Plant-based meat: Anticipating 2030 production requirements

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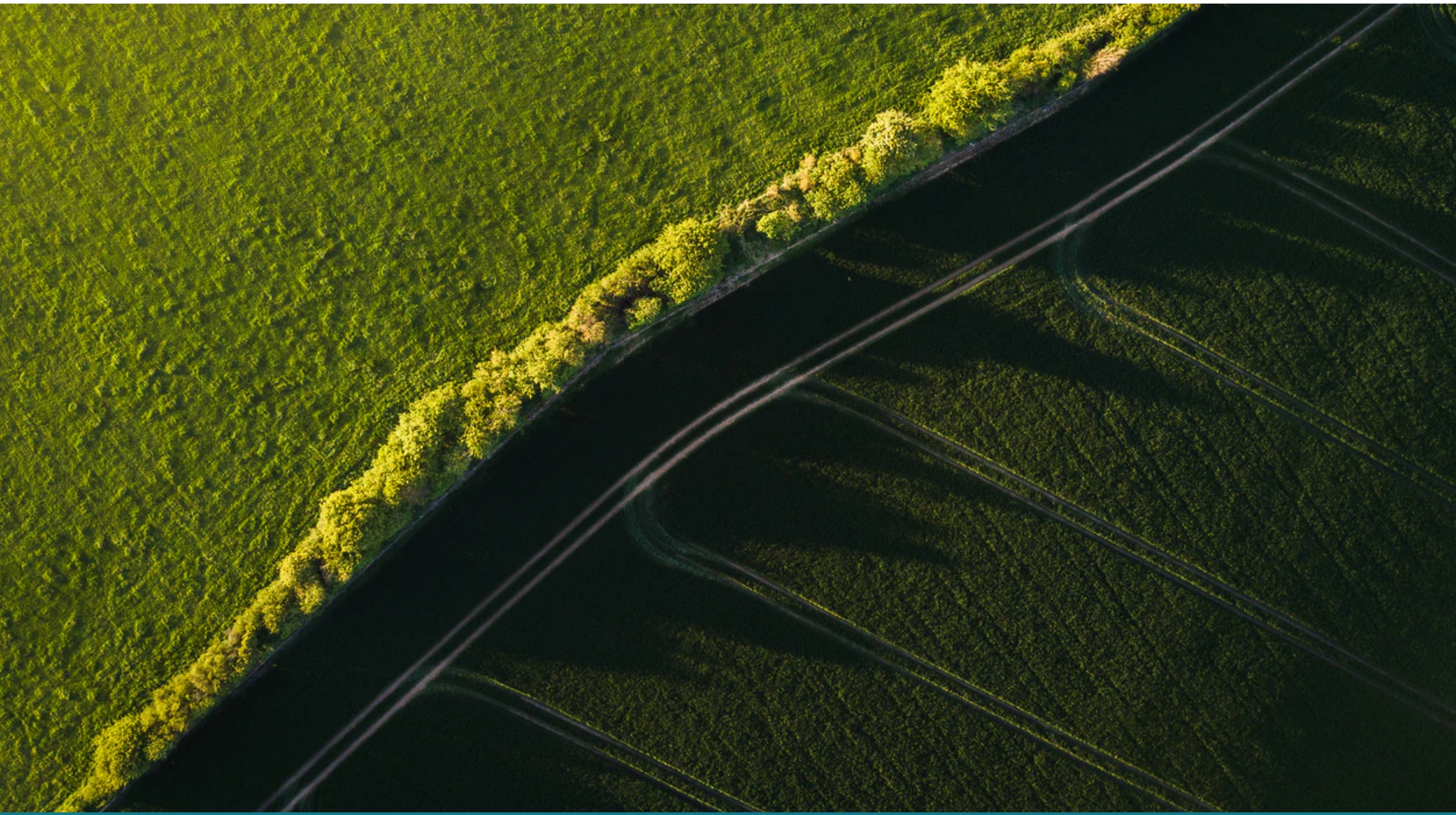

Executive summary

In recent years, consumer demand for plant-based meat has often outpaced the industry's supply chain capabilities. Failure to meet industry production targets may ultimately manifest as higher prices, higher production costs, manufacturing delays, and limited availability to consumers. Given the forecasted increases in global demand for protein and shifting consumer preferences, the industry must prepare to meet the growing demand for alternative protein sources. This report estimates the production targets the industry must meet to satisfy an anticipated minimum of 25 million metric tons in annual global market demand for plant-based meat by 2030.

The analysis examines current ingredient utilization across plant-based meat products and forecasts global production volume requirements to hit production targets. We identify the potential for global supply squeezes of cornerstone ingredients like coconut oil and pea protein in the coming years. Early investment, innovation, strategic partnerships, and research for alternative ingredients or sourcing strategies can mitigate potential future ingredient shortages.

In addition to examining ingredient volumes, the report considers the industry's future manufacturing footprint. Based on generalized hypothetical production facilities used to produce structured plant proteins (SPP)[1]—the base material of plant-based meat—the authors estimate that at least 810 factories with an average annual production of 30,000 MT each must be in operation by 2030 to hit production targets. Greenfield construction and operation of these facilities will cost roughly $27B in global capital expenditure (CapEx) and at least $17B in annual operating costs. These forecasts may be overestimations due to our US-based cost data and assumptions, and should be taken as directional rather than tightly prescriptive since costs can vary significantly across geographies. Upfitting of existing food processing facilities can help, but early infrastructure investment and close collaboration among industry stakeholders is necessary to expand production capacity in the coming decade more efficiently.

Among other variables, our model is sensitive to the forecasted demand growth rate, current volumetric production estimates, the species and end product formats of plant-based meat and seafood produced, the usage levels of different ingredients in plant-based meat formulations, projected production of global crops and ingredients, production facility utilization rates, the balance of production methods used (e.g., high- vs. low-moisture extrusion), and the relative mix of small and large production facilities. Additionally, we conservatively assume that there will not be major innovation breakthroughs in crop breeding, protein fractionation, or plant protein structuring technologies such as extrusion or fiber spinning, even though we strongly believe that innovations

[1] GFI uses the term structured plant protein (SPP) throughout the report to refer to products of both low- and high-moisture extrusion products. More common terms like textured vegetable protein (TVP) technically refer only to products of low-moisture extrusion.

are likely in these areas with sufficient investment in R&D from the public and private sectors. More detail on report simplifications, assumptions, and potential sources of error can be found in Tables 1 and 6.

Our scenario-driven assessment provides a macroscale view of the plant-based meat industry's future footprint, including volumetric ingredient and manufacturing capacity requirements. The analysis demonstrates that manufacturing capacity, more than the availability of sufficient ingredient volumes, is likely to be the rate-limiting link of the plant-based meat supply chain unless mitigation steps are taken. We provide direction to both the public and private sectors—investors, ingredient processors, extrusion equipment providers, and manufacturers alike—about the urgency and opportunity to proactively and conscientiously expand global production capacity and satisfy growing consumer demand. We hope this analysis will serve as a foundation for additional analyses that incorporate empirical data, creative solutions, and more sophisticated models.

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1. Introduction and motivation

Global recognition of the impending effects of climate change is engendering an increasing sense of urgency to accelerate a transformation toward alternative protein production platforms. Several recent market research reports have projected that this transformation could occur rapidly. Still, these reports are often light on specifics of what would be required for such rapid shifts to occur. To realistically achieve these projections, the industry must keep a pragmatic and realistic sense of scale and speed when discussing industry growth.

Market adoption curves can occur with shocking speed in many sectors, but in the food and agriculture system, we must also keep in mind that transformation entails massive ingredient supply chain and infrastructure implications—not to mention impacts on global commodities markets—that require time and substantial capital to manifest. Sustained food system transformation necessitates durable changes in the end-to-end supply chain of food production and, of course, lasting shifts in consumer purchasing patterns.

To make credible claims about transforming the global agrifood system, the alternative protein industry should retain a clear-eyed perspective on the resource deployment necessary to do so. The private sector—investors, ingredient processors, equipment providers, and manufacturers alike—can realize significant financial upside by appreciating and planning for the enormous plant-based meat supply chain build that must take place in the coming decade. Likewise, governments should recognize that meaningful climate gains from a scaled shift toward plant-based meat will not be achievable in the near term unless they invest directly or provide incentives for early private investment in infrastructure for this burgeoning industry.

