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Challenges in Plant-Based Meat development in the Italian market between economic growth, consumer perception and umami taste

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I dedicate this thesis to the many challenges faced over these past five years.
To the long days spent balancing work and study, exhaustion and ambition.
To the unwavering willpower that carried me through the toughest moments.
And to myself, for proving that with determination, anything is possible.

ABSTRACT

The development of plant-based meat faces significant challenges at the convergence of economic growth, consumer perception and umami taste.

High production costs, limited scalability and competition with the well-established conventional meat industry present major obstacles to achieving price parity and widespread market adoption.

Additionally, consumer perception plays a crucial role: many potential buyers remain doubtful about the taste, texture and nutritional value of plant-based meat alternatives. Concerns over processing methods and ingredient transparency further influence purchasing decisions.

One of the most pressing scientific challenges is replicating the complex umami taste of meat, which is driven by compounds such as glutamates, nucleotides and Maillard reaction products.

Overcoming these challenges requires advancements in food science, including improved ingredient formulation, fermentation techniques and cost-reduction strategies.

This thesis explores innovative approaches to enhance both the economic and sensory viability of plant-based meat products. Successfully addressing these barriers is essential for driving Italian market growth, increasing consumer trust and ensuring the long-term sustainability of the plant-based meat industry.

CHAPTER I: INTRODUCTION

With the global population expected to surpass 9 billion by 2050, the challenge of sustainable development is becoming increasingly urgent. Today, billions of people around the world lack access to basic necessities: 2 billion people do not have safe drinking water, 3.6 billion lack proper sanitation and 2.3 billion do not have access to basic hygiene *(1).*

At the same time, global hunger is on the rise. Right now, 2.37 billion people either do not have enough food or are unsure when their next meal will come.

The growing demand for animal meat is now exceeding 300 million tons per year (figure 1). This demand is driving the expansion of livestock farming, which has important consequences:

- land use: 26% of the world's ice-free land is used for grazing and 33% of arable land is dedicated to growing animal feed *(2),*
- water consumption: 70% of the world's freshwater is used in livestock farming *(3),*
- climate impact: livestock farming contributes to 15% of global greenhouse gas emissions, more than the entire transportation sector, *(4),*
- biodiversity loss: 20% of the world's grasslands are deteriorating and many livestock breeds are at risk of extinction *(2).*

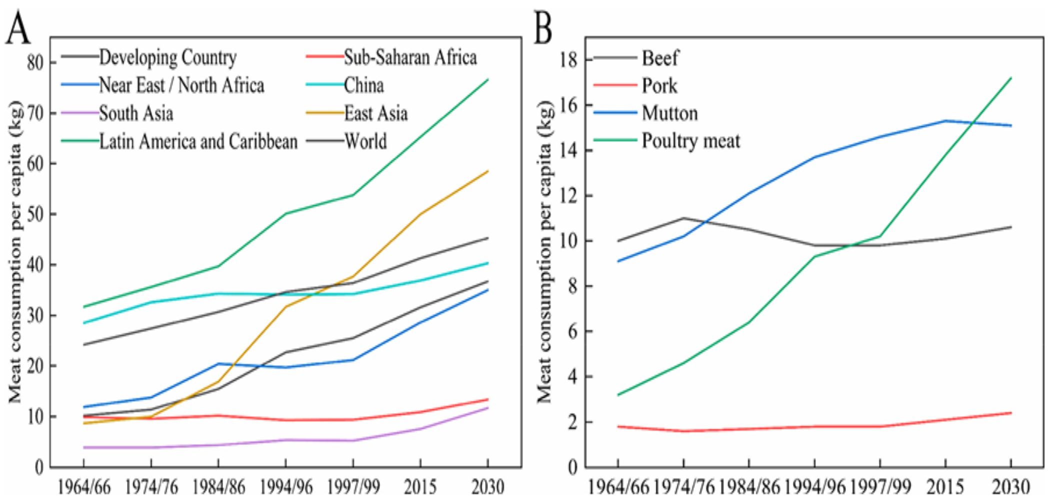


Figure 1. Meat consumption trends. (A) Meat consumption per capita by region and globally. (B) Per capita consumption of different species of meat. Data were obtained from an FAO perspectiv [14]

One promising solution to these challenges is meat analogues, foods designed to replace traditional meat without sacrificing taste or nutrition. Meat alternatives can significantly reduce land and water use, lower greenhouse gas emissions and eliminate the need for antibiotics in food production.

