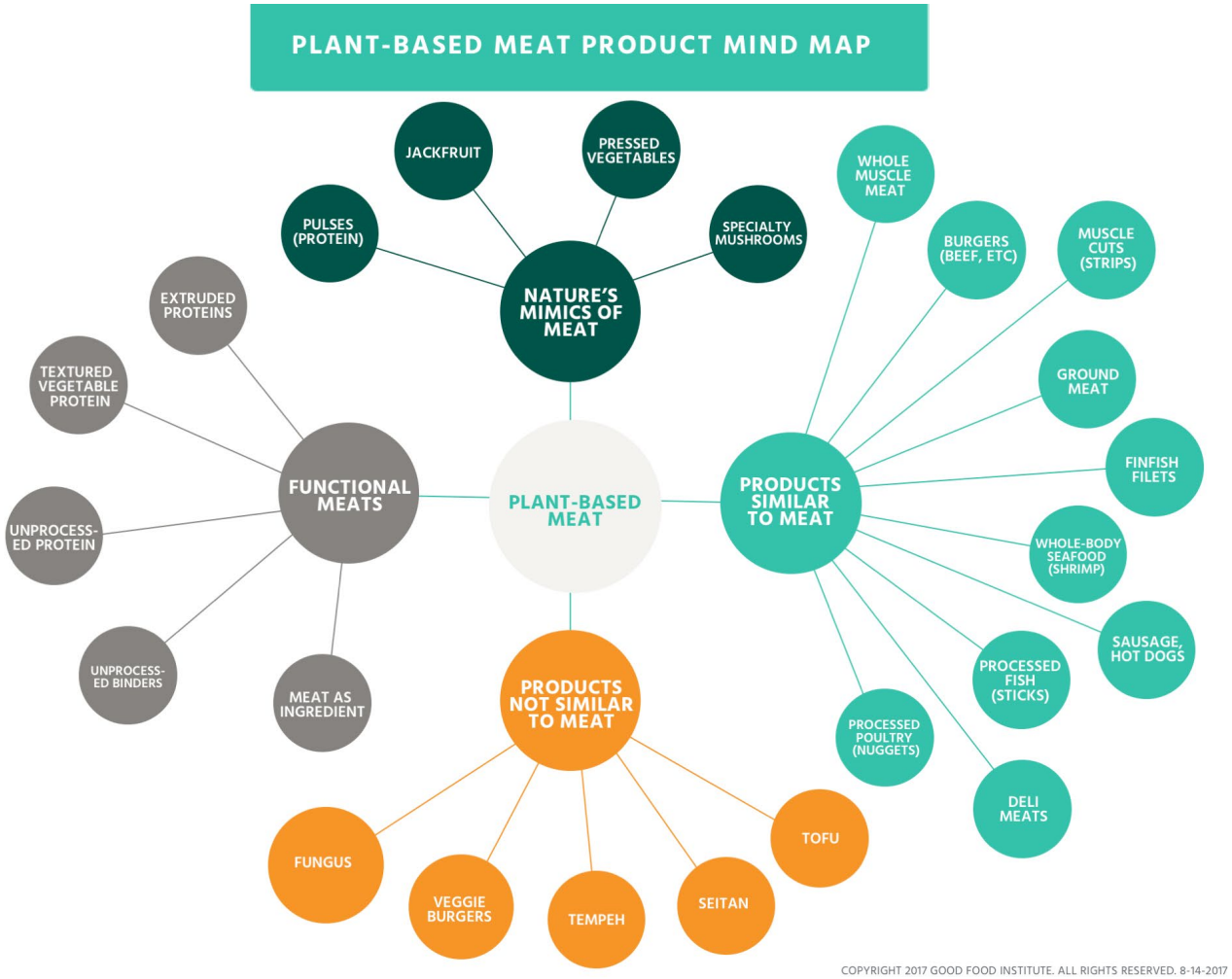

Figure 1. Plant-based meat product mind map

A. PRODUCTS SIMILAR TO MEAT

Products that attempt to replicate animal meat in texture, flavor, and aroma have been the focus of several recent and groundbreaking developments in plant-based meat. New products in this category, such as the Beyond Burger and the Impossible Burger, are built from the ground up to mimic animal meat's characteristics. This particular segment of the plant-based meat industry is redefining "meat" as a product defined by its molecular structure and composition rather than its animal origin. By emulating key characteristics of specific animal-based meat products, plant-based meat can now enjoy greater success as the meaty, center-of-the-plate entr entrée. Furthermore, where demand for plant-based meat was once driven predominantly by vegetarians, today's products—such as the Impossible Burger—which tastes, smells, and "bleeds" like a fresh beef burger, appeal to a range of "flexitarian" consumers who are generating considerable market growth for plant-based meat.