1.1 Anticipating demand for plant-based meat and seafood

This report provides a generalized perspective on the global production footprint necessary to sustain growth through 2030, intending to identify potential bottlenecks. Of course, to develop a perspective on the global supply chain needs for the industry, we must establish a production target by estimating the plant-based meat industry's future market demand.

To do so, we took a simple approach by first identifying the recent historical (2017-2019) annual average retail sales growth rate of plant-based meat in the United States: 18%.[2] We

[2]Sources: **sales data for 2018 and 2019**; **sales data for 2017**.
Assuming that modest growth continued from August 2017 and that full-year 2017 sales were 585M, the CAGR through the end of 2019 would be 18%. 2020 retail

assumed this rate applies globally and will remain constant through 2030. This facile methodology led us to estimate that plant-based meat sales will comprise roughly **6%** of the global meat market in 2030. From here, we converted market share estimates into volumetric requirements. The Food and Agriculture Organization estimates that in 2030 the global meat (which includes terrestrial meat and seafood) demand for human consumption will be 398 million metric tons (MMT) retail weight[3]. At 6% market penetration, the industry will need to produce **25 million metric tons (MMT)** of plant-based meat in 2030 to meet market demand.

The estimated 25 MMT volumetric demand used to inform the report comports with recent market projections from independent stakeholders. An **analysis** by the **Boston Consulting Group** forecasts demand for alternative meat in 2030 to be about 23 MMT. A **report** from **EY** postulates that alternative meat will comprise about 10% of the global meat market (by value) in 2030, which corresponds to 39 MMT of alternative meat demand, assuming price parity between plant-based and conventional meat in 2030.

Note: The demand estimation used in this report should not be construed as GFI's position on the future of plant-based meat. The purpose of this analysis is *not* to forecast future market demand, but to demonstrate the innovation and investment required to hit commonly-cited production targets.

1.2 Boundaries of this analysis

The plant-based meat supply chain comprises a complex web of suppliers, processors, and service providers. Participants span from farmers who grow and harvest original crop inputs to distributors responsible for keeping grocery store shelves stocked with plant-based meat.

numbers were not used due to the skew from Covid-related purchasing shifts (retail sales of plant-based meat rose 45% from 2019, but this rate is unlikely to be sustained).

[3] Sources: Production projections calculated from FAO Food and Agriculture Projections to 2050 (Scenario: Business as Usual) and OECD-FAO Agricultural Outlook conversion factors.

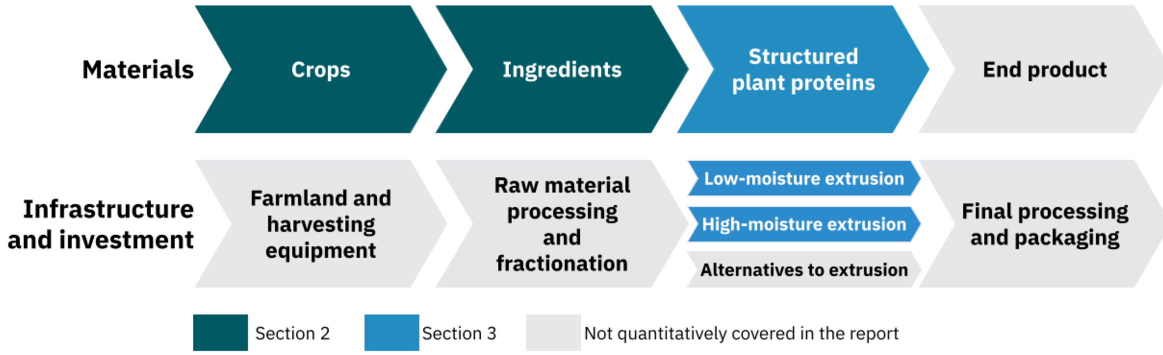


Figure 1: Illustrative plant-based meat production supply chain
Source: The Good Food Institute research.

This report estimates the global resource needs for the plant-based meat industry in the year 2030, assuming the industry must produce at least 25 MMT to address anticipated market demand.

- **Section 2** analyzes common ingredients used in plant-based meat and estimates the global crop and ingredient production volumes required to meet a 25 MMT production target.
- **Section 3** evaluates extrusion, the dominant manufacturing technology used to transform ingredients into SPP for plant-based meat. It estimates the number of manufacturing facilities that should be in operation to meet a 25 MMT production target. Furthermore, it forecasts the expected total global capital expenditure (CapEx) needs and operating costs to transform ingredients into plant-based meat.

The report offers recommendations for actions the plant-based meat industry can take now to avoid future ingredient bottlenecks, infrastructure shortcomings, and—ultimately—slippage in product availability or consumer satisfaction.

As **Figure 1** shows, there are elements of the industry supply chain that are not evaluated in this report.

- **Upstream—crop fractionation and raw material processing infrastructure**: Crop fractionation and raw material processing, which are out of the scope of this analysis, are essential elements of the plant-based meat supply chain. For decades, infrastructure for performing these steps has existed to service billions of tons of crucial commodity crops (e.g., wheat, soy, and corn). We anticipate that modifications to existing processing facilities will be required to generate specific functional fractions necessary for plant-based meat. Likewise, the industry stands to benefit from utilizing the protein-rich side streams of crops with scaled supply chains whose primary uses today are the oil-, starch-, and fiber-rich fractions. It will be equally important for the industry to proactively examine raw material processing needs (and identify uses for the residual starch- and fiber-rich fractions, in particular) of novel crops that gain traction with plant-based meat manufacturers. Finally, we expect that significant investment will be required to scale up the processing capacity for protein isolates and concentrates to keep pace with plant-based meat demand.

- **Downstream—end product processing, preparation, and packaging**: After a plant-based meat company manufactures (or purchases) SPP, they transform the generalized SPP extrudate into a unique formulation. This typically involves imparting minor flavor, texture, and final processing steps (for more detail, see GFI's **Plant-Based Meat Manufacturing Guide**) to improve organoleptic properties and differentiate their products from their competitors. This report excludes infrastructure and investment estimates on final processing, preparation, and packing steps because these will vary extensively from manufacturer to manufacturer.

Table 1: Key simplifications of the analysis

Simplification	Rationale and implications
Demand forecast: growth rate	The methodology of our market demand projection, applying historical annual average growth to the future market, is a simplistic approach to gauging future demand. However, even the most rigorous forecasts will have limited explanatory power when estimating the market conditions of a rapidly growing industry in a decade. Over a decade, even minor fluctuations in annual demand growth can have vast implications on ingredient volumes and infrastructure investment needs. While this analysis is based on specific market share estimates in 2020 (1%) and 2030 (6%), the report's high-level implications and recommendations for ingredient and infrastructure investment hold true whether plant-based meat accounts for 5%, 10%, or even 20% of the global meat market in 2030.
Demand forecast: seafood	This analysis includes plant-based seafood, which currently has a lower market share than plant-based beef, pork, poultry, and other terrestrial meats within their respective categories. While the adoption of plant-based seafood seems unlikely to happen as quickly as plant-based terrestrial meat because of this lag, there is still significant potential to grow in the future. Our lower expectations for plant-based seafood are counterbalanced by the fact that wild-caught seafood (which comprises 50% of seafood at present) has hard supply limits that will be especially salient in the coming decades with continued fisheries collapse due to environmental disruption and over-exploitation. For example, McDonald's has had to switch the fish sources used in their Filet-O-Fish sandwich multiple times due to depleted stocks of first cod, then hoki (today, they primarily use Alaskan pollock). The attendant price increases from overfishing could provide an accelerant to the plant-based seafood industry in the