There are two main types of meat analogues:

1. Plant-Based Meat: made from plant proteins, fats and carbohydrates, with added vitamins and minerals. This type has been around for a long time and is more affordable and widely accepted by consumers. *(5)*

2. Cell-Based Meat: called lab-grown meat, this is produced from animal stem cells in a controlled environment, creating meat with real muscle and connective tissue. *(6)*

For now, plant-based meat is expected to lead the industry and may become a more viable option for those who want real meat without the ethical and environmental downsides.

So, switching to plant-based meat offers huge benefits for the environment, economy and animal welfare:

1. lower costs: the main ingredients (soybeans, peas, and wheat) are 3.8 to 12.7 times cheaper than traditional livestock (cattle, pigs and chickens),

2. environmental impact: plant-based meat production uses less energy, produces fewer greenhouse gas emissions, requires less land and water compared to animal farming,

3. health benefits: people who replace animal meat with plant-based meat had a lower risk of cardiovascular disease (A. Crimarco et al., 2020 - study from Stanford School of Medicine),

4. animal welfare: choosing plant-based meat eliminates the need for raising, transporting and slaughtering animals, addressing ethical concerns in food production.

Switching to meat alternatives could be a game-changer for the planet. By embracing these advantages, we can help protect the environment, improve public health and create a more sustainable food system for future generations *(7).*

1.1 Plant-based Meat

Plant-based meat (PBM) is revolutionizing the way we think about food.
It is made from plant extracts, it contains essential nutrients such as vitamins, minerals and trace elements.

The goal of plant-based meat is to replicate the taste, texture and appearance of traditional animal meat. Older versions of meat substitutes often fail, breaking down too easily in the mouth and lacking the fibrous texture of real muscle tissue. Recent advancements have greatly improved the texture and overall experience, making plant-based meat more like the real thing.

Scientists are now developing methods to reconstruct plant proteins to better mimic the muscle fibers of animal meat. Research shows that high-moisture meat analogues have better elasticity, structure and strength compared to their low-moisture counterparts *(8).*

Plant-based meat is created through a scientific process that transforms plant proteins into a meat-like structure:

1. breaking down proteins: plant proteins are heated at high temperatures, causing their globular structures to unfold,
2. rearranging the molecules: under heat, pressure and shear forces the molecules align into a continuous molten state,
3. forming fibers: as the protein cools, it cross-links into fibrous structures, creating a texture like real meat *(9).*

As technology advances, we can expect even better-tasting, more realistic plant-based meat products that will further encourage consumers to make the switch.

Innovations in food technology are helping close the gap between plant-based and animal meat. Some of the most important processing methods include *(10) (Figure 2):*

- spinning technology: an early method that makes protein fibers by spraying a protein solution into an acid bath. It Includes wet spinning (low efficiency, high waste) and electrospinning (produces nanoscale fibers but requires expensive equipment). Electrospinning is replacing wet spinning due to reduced chemical waste.
- extrusion technology: a process that applies heat, pressure and shear forces to realign plant proteins into fibrous structures like muscle tissue.
- shear cell technology: it uses shear force to align plant proteins into fibrous structures like meat. It is also more precise than extrusion, consumes less energy and offers better texture control.
- 3D printing: it is used to control the structure and layering of plant-based proteins for a more realistic texture.