The taste profile of meat is highly complex, comprising thousands of molecules that interact chemically in subtle and not always predictable ways with other food components during the cooking process. Because of its complexity, the flavor of meat is neither trivial nor easy to replicate with alternative ingredients. To create more and better plant-based replicas, we need to study the molecular structure of animal meat and develop innovative plant-based ingredients that mimic this structure.

B. PRODUCTS NOT SIMILAR TO MEAT

Many innovative plant-based meat companies have developed products that are intended to be used directly in place of meat but are not designed to replicate every aspect of the animal-based products they replace. These include products made from whole-food ingredients, such as classic veggie burgers; products intentionally created to have a taste profile different from animal-based meat, such as plant-based sausages flavored with vegetables and fruit; and products considered to be more health-conscious, such as tofu or tempeh. These products appeal to consumers looking for foods that are not sourced from animals. Growth opportunities in this area include increasing the market presence of these products—in terms of both quantity and variety—at competitive prices, while expanding ingredients and flavor profiles to appeal to a wider range of consumers.

C. FUNCTIONAL MEAT PRODUCTS

Functional plant-based meat ingredients, such as proteins and binding agents, are not intended to taste identical to animal meat but are designed to be texturally similar and serve the same purpose as meat in prepared foods (e.g., ground crumbles made from plant ingredients, used in heat-and-serve lasagna). Since it is typically used as an ingredient, functional plant-based meat may require special formulation, just as animal meat is prepared, flavored, or tenderized for a specific purpose. Though functional plant-based meat does not alone serve a center-of-the-plate purpose, it can play a pivotal role in replacing animal meat in the expanding prepared meals market comprising various types of heat-and-serve entrees.

Innovation in this area includes creating plant-based meat ingredients that retain their shape, texture, and flavor through freezing, thawing, and cooking in a full range of prepared products. Additionally, by developing functional plant-based protein ingredients, production capacity of plant-based foods can be increased to improve the price parity of alternatives to popular heat-and-serve products, such as plant-based chicken nuggets, to serve lower-cost markets, such as schools.

D. NATURE'S MIMICS OF MEATS

Certain plant and fungal foods can also displace animal meat as the focus of a meal by providing a whole-food product with a savory taste and the mouthfeel of meat. These less processed foods, such as jackfruit, pulses, and certain mushrooms, are often naturally fibrous or high in protein. Some companies already produce "mushroom bacon," while others use jackfruit to mimic barbecue pulled pork. Innovation in this area includes developing a scaled method of growing these natural meat mimics and creating a supply chain (fresh, frozen, or shelf stable) to distribute the products. Innovation can also focus on developing better marinades and sauces to expand product variety and developing marketing strategies to encourage broader appeal and acceptance.

IV. PLANT-BASED MEAT TECHNOLOGY MIND MAP

Successful innovation in the types of plant-based meat products described above requires a corresponding development of relevant technologies. To provide ample supply and price parity with animal meat, plant-based meat production will require research and development in many interrelated areas. The plant-based meat technology mind map (figure 2) illustrates five key areas: sourcing, isolation and functionalization, formulation, processing, and distribution. These areas come with unique challenges but provide considerable opportunities for meaningful industry innovation.