	coming years that is distinct from the drivers of farmed plant-based terrestrial meat and farmed seafood (aquaculture).
Demand forecast: geographic considerations	The demand forecast takes a holistic, global demand perspective. In reality, the industry must understand in which regions the greatest demand growth is expected. Regional differences in demand for plant-based meat will determine the unique raw materials, ingredients, and end products likely to be needed in the greatest volumes. Furthermore, regional variation could potentially influence the manufacturing techniques used to produce SPP.
Plant-based meat manufacturing approaches	The report assumes that in 2030, 100% of plant-based meat will be manufactured via extrusion. In practice, this will almost certainly not be the case. Researchers and companies are developing novel and proprietary extrusion alternatives, including **shear cell technology**, **3D printing**, **spinning technology**, and other **novel manufacturing approaches**. Other companies are ditching extrusion or sophisticated structuring approaches altogether, instead using simple ingredient blending and mixing approaches to create comminuted products in facilities that closely resemble traditional meat processing plants. Nonetheless, we selected extrusion—both low- and high-moisture—because it is the prevailing approach used to make plant-based meat, and many experts suggest that it will remain as such throughout the next decade or two.
Estimated unit costs of producing SPP	This analysis concerns the ingredient volumes and production infrastructure necessary to manufacture sufficient SPP for the plant-based meat market. While **Section 3** provides high-level, directional estimates of capital and operating expenditure to operate SPP production facilities, we do not analyze the cost of goods sold (COGS) per unit of production. A comprehensive techno-economic analysis is beyond the scope of this paper.
Ingredients and usage levels	The ingredient production volume analysis assumes that the plant-based meat formulation and ingredient landscape in 2030 roughly mirrors the ingredient composition of the top products in today's market. This includes a heavy emphasis on soy, wheat, and pea as primary protein sources and lumps the remaining proteins together as a chickpea-and-pea blend. We do not analyze or predict how formulations will change if other plant protein, lipid, or functional additive sources gain significant market share between now and 2030, but presumably similar supply scaling dynamics will apply for other inputs. Furthermore, the generic formulations used in this analysis to estimate ingredient needs capture only the major inputs and do not capture lower-volume ingredients such as binders, flavorings, or other key components.

This report should be considered a living document, subject to frequent revision, updates, and more sophisticated modeling as new information becomes available. The results presented here should not be interpreted as an authoritative prediction but rather a working model for providing directional guidance based on future crop, ingredient, infrastructure, and investment demands for the plant-based meat industry.

2. Ingredient needs at industrial scale

In the growing market for plant-based meats, a select group of ingredients has emerged as the leading source of essential macronutrients. As the global market for plant-based meat grows, it will be essential to understand future demand for and availability of these ingredients to prevent unanticipated raw material bottlenecks or shortages in the industry. Accordingly, this portion of the analysis aims to assess common ingredients used in plant-based meat and estimate the global ingredient volumes needed to meet a volumetric production target of 25 MMT for plant-based meat in 2030 (**Section 2.1**). The analysis then compares anticipated ingredient volume needs for the plant-based meat industry to Food and Agriculture Organization (FAO) projections of global raw commodity and ingredient production in 2030 (**Section 2.1**). Finally, **Section 2.2** offers recommendations to plant-based meat manufacturers and ingredient suppliers on strategies to avoid future ingredient shortages.

Box 1: Key ingredients present in the top 75 plant-based meat products

To elucidate the plant-based meat ingredient landscape, we analyzed the ingredient lists of 75 products with the highest U.S. sales in 2020. We found widespread use of a small set of ingredients across all three key plant-based meat product categories analyzed. Percentages represent the share of products from each category that contained the respective ingredient. This list comprises the eight most commonly utilized ingredients. It does not include all ingredients used by the industry.

Key ingredient	Burgers, meatballs, and grounds	Sausage links and patties	Nuggets, tenders, and cutlets
Soy protein concentrate	48%	36%	40%
Soy protein isolate	40%	48%	64%
Wheat gluten	48%	72%	76%
Pea protein*	32%	32%	20%
Coconut oil	40%	28%	-
Canola oil	76%	44%	19%
Sunflower oil	40%	36%	40%
Cocoa butter	12%	-	-

Source: The Good Food Institute research.
*Includes both pea protein concentrate and isolate as this differentiation is not made in many ingredient lists.

Unless a significant market disruption takes place, the plant-based meat industry will continue to rely heavily on a select group of ingredients and their respective raw commodities. Wheat and soy, for instance, are produced at a massive scale, and their crop fractions are used in a variety of industries. The consistent, inexpensive, and high-volume ingredient supply that common commodity crops offer make them extremely attractive to plant-based meat producers. The market biases in favor of well-established, commoditized ingredients because the supply chains for novel plant proteins and lipids are currently underdeveloped and are difficult and costly to build.

2.1 Ingredient needs in the plant-based meat industry

To calculate expected global ingredient volumes to hit a minimum production target of 25 MMT, we first identified plant-based meat formulations that could dominate markets in 2030. In analyzing the ingredient lists of the top 75 plant-based meat products by sales in the United States in 2020, we found that **62% of products are wheat- and soy-based, 16% of products are pea-based, and 14% are soy-based products**. The remaining share we attributed to ‘emerging protein’ products, which in our model is made up of a **chickpea- and pea-based formulation (8%)**. The ingredient production volume analysis assumes that the plant-based meat landscape in 2030 roughly mirrors the ingredient composition of the top products in today’s market.

Wheat/Soy-based (62% or 16 MMT)	**Pea-based** (16% or 4 MMT)
Water, **soy protein concentrate**, **wheat gluten**. Less than 2% of salt, methylcellulose, corn oil, onion powder, garlic powder, caramel color, yeast extract, malt extract, natural flavor, spices.	Water, **pea protein**, expeller-pressed **canola oil**, refined **coconut oil**, rice protein, natural flavors, **cocoa butter**, mung bean protein, methylcellulose, potato starch, apple extract, pomegranate extract, salt, potassium chloride, vinegar, lemon juice concentrate, sunflower lecithin, beet juice extract.
Soy-based (14% or 3 MMT)	**Chickpea/Pea-based** (8% or 2 MMT)
Water, **soy protein concentrate**, **coconut oil**, **sunflower oil**, natural flavors. Less than 2% of potato protein, methylcellulose, yeast extract, cultured dextrose, food starch modified, soy leghemoglobin, salt, mixed tocopherols, **soy protein isolate**, vitamins, and minerals.	Water, textured pulse protein (chickpea flour and **pea protein**), **sunflower oil**, chickpea flour, **coconut oil**, porcini mushrooms, sea salt, vegan Worcestershire sauce, black pepper, garlic powder.

Figure 2: Archetypal plant-based meat formulations used in this analysis
Source: The Good Food Institute research.
Note: Each formulation has been defined by the main sources of protein, but some formulations may include additional protein ingredients with minor volumetric contributions. These were not accounted for in this report but were included in a broader analysis of ingredient requirements.

We consulted with plant-based formulation experts and analyzed publicly available information on product labels (nutrition facts and ingredient lists) to estimate the relative ingredient contents in each product by weight. While each formulation in **Figure 2** contains a variety of ingredients, this analysis focuses on key proteins and lipids, in bold, that are prevalent across many products and formats and are utilized today at the greatest volumes. The high usage and prevalence suggest that they are most likely to experience bottlenecks as the industry grows.

We used the 62%/16%/14%/8% formulation share breakdown indicated in **Figure 2** to extrapolate global ingredient needs for the industry in 2030. To illustrate the approach, consider one important ingredient: wheat gluten. We multiplied the share of plant-based meat in 2030 containing wheat gluten, 62% or 16 MMT, by the estimated fractional weight of wheat gluten in the wheat/soy-based formulation: 10%. We therefore expect the industry will require at least 1.5 MMT of processed wheat gluten for plant-based meat in 2030.

To contextualize the volumetric demand estimates for each ingredient, we compared the plant-based meat industry's projected ingredient volumes to **FAO-projected global production volumes** of the corresponding ingredients in 2030. **Table 2** reveals that the plant-based meat industry alone may require a nontrivial share of total global production for certain ingredients and corresponding raw commodities, several of which are expanded upon below.