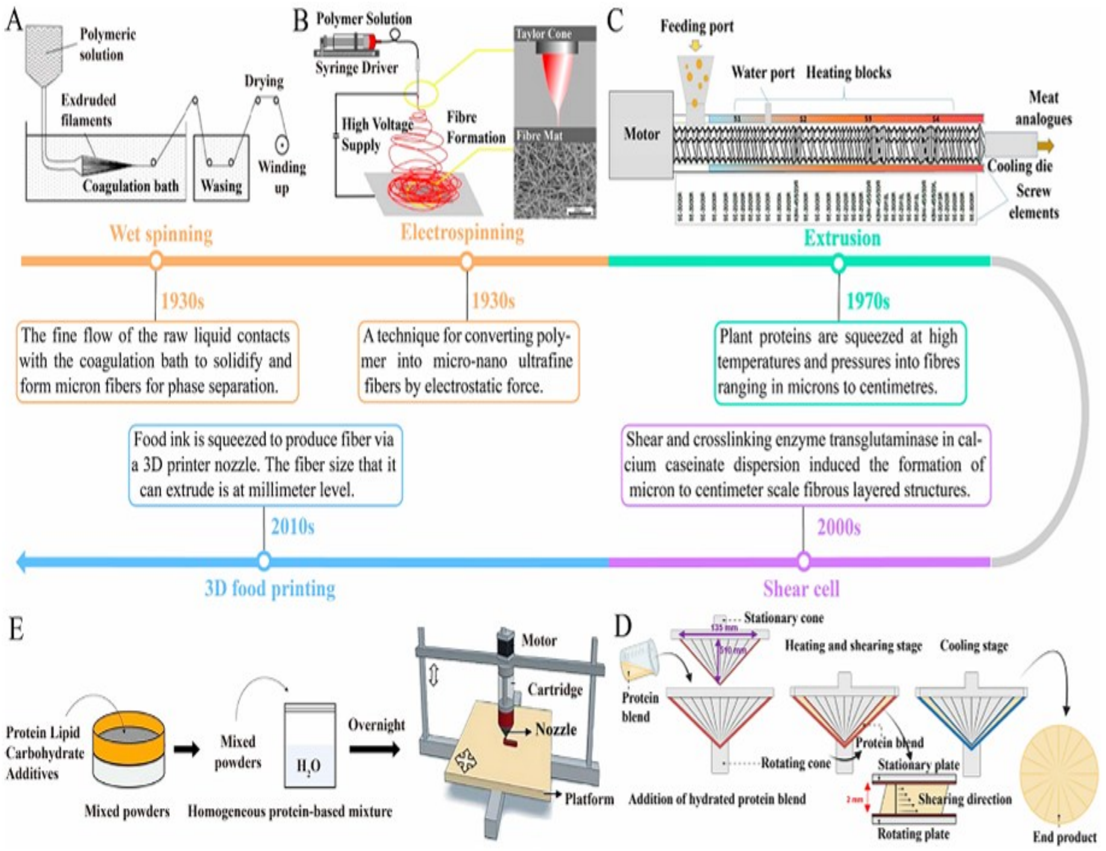


Figure (2) Development of plant-based meat processing methods. (A) Process flow diagram for manufacturing plant protein composite fiber by wet spinning;[72] (B) process flowchart for manufacturing plant protein composite fibers by electrospinning;[35] (C) process flow diagram for manufacturing plant protein by extrusion;[73] (D) process flow diagram for manufacturing plant protein by shear cell;[40] (E) process flow diagram for manufacturing plant protein by 3D printing.[74,75]

The quality of meat alternatives (consistency, taste and color) depends largely on ingredient selection. These products typically contain:

- 50–80% water,
- 4–20% non-textured protein,
- 10–25% vegetable-based textured proteins,
- 3–10% flavor-enhancing additives,
- 0–15% fats,
- 0–5% coloring agents,
- 1–15% binding agents.

When combined, these ingredients create the sensory and textural characteristics expected in meat substitutes (Sha & Xiong, 2020).

Water plays a crucial role in meat alternatives, not only keeping costs low but also contributing to juiciness, softening the texture and aiding in emulsification.

To improve water-holding capacity, manufacturers use protein concentrates from soy, wheat gluten or adhesive agents (starches and hydrocolloids).

Proteins, added primarily for nutrition, help shape the texture, taste and overall appearance of the product. In fully vegetarian or vegan products they completely replace meat with mimic its texture (Singhal et al., 2016).

However, meat extenders (protein ingredients mixed with meat) do not fully replicate the texture, appearance or flavor of real meat on their own. True meat alternatives, on the other hand, are designed to closely resemble whole meat in form, texture and taste without containing any animal-derived components (Kumar et al., 2017). These proteins have also other purposes: oil retention, solubility, emulsification, gelation and foaming, all of which are essential for creating meat-like textures.

The functional properties of proteins largely depend on their amino acid composition, chemical structure and secondary or higher-level structures. Additionally, environmental factors such as temperature, pH and ionic strength can influence protein structure and functionality, affecting the quality of the final product (Singhal et al., 2016).

Among plant-based protein sources, as mentioned before, soy protein is the most widely used due to its desirable characteristics and cost-effectiveness. However, other oilseed proteins, such as those derived from peas, lentils and chickpeas, have also been explored for meat alternatives (Grabowska et al., 2016).