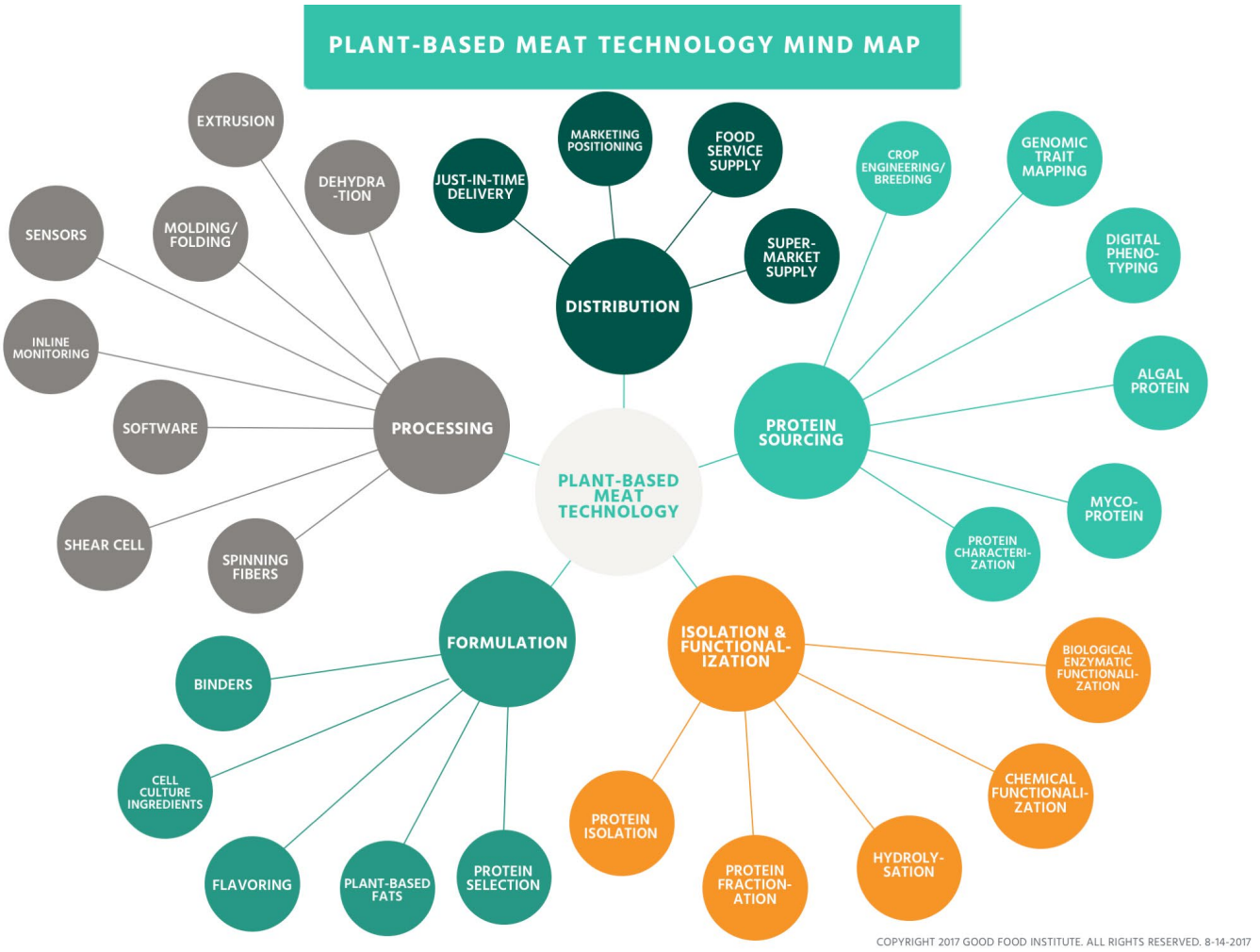

Figure 2. Plant-based meat technology mind map

A. PROTEIN SOURCING

The vast majority of commercially available plant-based protein ingredients comes from only 2 percent of the 150 plant species on which today's global food supply depends. A significant pool of potential plant protein sources is thus available for exploration, and this does not even take into account the almost 250,000 additional plant species not used in agriculture today. Innovation opportunities in this area include expanding and diversifying our use of plant protein sources, determining which sources are best suited to particular plant-based meat products, and ensuring that the proteins from these novel sources are optimized specifically for plant-based meat rather than plant-based foods in general. The methods of protein production described below could potentially provide protein supplies that are both lower cost and more nutritious.

With the identification and utilization of novel plant protein sources comes an opportunity to cultivate innovative farming practices. Concerted breeding or strain improvement efforts can provide underexploited plant protein crops with gains in yield, robustness, and disease resistance similar to what has been achieved for decades with commodity crops, such as corn and soy. This can decrease the cost of these novel protein sources and increase yield, making them more attractive to farmers seeking new crop opportunities.