Increased global population and growing per-capita consumption of land-intensive animal proteins have combined to create pressure to expand global farmlands, contributing to deforestation and declines in biodiversity. As alternative proteins can be produced much more efficiently than animal protein products, if these alternative protein products can displace the consumption of animal protein and thus alleviate demand for animal feed crops, the result will be decreased rates of growth or even absolute decreases in arable land needed to feed the global population. In many cases, alternative proteins can source their feedstocks from animal feed crops or crop co-products currently used as animal feed, such as the protein sidestreams from canola oil processing. In other cases, alternative proteins will rely on new cultivars or crops but will still reduce overall farmland utilization by supplanting acreage that had previously been used for animal feed crops via demand shifting away from animal proteins. There are a number of promising data points suggesting that alternative proteins displace animal protein consumption:

- **According to Nielsen**, 98% of meat alternative buyers also purchase animal-based meat.
- Analytics company Numerator found that **Impossible products were displacing animal-derived foods for 72% of total purchases** over a 13-week study in grocery stores.
- Market research firm NPD's SupplyTrack service **found that 3/4 of the growth in sales of meat alternatives in the U.S. foodservice channel came from displacement of animal protein sales**.

While these initial results are promising, more research on the question of displacement is needed across additional geographies, product types, and demographic groups. It is also important to note that simply diverting crop processing for food ingredient production is sometimes not possible for certain cultivars. For example, **rapeseed cultivars with high levels of erucic acid cannot be used to produce food-grade oil** and instead are used for industrial lubricants, plastics, etc.

Table 2: Volumetric demand of plant-based meat ingredients and the relative burden on global production capacity for ingredients and corresponding raw commodities, 2030

Ingredient	Projected Demand (MMT)	Share of Projected Global Ingredient Production	Share of Projected Global Raw Commodity Production
Soy protein concentrate	2.43	3x	Soy: 2%
Soy protein isolate	0.01	1%	
Wheat gluten	1.48	98%	Wheat: 2%
Pea protein	0.74	10x	Pea: 34%
Coconut oil	0.61	16%	Coconut: 19%
Canola oil	0.31	1%	Canola/Rapeseed: <1%
Sunflower oil	0.24	1%	Sunflower Seed: 1%
Cocoa butter	0.04	2%	Cocoa Beans: 2%

Source: The Good Food Institute research, **FAO Food and agriculture projections to 2050**.

For the key ingredients listed in Table 2 where the percentage share of projected global ingredient production is high, expanding intermediate processing such as protein isolate/concentrate production capacity via increased investment will be sufficient to address the bottleneck without necessarily committing any new acreage to cultivation. However, some additional cultivation of the commodity may be required if particular cultivars are required. For key ingredients where the share of projected global raw commodity production is relatively high, increases in crop production, along with a corresponding increase in intermediary processing capacity, will be required. Even in this case, if higher yields can be obtained via intensification practices like breeding or improved agricultural practices, then no new acreage necessarily needs to be committed to cultivation.

Coconut oil: *By 2030, the plant-based meat industry may require at least* ***16%*** *of the global supply*. Demand for coconut oil is expected to **grow significantly in the coming years** due to its widespread use by the food and cosmetics industries. Thanks to its high saturated fat content and resulting functional properties, coconut oil has become an essential component of a large share of plant-based products. Over **70% of current coconut oil production takes place in Indonesia and the Philippines**. The commodity is heavily export-dependent, which can lead to supply constraints and price volatility. If coconut oil retains its dominance in plant-based meat formulations and alternative means of production are not developed, additional investments in processing capacity and coconut cultivation would likely be required to keep pace with increased demand. The plant-based meat industry's heavy reliance on coconut oil coupled with its volatile supply chain suggests that the industry should seek to rapidly diversify into alternative fats that provide substantially similar, or superior, organoleptic qualities. Novel manufacturing methods for producing similar fats—such as using microbial strains or modifying more abundant plant fats—should also be explored.

Pea Protein: *By 2030, the plant-based meat industry will require* ***10x the projected global supply*** *of enriched forms of pea protein and 34% of pea production overall, assuming current yields*. Pea protein, commonly sold as an isolate, has experienced significant demand growth in the last decade. Its taste and functionality, lower environmental impact, and non-GMO and non-allergenic qualities have led to its widespread use in plant-based meat, and ingredient suppliers are **significantly increasing production capacity** to satisfy market demand. **Roquette recently announced** that their yellow pea facility in Canada could process up to 125,000 metric tons of peas annually once at full capacity. Due to a relatively low protein content of 28%, the manufacture of pea protein concentrate and isolate leads to a large volume of byproducts, particularly starch. A lack of viable commercial uses for pea protein byproducts has made pea protein production **highly susceptible** to volatile commodity prices. While the growth of plant-based protein foods will put pressure on the global pea supply, the biggest bottleneck is processing capacity. Additional investments into intermediary processing capacity to create pea protein isolates and concentrates will quickly unlock much greater volume. Without greater investment to improve the commercial viability of pea protein byproducts, the price of the ingredient may become restrictive, and its potential use by the plant-based meat industry cannot be fully realized.

Again, it is important to note that overall increases in farmed acreage are not necessary to meet increased demand, even in cases where raw commodity supply will be strained. Beyond the opportunity to divert animal feed acreage to growing higher-value crops like peas, there is also significant room for **breeding approaches to increase the protein content** of yellow peas or processing innovations to improve its extraction efficiency, thus allowing for a much higher yield of pea protein isolate per acre.

Soy Protein: *By 2030, the plant-based meat industry will require* ***3x the projected global supply*** *of soy protein concentrate and* ***1%*** *of the global supply of soy protein isolate, but only 2% of soy production overall.* Given its commercial maturity, high protein concentration, and beneficial flavor profile, soy protein concentrate and isolate are among the **most commonly-used sources** of plant protein. Because soy protein is a derivative of one of the most widely traded commodities, supply chains for soy protein concentrate and isolate are well-developed from farm to fork. As with pea, the expansion of intermediary processing capacity to create soy protein isolates and concentrates would enable the industry to close the gap between demand and supply rapidly. A small subset of consumers express concerns about soy's allergenicity, which could present modest demand-side headwinds for this plant protein. Nonetheless, it is positioned to remain a dominant source of protein as the plant-based meat industry grows in the coming years.

2.2 Growing and diversifying ingredient supply

The industry must produce a sufficient ingredient base to service the rapid demand growth for plant-based meat adequately. Both manufacturers and ingredient suppliers should consider the following proactive measures to mitigate future ingredient shortages and, importantly, to optimize crops and ingredients to improve the organoleptic properties of plant-based meat and minimize byproducts.

Check out GFI's **Alternative Protein Solutions Database** for additional, concrete strategies to advance the industry.

Exploring opportunities in emerging protein sources. While the well-established plant-based meat ingredients (e.g., soy, wheat, pea, coconut, sunflower) will maintain primacy in the coming decade, a variety of emerging protein sources—including certain legumes, oilseeds, vegetables, nuts, and cereals—show strong growth potential. The market for plant-based meat offers a tremendous opportunity for new ingredients with diverse nutritional and functional profiles to establish themselves as legitimate alternatives to the ingredients most frequently used today. The industry also lends itself to opportunities to leverage indigenous crops better suited to growth in various geographic regions, in contrast with the extreme global commoditization seen in the animal feed industry. However, building out these novel supply chains is no small task and requires close cooperation between—and significant investment from—growers, ingredient processors, and manufacturers. Governments, multilateral agencies, and global development philanthropies can play a role in market-shaping activities such as farmer and processor loans, market guarantees, crop insurance schemes, and extension education programs to support the development of robust supply chains for emerging plant protein sources.

Box 2: Plant protein ingredients and ratings across key parameters

GFI's **Plant Protein Primer** is an essential resource for comparing plant protein sources on key attributes like nutrition, functionality, price, and sourcing. The guide includes profiles of major and emerging plant protein sources, combination and processing strategies, and consumer perceptions. The table below is a partial excerpt of the full Plant Protein Primer analysis of various plant proteins.