In addition to soy and oilseed proteins, cereal-based proteins from sources like maize, rice, wheat and defatted bean flours are also utilized. These plant proteins are commonly processed into protein concentrates or isolates to improve their functionality in meat analogs.

Soy protein is commonly used in meat alternatives in the form of soy flour, soy protein isolates or soy protein concentrates. It is favored for its functional properties, including water-holding, gelling, fat absorption and emulsification.

Among soy-based products, soy flour is the least processed, available in different varieties such as toasted, full-fat, and defatted flour. Defatted soy flour, produced by grinding defatted soy flakes, contains about 50% protein. In contrast, soy protein concentrates and isolates undergo further processing to increase protein content. Concentrates, produced using liquid alcohol extraction, contain around 70% protein, while isolates, extracted using alkaline solution and acid precipitation, have a higher purity of about 90% protein *(11)*.

Soy protein isolate is particularly valued for its bland flavor and light color, making it an ideal base for meat analogues. However, while high purity is not always necessary for meat substitutes, some additional components in soy protein can be beneficial in improving the overall product.

Wheat gluten is another essential protein source for meat substitutes due to its ability to form fibrous protein layers. This characteristic makes it particularly useful in creating meat-like textures.

Hydrogen bonds, disulfide bonds and hydrophobic interactions help form and stabilize these structures, which is crucial in maintaining the texture of meat alternatives *(12).*

Legumes, such as lentils, chickpeas, lupins, peas and various beans, have been studied for their ability to form gels, foams and emulsions, making them valuable ingredients in meat substitutes.

Among these, pea protein has emerged as the most viable option for meat substitutes, especially when structured using high-moisture extrusion. Pea-based products tend to be softer than soy-based alternatives, but their structural strength can be enhanced by modifying protein-hydrogen interactions *(13)*.

Research has also explored the functional properties of lentil, lupin, and chickpea proteins, which have shown excellent foaming and emulsification stability. Specifically, pea protein isolates have demonstrated the ability to form fibrous meat-like structures, with higher protein content leading to increased hardness and chewiness due to enhanced protein cross-linking (Berghout et al., 2015; Ladjal-Ettoumi et al., 2016).

Proteins from **oilseeds**, such as canola and rapeseed, have also gained attention due to their emulsification and foam-forming properties.

Under high pressure or heat, rapeseed proteins can undergo gelation, forming meat-like textures.

Canola protein, which consists mainly of globulins and albumins, can form cohesive gel-like structures in the presence of salts. Studies have shown that when canola protein is combined with k-carrageenan, it forms strong and flexible protein networks, indicating its potential as a structural agent in meat alternatives *(14)*.

While plant-based proteins provide the structural foundation for meat alternatives, the role of **fats** and **oils** is equally crucial.

Most meat replacements contain lower fat content because they are typically made from defatted materials. However, the addition of oils or fats during processing plays a significant role in the formation of fibrous structures in plant-based meat.

Studies have shown that oil levels exceeding 15% during extrusion processing can lubricate materials, disrupt macromolecule alignment and negative impact on the texture of the final product, making it less meat-like (15).

Despite these challenges, incorporating vegetable oils and fats in plant-based meats has notable benefits, such as improving flavor, softness and mouthfeel.

Commonly used plant-based fats and oils in meat substitutes include: canola, rapeseed, soybean, palm, coconut, sunflower. These oils contribute to the richness and overall taste of plant-based meat, making them essential ingredients in product formulation.

Fat retention, better texture and structural integrity are helped by **binding agents**. They can be derived from both plant-based and animal-based sources.

Common binding agents include:

- wheat gluten: it provides adhesion and elasticity,
- soy protein isolates, concentrates and flours: act as structural enhancers,
- egg albumen: it improves adhesion and enhances protein content,
- xanthan gum, carrageenan and other polysaccharides (guar gum, cellulose, pectin): used as extenders and stabilizers.

Binding materials have been used in texturized products since the 1980s, with formulations including *(16):*

- Milk and water (10–20%)
- Gluten (1–5%)
- Albumin (10–20%)

The effectiveness of binders depends on their concentration, as well as the type of plant-based proteins used.

Beyond texture and structure, **flavor** is another critical factor in developing plant-based meats.