There is also room for more sophisticated breeding or enhancement to develop strains that are uniquely suited to plant-based meat applications. For instance, specifically breeding plants for high levels of proteins that can be easily isolated will improve efficiency in obtaining purified proteins from the whole plant. Surprisingly, though they are still the most commonly used protein sources for plant-based meat, wheat and soy have historically been bred for starch or oil rather than protein. Efforts to optimize protein sources for plant-based meat can be rapidly accelerated using whole-genome sequencing and digital phenotyping to map desirable traits onto specific genomic loci. This facilitates targeted breeding and drastically reduces the number of generations required to obtain improved strains.

Fungus-based protein is also a promising area for expansion and opportunity. Optimized strains of a wide variety of mushrooms and other fungi could be cultivated in growing rooms or bioreactors for large-scale production.

B. ISOLATION AND FUNCTIONALIZATION

Once a source of plant protein is identified, the plant must be harvested, milled, and processed to obtain a more purified and concentrated protein that can support mass production. Plant-based meat typically relies upon plant-protein concentrates or isolates as raw materials. The inherent characteristics of the proteins, such as size and amino acid composition, determine how well the protein concentrate or isolate will function in the final product. The quality and performance of plant-based meat would be greatly advanced by implementing environmentally friendly methods for protein conditioning, which increase the desirable functional traits of a protein, such as gelation capacity, solubility, and fat adsorption. For instance, biological (enzymatic), chemical, and physical methods can be used to hydrolyze (break down) proteins to increase solubility or crosslink them to increase gelation. Additionally, fractionation (separation) can be used to select proteins that exhibit a desirable set of characteristics. For example, high molecular-weight proteins may perform better in texturization, while slightly hydrophobic proteins may increase fat-holding capacity. Systematic research aimed at identifying which functional traits of proteins are most desirable for particular types of plant-based meats would inform best practices for protein conditioning.

Several studies have found that the results of enzymatic functionalization can vary depending on the protein source because the effects of enzymatic treatment are specific to the sequence composition of each plant's dominant storage proteins. We need a more exhaustive analysis of the response of various plant proteins to specific sets of enzymes and conditions (pH, enzyme concentration, substrate concentration, temperature, exposure time, etc.). These data may enable greater predictive capability for developing optimal protein conditioning regimens to produce desired functional traits.

C. FORMULATION

Proteins are not the only components of meat; meat is also composed of water, fat, and polysaccharides. Thus, procuring a plant protein fraction with optimal functional properties is merely the start of formulating the final, edible meat alternative. The process of formulation involves establishing the correct mix of ingredients to create the desired taste, texture, smell, and structure of a new plant-based meat product. A first step toward successful formulation is to combine a molecular analysis of animal meat with an understanding of the texturization capability of plant proteins to match the texture and flavor components of specific meat products. Many functional characteristics beyond flavor and texture are also important, such as maintaining integrity during cooking. For this, novel binders that exhibit greater resistance to thermal degradation can be explored.

Proteins with high water-holding capacity can bolster the water content of plant-based meat to improve the juiciness of the end product. Likewise, for non-extruded plant-based meat products, proteins that exhibit greater fat-holding capacity can increase fat content by molecularly entrapping the fat. But for extruded products, the inclusion of fats can be technically challenging because fats disrupt the mechanical shear exerted during extrusion. Fat encapsulation or topical fat coating after extrusion may allow fat content to be increased, thus improving mouthfeel and flavor, without interfering with the protein structure. For all these approaches, antioxidants may be needed to stabilize the fats and protect them from rancidity.

Finally, formulation includes the culinary art of flavor selection. Plant-based proteins—especially hydrolyzed proteins, which are more soluble and thus exhibit greater functionality—are often prone to bitter or "beany" off-flavors. This could be addressed by creating new bitter-blocking agents as part of a larger opportunity for developing new flavoring components, particularly those derived from natural sources, and specifically designed to address the challenges of working with plant-based proteins. The selection and incorporation of flavoring in the production process is vital for creating plant-based meat that replicates the flavors of animal meat. Formulation must also consider the nutritional qualities of the plant-based meat product as compared to those of animal-based products. Given the complexity of formulation, the process must include both culinary experts and food scientists.