Protein Source	Protein Concentration	Nutrition	Allergenicity	Commercial Stage	Flavor	Functionality	Cost	Global Crop Supply
Soy	Excellent	Excellent	Poor	Excellent	Low	Excellent	Good	Excellent
Pea	Good	Good	OK	Good	OK	Good	Good	OK
Wheat	OK	OK	Poor	Excellent	OK	Excellent	Excellent	Excellent
Mung bean	Good	OK	OK	Good	Good	Good	Low	OK
Chickpea	Good	OK	OK	Good	OK	Good	Low	Good
Lupin	Excellent	OK	Poor	OK	Low	OK	-	OK
Sunflower	Good	Good	Excellent	OK	OK	Good	Low	Good
Fava bean	Good	OK	Low	OK	OK	OK	Low	OK
Peanut	Good	Good	Poor	OK	Good	Good	-	Good
Rice	Low	OK	Excellent	Good	Good	OK	OK	Excellent

Legend

	Protein Concentration	PDCAAS*	Allergenicity	Commercial Stage	Flavor	Functionality	Cost (/kg protein)	Global Crop Volume (MMT[†])
Excellent	>30%	>0.80	Usually mild, low pop.	Commodity	Flavorless	Low conc. effect	<$2	>100
Good	20-30%	0.60-0.79	↕	Large	↕	↕	$2-4	10-99
OK	10-20%	0.40-0.59	↕	Small	Acceptable	↕	$5-9	1-9
Low	5-10%	0.20-0.39	↕	Start-up	↕	↕	$10-19	0.1-0.9
Poor	<5%	<0.20	Severe in sig. pop.	R&D	Objectionable	Water insoluble	>$20	<0.1

*Protein Digestibility Corrected Amino Acid Score

[†]million metric tons

Improving the economic viability of existing ingredients by focusing on sidestream utilization. Sidestream use should be an explicit consideration as ingredient suppliers and plant-based meat manufacturers screen and breed specialty crops. The economic viability of novel crop supply chains can be greatly enhanced by identifying value-added applications for starch- and fiber-rich fractions (e.g., as fermentation feedstocks). Likewise, the industry should also investigate potential opportunities to use the sidestreams of other industries, such as **spent grain used for brewing**, as functional and cost-effective inputs for plant-based meat.

Forging partnerships among ingredient suppliers and manufacturers. Strategic relationships increase market information by providing suppliers with timely information on demand changes for their products. Ensuring future income through guaranteed offtake agreements can de-risk new investments in processing infrastructure, empowering processors to build capacity in advance of the materialization of market demand. These relationships also harmonize the maturation of ingredient supply chains with the needs of manufacturers, allowing plant-based meat producers to provide feedback on the degree to which ingredients are meeting functionality and consistency standards. In recent years, **Cargill** **announced an investment** in **PURIS** to increase the production and processing capacity of its proprietary pea protein, enabling PURIS to fine-tune its protein for the plant-based meat industry.

Investing in new technologies for saturated fat production and methods of non-saturated fat incorporation in plant-based meat. Over-reliance on existing sources of plant fats, particularly coconut oil, risks potential future supply shortages of these ingredients. R&D investment in new approaches for producing functional fats—including **chemical transformation**, **precision fermentation** (see, for example, **C16 Biosciences** and **Nourish Ingredients**), and **oleogel formation**—is necessary to reduce dependency on and improve the functionality of current lipid offerings.

3. Facility footprint and investment needs at industrial scale

The goal of this portion of the analysis is to estimate the manufacturing infrastructure and corresponding investment necessary to transform ingredients into 25 MMT of SPP—our assumed base material of plant-based meat—annually by 2030. We develop generalized SPP production facility archetypes and estimate the number of these production facilities that should be in operation by 2030 (**Section 3.1**). We also develop generalized cost profiles of the archetype facilities and use them to forecast the expected total, global capital expenditure (CapEx), and operating cost needs to meet the 25 MMT production target (**Section 3.2**).

But first, we must account for the predominant methods of producing SPP.

The history of manufacturing meat analogs can be categorized into four buckets:

- **V1.0 (traditional processes):** Products like **seitan are produced** in a reasonably simple manner, by kneading a dough of wheat flour, yeast, and water. Traditional meat analogs like seitan have been produced for centuries, but they bear minimal organoleptic resemblance to conventional meat.

- **V2.0 (low-moisture extrudates):** Since the 1960s, **low-moisture extrusion** has been used to produce textured vegetable protein in the form of **strips**, **crumbles**, and **flakes**. Plant-based meat manufacturers use this shelf-stable, low-moisture extrudate (LME) to produce comminuted products like sausages, burgers, and meatballs. Plant proteins processed using LME are also widely used as extenders in the conventional meat sector.
- **V3.0 (high-moisture extrudates):** The 2000s saw the advent of high-moisture extrudates **(HME)** produced via **twin-screw extrusion** lines. This approach, which today is not as widely utilized in the plant-based meat industry, more convincingly replicates the taste and texture of conventional meat. Plant-based meat companies such as Good Catch and Beyond Meat use HME SPP as the base material for some of their product offerings.
- **V4.0 (next-generation techniques)**: There are now efforts by researchers, manufacturers, and entrepreneurs to expand the reach of plant-based meat production methods to further optimize for texture and taste. Researchers and companies are developing novel alternatives to extrusion including **shear cell technology**, **3D printing**, **spinning technology**, and other **novel manufacturing approaches**.

Based on the guidance of industry experts, the forthcoming assessment assumes the market for SPP in 2030 will be supplied by a combination of **LME** (V2.0) and **HME** (V3.0). While the market is likely to shift towards more sophisticated texturization approaches in the coming decades, we expect that in 2030 a substantial majority of SPP will continue to be produced via LME due to its high throughput production capability, fundamental cost advantages, ability to produce shelf-stable products, and broad availability in countries around the world. Industry experts suggest that today LME accounts for about 85% of SPP manufacturing. Furthermore, they expect that in the coming decade there will be a modest increase in HME production, but LME will nonetheless remain the dominant form of extrusion. Therefore, the forthcoming estimations of the industry's SPP manufacturing needs in 2030 assume LME accounts for 80% of the global SPP volume and HME accounts for 20% of the global SPP volume.

Both **LME** and **HME** are produced along an extrusion line. The extrusion line is amenable to continuous processing and consists of a system for handling and delivering raw material (typically isolates and concentrates of soy, pea, and wheat), preconditioning equipment, an extruder barrel with single or twin screws, and—in the case of **HME**—a cooling die with a control system to change parameters such as shear force and temperature. Multiple extrusion lines may be housed within a single extrusion facility.

For a detailed explanation of the technology and process behind plant-based meat manufacturing with extrusion, check out GFI's **Plant-Based Meat Manufacturing Guide** and this **review paper on extrusion of pulse proteins**.

3.1 Estimating global facility needs

LME and HME extrusion lines will be predominantly responsible for producing 25 MMT of SPP in 2030. Accordingly, we start by estimating the number of extrusion lines necessary to satisfy global production targets. In doing so, we devise four archetypal extrusion lines for consideration in our analysis—two LME lines and two HME lines—and establish their respective average SPP throughputs.

- **Line 1: LME (throughput: 1,000 kg/hr).** Ingredient suppliers and plant-based meat manufacturers operate extrusion lines at this capacity today in small- to medium-scale facilities.
- **Line 2: LME (throughput: 2,500 kg/hr).** Extrusion lines of this capacity are often located in large-scale facilities operated by ingredient suppliers who sell their SPP to plant-based meat manufacturers. This scale represents the upper bounds of SPP throughput based on today's manufacturing technologies.
- **Line 3: HME (throughput: 500 kg/hr).** Due to the limitations that cooling dies impose on the HME production process, 500kg/hr has been the maximum throughput achieved at industrial scale until very recently.
- **Line 4: HME (throughput: 1,000 kg/hr).** Recently, **Buhler** announced the **launch of a new high-performance cooling die** that will enable industrial HME production at a throughput of 1,000 kg/hr. It is highly likely that other industrial equipment manufacturers will soon follow suit.

The extrusion throughput estimations reflect the current, not future, state of the art and are therefore conservative given that our scenario is set in 2030. As the market for plant-based meat continues to grow, equipment manufacturers will be increasingly incentivized to offer extrusion solutions for LME and especially HME that yield even higher throughputs.