One of the biggest challenges in plant-based meat is replicating the taste of real meat. Consumers expect a rich, savory flavor similar to traditional meats, which is achieved by using flavor precursors, spices and iron complexes such as ferrous chlorophyllin or heme-containing proteins *(17).*

During processing and heating, chemical changes occur in the raw materials, altering flavor perception. However, high pressure and temperature in processes like extrusion can cause:

- loss of volatile flavor compounds,
- interactions between salts, acids and sugars that affect texture and taste,
- Maillard reactions, which create new flavored compounds from amino acids and sugars.

Key elements used to mimic meat flavors include:

- reducing sugars (xylose, glucose, ribose, fructose),
- amino acids (cysteine, proline, lysine, serine, methionine, threonine),
- nucleotides and thiamine for depth of flavor.

Color is also a key factor in consumer perception of meat substitutes. Since proteins like soy and wheat gluten have yellow-brown hues, they need **coloring agents** to mimic the natural appearance of raw and cooked meat.

Common thermostable coloring agents include:

- caramel colors,
- annatto and malt,
- cumin, turmeric and carotene.

A meat-like color change occurs in conventional meat when nitrosylmyoglobin converts into nitrosylhemochrome, producing a red-to-pink transition. To replicate this in plant-based meat, heat-labile colorants and reducing agents are added *(18).*

Popular colorants for Meat Substitutes:

- beetroot extract and betanin: to achieve a red/pink color,
- reducing sugars (dextrose, mannose, arabinose): to promote

  browning reactions similar to the Maillard reaction,
- maltodextrin and hydrated alginate: to prevent color migration and

  enhance color retention.

Two main techniques are used to integrate colorants into plant-based meat:

1. pre-mixing with proteins before structuring,
2. injecting colorants during the extrusion process.

However, achieving the exact color of traditional meat remains a challenge due to differences in pH stability between plant-based ingredients and real meat. This issue can be addressed by adjusting the pH with acidulants such as citric acid, acetic acid and lactic acid *(19).*

1.2 Evolution of Plant-Based Meat

The history of meat substitutes shows how humanity has been seeking protein alternatives to meat since ancient times. Products like tofu and tempeh have been consumed in Asia for centuries, but what we now call "fake meat" is a much more recent development, originating primarily at the end of the 19th century.

John Harvey Kellogg's initiative with Nuttose in 1896 is a key example of how the food industry began exploring solutions to replace meat in response to various factors, such as food scarcity during wartime or ethical reasons related to vegetarianism.

In the U.S. early products like Protose (1899) are some of the first examples of commercially available "fake meat." These products were sold by mail order and marked an important step in the evolution of this market.

Over the years, interest in plant-based meat substitutes grew, especially among vegetarian communities and those seeking affordable alternatives to meat during times of crisis. In 2009 with the founding of Beyond Meat, plant-based meat really began to take off. The launch of the Impossible Burger in 2016 was another major milestone, aiming to replicate the taste, texture and cooking properties of real meat. In the following years, the market exploded: fast food chains like Burger King and KFC, as well as brands like Nestlé and Kellogg’s with "Incogmeato" line, began offering plant-based burgers and other products.

The 3D printing of plant-based steaks, as done by "Redifine Meat" in 2018, represented another innovative step, opening new technological possibilities for creating plant-based meat.

Today, plant-based meat is not just an alternative for vegetarians and vegans but a significant trend in the global market, driven by interest in more sustainable diets and health benefits.

Looking at the current landscape, "fake meat" is now a well-established reality, and it's interesting to see how innovation continues to push the boundaries of what can be done with plant-based ingredients.

While plant-based meat products have spread and improved over time, the food industry related to non-animal-based meat has also made significant strides, providing a wide range of viable alternatives for other "less obvious" meat items *(20).*

CHAPTER II: ECONOMIC IMPACT OF PLANT-BASED MEAT

The growing interest in plant-based meat has led many companies to develop alternatives to traditional meat. Brands like Beyond Meat and Impossible Foods are pioneers in this revolution, offering plant-based burgers that replicate the taste and texture of meat using innovative ingredients such as pea protein and plant-based heme.

Another successful example is Vivera, which launched a vegan fillet and sold approximately 40,000 units in just one week.

Nestlé has also invested in this sector with its Garden Gourmet brand, featuring plant-based burgers and nuggets. Similarly, Unilever acquired The Vegetarian Butcher, expanding its range of meat-free products.