D. PROCESSING

After successful formulation, the mixture must be shaped into an appropriate form. Methods for transforming plant-protein mixtures into meat substitutes include a variety of manufacturing processes, such as stretching, kneading, shear-cell processing, press forming, folding, layering, and extrusion. Each of these processes can produce unique forms and textures of plant-based meat and affect the nutritional quality of the final product. Furthermore, different plant proteins perform differently in each of these manufacturing processes due to their unique compositions and functional properties. Therefore, understanding how particular plant proteins and combinations of plant proteins from various sources react to specific production techniques is crucial for manufacturing accurate replacements for animal meat.

Like all manufacturing systems, plant-based meat production requires methods for evaluating and controlling quality. Currently, technology to help evaluate and improve the consistency of plant-based meat production is in the early stages of research. Real-time production-system monitoring may be enhanced by inline morphology sensors designed to detect the internal structure of the product during processing. Quality control systems of this kind would reduce waste and increase consistency of the final product. Offline diagnostic tools, such as neutron scattering methods for fiber evaluation, can aid in making more realistic plant-based meat in the R&D phase.

In addition to sensors and analyzers, innovation in software would improve plant-based meat processing. Software tools to model and predict the performance of plant-based proteins would provide understanding and help control the undesirable variability currently observed in plant-based meat production and guide development of new processing methods.

A significant portion of animal meat is processed into sausages, cold cuts, hot dogs, and similar products. For these foods, extrusion is the most common method for developing shape and texture. Many of these popular types of meat can be reproduced with plant proteins and fats using essentially the same production methods. But improvements in processing methods and machinery are necessary to better mimic the taste and texture of more sophisticated or highly structured types of animal meat products.

E. DISTRIBUTION

Plant-based meat is also distinct from animal meat with respect to marketing, positioning, distribution, and production. Some types of plant-based meat can be sold fresh or frozen, while others can be freeze-dried for later use and do not require the intensive cold supply chain needed for most animal meat. Additionally, plant-based meat production may be more flexible and responsive to market demands, as it is not dependent on upstream processes like breeding and slaughter. These distinctions could potentially result in significantly less waste. Schools with variable schedules or hospitals with variable numbers of patients could quickly adjust their orders for plant-based meat, placing less hardship on producers, who may simply throttle output since no animals are waiting in trucks to be slaughtered. Many industries use this just-in-time inventory model to lower costs and reduce waste throughout their supply chains. Similar innovations in supermarket distribution and other marketing methods could revolutionize the availability and accessibility of plant-based meat, thus expanding consumer acceptance.

V. OPPORTUNITIES FOR INVOLVEMENT

Opportunities abound for academic researchers, established food conglomerates, and entrepreneurs to contribute to the growing market for plant-based meat, whether through building supply chains for novel protein sources, improving production methods, or designing new products.

The areas outlined above represent not only tremendously profitable market opportunities but also a substantial opportunity to address urgent challenges in our global food supply. By addressing needs along the supply chain, the quality, cost, and availability of plant-based meat products will improve dramatically, positioning them as economically viable and sustainable alternatives to animal meat. For this to happen expeditiously, both private and public sector funding for research and development are critically needed.

As a leader in the advancement of policy, innovation, and industrial development to move the food system away from conventional animal agriculture, GFI is actively investigating and pursuing key strategies to expand the field and catalyze further development of the plant-based meat industry to create a more healthy, humane, and sustainable food supply. See GFI.org for more information.

ABOUT THE GOOD FOOD INSTITUTE

The Good Food Institute is a 501(c)(3) nonprofit organization whose mission is to build a healthy, humane, and sustainable food system through markets and food technology. GFI is accelerating the market expansion of affordable and appetizing "clean meat" and plant-based alternatives to conventional animal products. GFI is taking ethics off the table for consumers by making the sustainable and humane choice the default choice.

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Note: This report is intended to provide a snapshot overview of the current state of technology in the plant-based meat industry. However, due to the nature of the industry, some technological advances may be the intellectual property of the companies that developed them and thus are not covered in this report. Furthermore, this report should be considered a living document, subject to frequent revision and updates as new information becomes available. Please refer to the first page for the date of last revision.