Having established the average output per extrusion line, the analysis now turns to developing a hypothetical blueprint of SPP manufacturing facilities, each of which houses one or more extrusion lines. Based on discussions with experts at equipment manufacturing companies and consultation with industry techno-economic assessments (**here** & **here**), we devised four model SPP facilities:

- **Facility A: medium LME (throughput: 1,000kg/hr).** One *Line 1* extrusion line.
- **Facility B: large LME (throughput: 10,000kg/hr).** Four *Line 2* extrusion lines.

- **Facility C: medium HME (throughput: 1,000kg/hr).** Two *Line 3* extrusion lines.
- **Facility D: large HME (throughput: 10,000kg/hr).** Ten *Line 4* extrusion lines.

To translate the expected average hourly output of each of the four model facilities into annual production volumes, we must consider each facility's **capacity utilization.** Facilities A-D are assumed to operate 24 hours per day, seven days a week, 350 days per year at 85% of maximum potential throughput capacity. The two weeks of facility downtime and 85% capacity utilization estimate agree with standard food processing facility practices to allow for voluntary and involuntary downtime and equipment maintenance. According to industry experts, conventional meat processing facilities typically operate at **75%-95% capacity**.

Table 3: Estimated global extrusion line and extrusion facility quantities

Global production volume assumptions	Facility A	Facility B	Facility C	Facility D
Extrusion lines per facility (#)	1	4	2	10
Annual output per facility (MMT)	0.007	0.07	0.007	0.07
Share of global SPP production (%)	12	68	3	17
Extrusion facilities (#)	**413**	**234**	**104**	**59**

Source: The Good Food Institute research.

Accounting for the average hourly throughput of the extrusion lines and anticipated facility capacity utilization, we estimate (see **Table 3**) that medium-scale factories like **facility A** and **facility C** each produce 0.007 MMT annually. For comparison, Impossible Foods **opened a plant-based meat manufacturing facility** in 2017 with the capacity to produce roughly 0.005 MMT annually. Furthermore, we estimate that large-scale factories like **facility B** and **facility D** each produce 0.07 MMT annually. Ingredient processors operate large-scale LME facilities manufacturing processed foods (including pasta, snacks, textured vegetable protein, etc.) that produce at least 0.07 MMT annually.

Due to the industrialization of the plant-based meat sector and the efficiency gains conferred by economies of scale, we posit that by 2030 the clear majority (85%) of SPP will be manufactured in large-scale facilities (**facility B** and **facility D**). These facilities will likely be operated by large commodity firms and ingredient suppliers who are providing food companies with SPP. Certain plant-based meat manufacturers with a large footprint, such as Beyond Meat may be **incentivized to develop in-house facilities** of this scale to be more vertically integrated. The remainder of SPP (15%) will be produced in facilities with lower throughput (**facility A** and **facility C**), primarily for plant-based meat companies with a smaller footprint and for those serving geographies with lower demand. Our estimated 85%/15% share breakdown is **directionally similar to that of the meat processing industry in the United States**, whereby the vast majority of meat is processed in large-scale facilities by a small cohort of processing companies.

We now return to a central question of **Section 3**: How many SPP extrusion lines and extrusion facilities are needed to supply at least 25 MMT of plant-based meat in 2030? From **Table 3**, we anticipate that roughly 2,000 extrusion lines in 810 extrusion facilities globally are necessary to meet the production target. For comparison, **according to the North American Meat Institute**, in 2018 there were over 7,500 federally inspected slaughter and/or meat processing facilities in the United States alone.

As we acknowledge in **Section 1.2**, it is an oversimplification to assume that all plant-based meat will be produced via low- and high-moisture extrusion (instead of shear-cell, 3D printing, etc.) in 2030. Similarly, it is possible that technological advances in extrusion processes will upend current paradigms regarding facility throughput. However, this analysis examines the implications of industry growth under current technological and supply chain limitations to illustrate the point that projected growth cannot realistically be achieved, even in the near term, without significant innovation and investment.

3.2 Anticipating global facility CapEx and operating costs

In addition to understanding hypothetical equipment and infrastructure needs for plant-based meat production in 2030, the industry must recognize the enormous level of investment required to create and operate this equipment and infrastructure. **Section 3.2** contains a bottom-up estimation of CapEx and operating costs for each of the four model extrusion factories, **facilities A-D**. We then extrapolate the global investment required to construct and operate the necessary number of facilities, per **Section 3.1**, to meet a minimum SPP production target of 25 MMT.

We start by assessing the CapEx of our hypothesized **facilities A-D**. The factories, as modeled, meet **good manufacturing practice (GMP)** requirements for the food processing industry. As per **Table 4**, key CapEx costs per facility include:

- **Land acquisition:** purchase or lease of land upon which the facility will be located. Land acquisition costs in this analysis are based on discussions with industry experts as well as **reports by food processing site location consultants**.
- **Extrusion lines:** cost of extrusion lines—which generally are comprised of an extruder barrel with single or twin screws, an extrusion control system, a vapor exhaust system, heat exchangers, and a liquids addition system—in addition to costs associated with raw material handling (i.e., **gravimetric feeder**), equipment automation, and installation and commissioning. HME lines, as are present in **facility C** and **facility D**, also include the cost of cooling dies. Equipment cost estimates were derived from proprietary quotes obtained from equipment manufacturers.
- **Facility development:** space for manufacturing, offices, and warehousing. Warehousing space for such facilities includes room for dry storage of raw materials and, in the case of facilities that produce HME (**facility C and facility D**), cold storage of the finished goods. Cold storage requirements are an important driver of the cost differential between LME and HME sites, though it is worth noting that preservation steps such as retort processes could alleviate the need for cold storage of HME products. Site development costs were estimated in consultation with food industry engineering and construction firms.

Table 4: Estimated capital expenditure per facility for generalized hypothetical SPP extrusion facilities

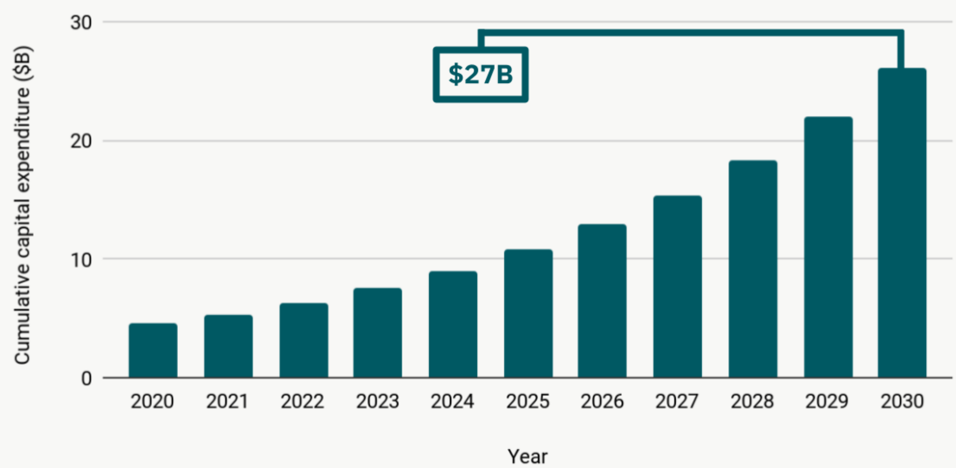
Facility CapEx components ($M)	Facility A	Facility B	Facility C	Facility D
Land acquisition	0.3	1.0	0.3	1.2
Extrusion lines	2.0	16.0	4.9	36.0
Facility development	10.5	43.2	13.1	54.0
Total CapEx ($M)	**12.7**	**60.2**	**18.2**	**91.2**

Source: The Good Food Institute research.

Table 4 demonstrates the hypothetical average CapEx for **facilities A-D**, which illustrates a range of $12.7M for **facility A** (medium-scale LME) to $91.2M for **facility D** (large-scale HME). Employing these estimates, we return to a central question of **Section 3.2**: what is the anticipated industry-wide cumulative CapEx required to outfit the necessary facilities to meet 2030 global production targets? We estimate that by 2030, the industry collectively must invest at least $27B in CapEx into the estimated 810 SPP extrusion facilities.