Even companies traditionally associated with meat production have entered the plant-based market. Tyson Foods, one of the world's largest meat producers, developed the Raised & Rooted line, while JBS, the Brazilian meat giant, launched Planterra Foods with its OZO brand.

This trend is also evident in the retail and the restaurant industry. Chains like Burger King offer the Impossible Whopper, while McDonald's introduced the McPlant, developed in collaboration with Beyond Meat, to meet the growing demand for vegan options.

Italy is one of the largest potential drivers of market engagement, particularly in novel sectors such as alternative proteins.

This passage highlights the growing period of Italy's plant-based food market, driven by health-conscious consumers and the importance of legumes in Italian diets. Italian companies are expanding internationally, leveraging their high-quality, certified raw materials with a focus on sustainability and minimal ingredients.

Domestically, there is a notable decline in meat and dairy consumption, reflecting changing dietary preferences.

Italy is now Europe’s third-largest plant-based food market, with sales growing 21% from 2020 to 2022, surpassing 600 million euros, according to The Good Food Institute. This upward trend presents a major opportunity for institutional support to further strengthen Italy’s role in the plant-based movement *(21)*.

2.1 Market and consumption of plant-based meat in Italy

This report (Figure 3) shows the trends in retail sales across seven plant-based product categories (meat, milk and drinks, cheese, yoghurt, ice cream, dessert and cream) in Italy between 2021 and 2023, based on data from Circana.

Italy plant-based sales summary by category, 2021-2023

	Sales value			Unit sales			Sales volume		
	2023, € million	2022-23 change	2021-23 change	2023, million units	2022-23 change	2021-23 change	2023, million kg	2022-23 change	2021-23 change
Meat	199.0	12.8%	24.2%	75.8	10.1%	15.1%	14.6	7.6%	11.4%
Milk and drinks	315.1	4.6%	10.9%	159.2	0.0%	2.4%	151.5	-0.4%	2.1%
Cheese	15.2	39.9%	79.6%	6.7	28.5%	71.2%	1.0	33.1%	77.3%
Yoghurt	57.0	7.5%	10.2%	39.9	1.9%	2.0%	9.4	-0.8%	-1.9%
Ice cream	37.0	5.2%	17.3%	10.3	-4.4%	1.8%	3.4	-4.7%	0.9%
Dessert	9.9	3.9%	8.0%	5.8	-4.3%	-4.5%	1.7	-3.4%	-3.0%
Cream	7.5	7.6%	11.2%	5.2	-2.1%	-8.3%	1.4	-4.0%	-11.6%
Total	**640.8**	**8.0%**	**16.1%**	**302.9**	**2.8%**	**5.8%**	**183.0**	**0.2%**	**2.6%**

Figure 3: EN - Italy plant-based food retail market insights (October 2024) (22)

Between 2021 and 2023, the annual sales value of plant-based meat in Italy increased by 24.2% to €199 millions. Over the same period, unit sales increased by 15.1% to 75.8 million units and sales volume increased by 11.4% to 14.6 millions kg.

The Circana data for plant-based meat in Italy includes some non-analogue products such as vegetable croquettes and vegetable burgers. It was not possible to fully separate out only those products that aim to mimic the taste and texture of meat. The plant-based meat category does not include tofu, tempeh or seitan.

For comparison, the total sales value of those three products increased by 20% between 2021 and 2023, while sales volume increased to 14.6% *(22)*.

Partial-year data for 2024 (from January to April) shows a continued rise in sales of plant-food, with sales value increasing by 10.4%, unit sales increasing by 13.6% and sales volume increasing by 10.5% relative to the same time period in 2023 *(22)*.

2.2 Main firms involved in

BEYOND MEAT

Beyond Meat has been one of the pioneering companies in the plant-based food sector. Founded in 2009, the company began selling its products in the United States the same year. Over the years, it has expanded its product range significantly, offering a variety of items such as burgers (including the smash version), chicken, meatballs, sausages, ground meat (mince), and ready-to-eat meals. Their products are widely available both in supermarkets and online, making them accessible to a large audience.

The plant-based meat is primarily made using pea protein, which has become a key ingredient in many plant-based products found in stores, including major Italian supermarkets like Esselunga. Beyond Meat has played a key role in making plant-based alternatives more mainstream and convenient for consumers.

In addition to offering a variety of meat substitutes, Beyond Meat has also raised awareness about the environmental and health benefits of plant-based eating, helping to reduce the ecological impact of traditional meat production.

IMPOSSIBLE FOODS

Founded in California, Impossible Foods quickly established itself as a leader in the U.S. plant-based market. In 2016 with the debut of the Impossible Burger, the firm amazed people by its ability to "bleed" like real meat, mimicking the texture and flavor of beef in an impressive way. Following the success of the Impossible Burger, the company expanded its product range to include sausages, chicken nuggets, ground meat, and many other plant-based products.

Impossible Foods has focused on creating products that replicate the sensory experience of eating animal-based meat, using ingredients like soy protein and the key molecule heme, which is responsible for the "bleeding" effect. With a strong commitment to reducing the environmental impact of meat production, Impossible Foods has become a significant player in the movement toward more sustainable food options.

PLANTED

This Swiss company, specializing in plant-based meat, has a wide range of alternatives and is also present in Italy. Customers can find its products on platforms like Cortilia, a home delivery service available not just in Milan but also in other cities. Additionally, the company collaborates with Kebhouze, where its plant-based kebab is featured on the menu. The products can be shipped across Italy, selected directly from the company's website.

On the portal, you'll find plant-based products that resemble chicken, available in different forms such as skewers, strips, or natural pieces. They also offer "pulled planted," a plant-based alternative to pulled pork, with flavored variations like BBQ or herbed seasoning. Other items include breaded cutlets and plant-based kebabs.

UNCONVENTIONAL

Unconventional Burger is an Italian-made plant-based burger born from the work of Italian researchers, with its creation attributed to Mauro Fumagalli from the Research and Development Division of the Granarolo Group. He created a product with a shorter ingredient list (just 12 ingredients, compared to the 23 commonly found in similar American products).

Unconventional Burger is 100% plant-based, high in protein, and free from palm oil and preservatives. The ingredients include soy protein, vegetable oils (such as corn and coconut), starches (potato and tapioca), citrus fiber, and beetroot extract. The focus is on mimicking the taste, texture, color and cooking properties of meat as closely as possible, making it a compelling alternative for those seeking a plant-based burger option with a meat-like experience.

2.3 Consumer trends

The research conducts by ProVeg International (food awareness Organization) shows that meat consumers in Italy have notable shifts in their meat-consumption habits: 59% saying that they reduced their meat intake in the past year. Of these respondents, 17% decreased their meat consumption by 50% or more, while 42% made slight reductions. On the other hand, 33% report no change in their meat consumption, while 9% say that they have increased their meat intake. Beef and pork have seen the most substantial reductions, accounting for 34% and 26%, respectively *(23)*.

The main motivation behind this shift is health, cited by 54% of respondents, and other reasons include:

-Animal welfare: 27%

-Concerns over antibiotics in meat: 17%

Italian consumers highly trust health, nutrition and government websites, making these platforms crucial for engaging and educating the public about plant-based foods.

Additionally, social media plays a significant role in shaping food choices, with:

- 26% frequently read opinions about food products,
- 25% and 27% search for food information when dining out or traveling,
- 30% share food photos and receive updates on discounts and promotions.

This strong digital engagement presents a valuable opportunity for brands and institutions to promote plant-based alternatives through trusted online sources and social media strategies *(23).*

Ranking of Online Media by Trustworthiness:

1. Health and/or nutrition-society websites
2. Search engines (e.g. Google)
3. Government websites
4. NGO websites
5. Food company websites

2.4 Future of plant-based meat market

The global market for meat alternatives is projected to reach $8.1 billion by 2026, with a compound annual growth rate (CAGR) of 7.8% from 2019 to 2026. This growth is largely attributed to consumers becoming more aware of the health risks linked to traditional meat products and the need for better protein intake. Europe leads the global market with the highest share (51.5%), followed by Asia Pacific (11.8%), Latin America (6.3%), North America (26.8%), and the Middle East and Africa (3.6%). A survey conducted in the United States, China and India found that consumer approval of meat alternatives is highest in China (95.6%) and India (94.5%), compared to the U.S. at 74.7% *(24).*

The expansion of the market has been driven by the rapid growth of the food service industry and aggressive marketing strategies by companies promoting meat substitutes. Additionally, increasing health concerns in emerging markets have influenced consumer decisions.