Note: The estimates provided herein are not intended to precisely forecast the industry's SPP extrusion facility CapEx needs. Rather, they provide a directional and order-of-magnitude level-setting for the industry. It is likely that experience curves will allow for lower CapEx per facility once more of these facilities are built, but this trend may also be counteracted by price surges triggered by a rapid rise in demand for specialized equipment or construction materials. It is difficult to predict how these influences may interact, so we have used a simplified assumption that the cost to build each archetypal facility will remain constant over this time period.

Box 3: Estimated cumulative global CapEx needs to construct structured plant protein extrusion facilities by 2030



Source: The Good Food Institute research.

Of course, the SPP extrusion facilities that produce our hypothesized 25 MMT of plant-based meat in 2030 will also incur significant operating costs—raw materials, utilities, and labor principal among them. **Table 5** conceptualizes annual operating costs for the model **facilities A-D**. Per the assumptions in **Section 3.1,** we estimate that the facility operates at an 85% capacity utilization rate.

The utility costs for water and electricity were determined in consultation with proprietary operating cost reports from ingredient processing companies and cross-referenced with **reports on the operating cost profiles of food processing facilities**. Raw materials include the protein concentrates and isolates, profiled in **Section 2**, that are fed into the extrusion lines. Raw material costs were extrapolated from bulk retail prices of commercial vendors at online marketplaces (e.g., Alibaba) and further validated via discussions with industry experts. Because extrusion lines that produce HME incorporate more plant-based fats, like coconut and sunflower oil, in addition to plant proteins, the raw material costs of **facility C** and **facility D** are comparatively higher than the raw material costs of LME facilities. Labor costs are comprised of the hourly wages of facility workers and the salaries of facility managers. These estimates are based on discussions with industry experts and in consultation with **reports by food processing site location consultants**. Miscellaneous operating expenses include property tax, rent (if the space is leased), and the cost of packaging and shipping materials.

Table 5: Generalized hypothetical extrusion facility operating expenditures

Facility operating cost components ($M annually)	Facility A	Facility B	Facility C	Facility D
Utility: water	0.0	0.0	0.0	0.0
Utility: electricity	0.3	1.8	0.9	4.4
Raw materials	4.2	21.0	10.2	51.3
Labor	6.1	11.0	6.1	11.0
Miscellaneous	2.2	4.9	2.5	6.6
Total annual operating costs ($M)	**12.8**	**38.7**	**19.7**	**73.4**

Source: The Good Food Institute research.

Table 5 demonstrates the hypothetical average operating costs for **facilities A-D**, which illustrates a range of $12.8M for **facility A** (medium-scale LME) to $73.4M for **facility D** (large-scale HME) By multiplying the estimated number of facilities by the average operating costs per facility, our analysis shows that, collectively, the industry's 810 extrusion facilities will incur at least $17B in operating costs in 2030 to meet the 25 MMT SPP production target.

Note: The estimates provided herein are not intended to be precise forecasts of the industry's SPP extrusion facility operating costs needs. Rather, they provide a directional and order-of-magnitude level-setting for the industry.

3.3 Efficiently expanding industry-wide production capacity

It is no secret that, in recent years, the plant-based meat industry has been supply-constrained, not demand-constrained. **Anecdotes abound** of manufacturers running into difficulties expanding production capacity to meet the needs of restaurants and grocery stores eager to offer novel and sustainable products. Our analysis quantitatively demonstrates the enormous manufacturing footprint and level of investment necessary to avoid future supply constraints and successfully meet anticipated plant-based meat production targets through 2030. Below we provide recommendations to the industry on strategies to address the estimated six-fold expansion in SPP manufacturing capacity that must take place between now and 2030.

Check out GFI's **Alternative Protein Solutions Database** for additional, concrete strategies to advance the industry.

Expanding capacity at existing facilities. Today, there are thousands of facilities that process various packaged foods using extrusion and related technologies. It is reasonable to expect that plant-based meat manufacturers can, in many cases, purchase and upfit existing facilities instead of constructing entirely new factories. The upfitting process for LME facilities (**facility A** and **facility B**) can be relatively straightforward, especially if a facility previously produced dry snacks using extrusion. There are also opportunities to meaningfully increase the throughput of HME lines (present in **facility C** and **facility D**) at existing facilities by upfitting them with larger cooling dies. This is a low CapEx, and thus attractive, approach for manufacturers when compared to constructing new facilities altogether. Furthermore, companies can also **pair extrusion lines with other upstream processes** (e.g., raw material processing) under one roof to reduce overhead and raw material shipping costs.

Production equipment innovation. Investment in production equipment research and development would not only support likely improvements in product quality but could also ease capacity constraints if resulting innovations allowed for higher throughput and better utilization of existing and new production facilities without significantly increasing CapEx or OpEx costs. For example, creating new types of cooling dies that can provide structure and texture to extrudates at much higher throughputs than previously possible (such as the Buhler 1000 kg/hour die example) can dramatically increase production capacity with minimal infrastructure investment. Innovations that reduce equipment downtime by enhancing reliability and longevity could also improve facility throughput by increasing facility capacity utilization. Additional production capacity benefits could come from novel technologies that are not yet widely commercialized, such as 3D printing, shear cells, fiber spinning, or other approaches.

Partnerships and other commercial strategies. Partnerships between ingredient companies and equipment manufacturers, such as a recent collaboration between **Givaudan** and **Buhler** on a **manufacturing innovation center**, can significantly accelerate R&D and commercialization timelines of novel manufacturing approaches. Furthermore, plant-based meat manufacturers stand to benefit from **partnering with large co-manufacturers** with decades of food manufacturing experience to vastly expand their production volumes and move more quickly down the experience curve.

Long-term investments in capacity expansion. Production capacity for plant-based meat does not appear overnight. On the contrary, it often takes many years to conceive, finance, and construct an SPP processing facility. Financiers and ingredient processors seeking to expand their footprint in the rapidly growing plant-based meat industry should begin planning and investing now to meet the industry's ambitious production targets for this decade and beyond.

4. Parameter justifications and error estimation

In **table 6,** we summarize key assumptions and estimations that have been incorporated throughout this analysis and assess the anticipated impact on the findings in our report—namely, whether these factors have likely been over- or under-estimated. The top portion of the table lists factors where the assumptions were conservative and thus are areas where the ingredient volumes, manufacturing footprint, and investment estimates may look more optimistic in practice than its conceptualization in this analysis. The bottom portion of the table examines factors that were excluded or oversimplified in this analysis. Accounting for them in a more sophisticated iteration may yield an even higher bar for ingredient volume, manufacturing footprint, and investment needs for the industry.

Table 6: Estimation of potential sources of error and variance in our analysis

Potential sources of error and their implications	
Assumption or oversimplification	**Implications**
Raw commodity and ingredient production in the next decade will follow a BAU growth pathway	**FAO's Food and Agriculture Projections to 2050** provide three pathways of growth, 'Business-as-usual' (BAU), 'Stratified societies,' and 'Towards sustainability.' For our model, we chose the BAU growth pathway to provide a scenario in which input constraints result from failing to improve the way we produce crops and ingredients. It remains to be seen whether this is an over- or underestimate. **Some studies** indicate that average global crop productivity will decrease in the coming years due to climate change and associated severe

	weather events, as well as soil degradation from irrigation and erosion. However, the historical trajectory for agricultural productivity has been a consistent upward trend due to advances in breeding and other agricultural technologies, so it is unclear which of these opposing forces will dominate in the next decade.
Environmental performance of crop production will not change over the next decade	Average land use, freshwater withdrawal, and GHG emissions from crop production will remain constant over the next decade and will not be affected by environmental change or technological advances that improve agricultural efficiency.
Extrusion throughput experiences no breakthroughs over the next decade	Throughput of the LME and HME extrusion lines we model is based on current achievable production volumes. Thus we assume there are no breakthroughs in throughput capacity (for instance, via cooling die innovations) over the next decade. Therefore, if the industry continues to expand extrusion line throughput capacity in the coming decade, the number of extrusion lines and facilities—as well as the overall cost estimates—needed to meet production targets will be lower than the estimates provided in this report.
Facilities are built from scratch rather than incrementally adding extrusion capacity to existing facilities	The analysis assumes new SPP extrusion capacity comes entirely from greenfield projects. In reality, some of the extrusion capacity developing in the coming decade will be added to existing processing infrastructure incrementally. An upfitting approach significantly mitigates overhead while still conferring the economies of scale of high-throughput extruders. Should the industry adopt this approach to capacity expansion, the necessary number of extrusion lines and facilities and the overall cost estimates needed to meet production targets will be lower than the estimates provided in the report.
All extrusion facilities have the same cost profile regardless of geography	Facility cost profiles were developed using available data from extrusion factories in the United States. Further work is required to gather detailed cost estimates in other geographies, especially as much of the anticipated global demand growth for plant-based meat in the coming decade will come from consumers in Asia-Pacific, Europe, and South America. U.S.-based extrusion facilities often cost more than their counterparts in other geographies due to comparatively higher raw material, utility, labor, and land costs. Therefore, our global facility estimates are likely overestimations because a large majority of new facilities will be built outside of the United States.
The plant-based meat industry will use a limited set of formulations	The model does not take into account the full diversity of products and formulations that are currently in the market and that will be introduced in the future, meaning that it fails to include ingredients that may not be as commonly used but account for a small share of total ingredient use in plant-based meats.
The share of plant-based meat from each of the four archetype formulations will remain constant through 2030	The model assumes that the product landscape in 2030 will mirror that of 2020. However, it is possible, indeed likely, that novel ingredients will increasingly be incorporated into plant-based meat products in the coming decade, leading to different ingredient requirements than those presented in this analysis.
Demand for the selected ingredients will not be affected by cost	As demand for plant-based meat continues to rise and the ingredient supply faces additional constraints, ingredient costs may rise, leading the industry to seek substitutions with similar, or at least tolerable, functional properties. The model does not take into explicit consideration this substitution effect resulting from rising costs.

Capacity utilization is commensurate with large-scale conventional meatpacking plants	Industry experts suggest, anecdotally, that the facility capacity utilization (85%) we use in the report accords with that of ingredient processors who manufacture SPP at a large scale. However, the estimate is about 30% higher than typical capacity utilization for SPP extrusion facilities owned by plant-based meat brands. We chose the more aggressive estimates, which also comport with capacity utilization in a conventional meat processing facility, because we anticipate that the industrialization of plant-based meat production over the next decade will place pressure on the industry to most efficiently use the existing extrusion infrastructure.
80% of SPP is produced via LME (facilities A and B), and the remaining 20% of SPP is produced via HME (facilities C and D)	While many industry experts anticipate that LME will continue to dominate the market for plant-based meat due to its fundamental cost and throughput advantages, HME or other manufacturing approaches may emerge as the dominant design by 2030. These alternative manufacturing approaches will almost certainly have higher CapEx and operating costs, which means that our estimations will be on the low end if these technologies gain significant market share.
85% of SPP is produced in large facilities (facilities B and D), and 15% of SPP is produced in medium facilities (facilities A and C)	The assumption that 85% of SPP will be manufactured in large-scale facilities is directionally in line with estimates of large vs. small-scale processing volume of conventional meat. However, the plant-based meat industry may evolve differently. If the industry indexes toward a greater share of production from medium-scale facilities, the manufacturing footprint and global operating expenses will likely be greater than estimated in this analysis due to greater overhead per unit SPP production.
Operating cost excludes some factory overhead	While the operating cost analysis accounts for “miscellaneous expenses” in the form of property tax, rent, and packaging and shipping materials, facilities may incur a variety of additional costs, including building insurance, periodic equipment maintenance costs, fringe benefits, and other minor line items. These expenses are difficult to model in a generalized hypothetical model such as ours but typically account for a small share of a facility’s overall operating costs. Therefore, we expect our overall facility operating cost estimates may be modestly underestimated.
Cost, volume, and operational data is typically proprietary and not made available in reports or open access publications, making sourcing and verification difficult	Due to the proprietary nature of company and project financials, the small number of companies and facilities currently in operation, and the intense competition in the plant-based ingredients and end-product manufacturing sectors, locating accurate and comprehensive data is challenging. There is a lack of authoritative, open-access market research on supply and demand for key ingredients and production capacity. Thus, we expect that there may be errors based on estimations or anecdotal data sources that may skew the model and results. Whenever possible, we have checked our numbers and model assumptions with publicly available data or private sources for verification, but not all data has been independently verified by multiple sources.

5. Conclusions and next steps for model refinement

This analysis serves as a relatively simple first iteration of a model that will increase in complexity and accuracy as additional data are generated. In particular, building the remaining alternative protein sub-sectors, fermentation and cultivated meat, into the model and expanding consideration of additional plant-based meat manufacturing strategies will significantly increase the model's robustness and real-world applicability.

Our assessment is the first we are aware of to provide a macroscale view of the plant-based meat industry's future footprint, including both volumetric ingredient needs and extrusion production capacity requirements. It provides direction to investors, ingredient processors, equipment providers, policymakers, and plant-based meat manufacturers regarding the urgency, opportunity, and level of investment necessary to meet ambitious production targets and satiate anticipated consumer demand. Entrepreneurs can also use the report to estimate directional ingredient volumes and facility expenditure as they scale up from pilot to commercial-scale production of plant-based meat.

Soaring demand for plant-based meat will place substantial supply constraints on the industry. Ingredient and end-product production capacity will likely be the rate-limiting links of the plant-based meat supply chain in the coming decade. We estimate that it will take many hundreds of facilities and tens of billions of dollars in investment to develop a production infrastructure that can satisfy even modest shares of the global meat market.

It's important to note that there is ample precedent for this level of infrastructure investment expansion. Global renewable energy capacity investments **grew from $40 billion in 2004 to $282 billion in 2019**, a 14% compounded annual growth rate. During this period, renewable energy's share of final energy consumption **grew slightly from 17% to 18%** due to clean energy capacity increases only slightly outpacing total energy consumption growth. Like alternative proteins, clean energy is a cost-effective and more sustainable alternative to a massively scaled incumbent industry, has high upfront R&D and CapEx costs, and requires long-term, low-cost capital for infrastructure financing.

The industry should not underestimate the challenges and opportunities in expanding the plant-based meat supply chain to a scale rivaling that of conventional meat. However, it is worth noting that plant-based meat supply chains and production processes exhibit **several structural efficiency and flexibility advantages** over their conventional meat counterparts. These advantages can significantly improve the industry's resilience and reduce supply chain vulnerabilities, leading to a long-term competitive edge for producers of plant-based meat. These considerations—in addition to the profound benefits for the environment, public health, and food security—make these investments well worth it.

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Additional Acknowledgments

The authors would like to thank the following GFI team members for their insights.

Liz Specht for helping to develop the intellectual foundations of the analysis and providing a detailed review of the report.
Erin Rees Clayton for providing a detailed review of the report and offering tangible guidance on future model iterations.
Siddharth Bhide for sharing perspectives on the industry's use of LME and HME SPP processing strategies.
Priera Panescu for conducting a detailed review and providing expertise on the crops and ingredients highlighted in the report.

The authors are grateful to the following industry experts for their perspectives.

Preliminary models for estimating facilities and production volumes: Norm Sammons.
Feedback on the model behind the report: Mark Langley, Graham Markham, Natarajan Padmanabhan, and Dan Northrup.
Feedback on the report: Dave Reynolds.

About GFI

GFI is a 501(c)3 nonprofit organization developing the roadmap for a sustainable, secure, and just protein supply. We identify the most effective solutions, mobilize resources and talent, and empower partners across the food system to make alternative proteins accessible, affordable, and delicious.

Our vision:
A world where alternative proteins are no longer alternative.

Our programmatic priorities:

- **Science and Technology:** Advancing foundational, open-access research in alternative proteins and creating a thriving research and training ecosystem around these game-changing fields.
- **Corporate Engagement:** Partnering with companies and investors across the globe to drive investment, accelerate innovation, and scale the supply chain—all faster than market forces alone would allow.
- **Policy:** Advocating for fair policy and public research funding for alternative proteins.

Alternative proteins are a global solution to global problems. In addition to the United States, GFI works in places where we can have the greatest possible impact on our global food system: Asia Pacific, Brazil, Europe, India, and Israel.

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