In the future, plant-based meat products are expected to have a significant impact on conventional distribution chains, potentially giving rise to what is known as the "substitution effect." This phenomenon could lead to a gradual reduction, or even a complete replacement, of conventional food supply chains in favor of plant-based meat alternatives.

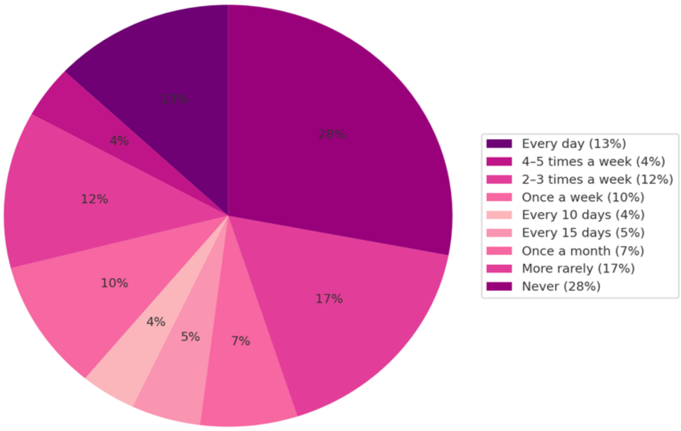
However, if this change occurs, the initial effects on the food economies of various countries are likely to be very negative: low-income or underdeveloped nations could face significant challenges, with potential impacts on employment, food security and income levels. In many emerging economies, traditional agricultural supply chains are a primary source of labor and welfare and these could suffer considerably from such a shift.

To address this scenario, it is essential that the transition to a more sustainable food system be managed and supported appropriately. The political class will play a crucial role in this process, needing to promote policies that balance innovation with the need to protect vulnerable economies. The approach should be inclusive, with policies supporting the retraining and conversion of agricultural supply chains, creating opportunities in new economic areas without compromising food security and the well-being of the most vulnerable populations (*25*).

CHAPTER III: MAIN FACTORS THAT INFLUENCE PLANT-BASED MEAT PURCHASE

The increasing consumption of plant-based food in Italy, now involving approximately 22 million people, represents a significant shift that extends beyond vegan and vegetarian consumers *(26)*.

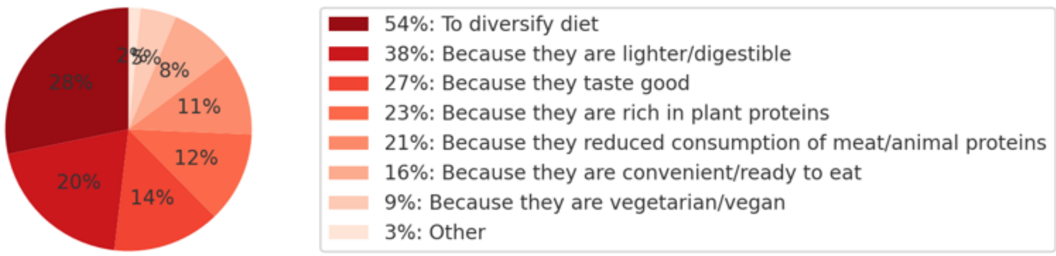
This trend also includes flexitarians; they are individuals who are open to modifying their dietary habits to better balance their intake of animal and plant-based products.



consumo di prodotti vegetali da parte dei consumatori italiani

Fonte: lodefood (https://lodefood.com/prodotti-vegetali-in-gdo)

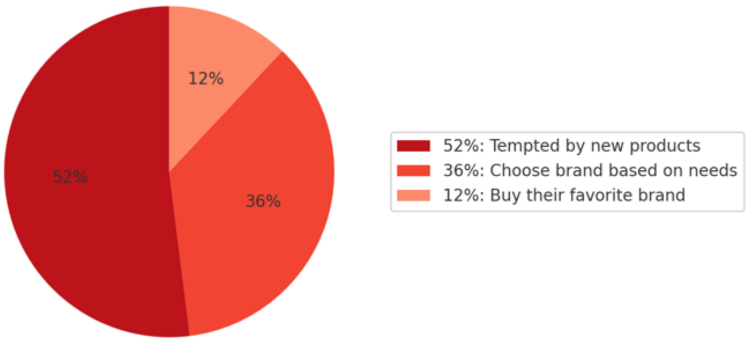
The growing interest in plant-based food is driven by multiple factors, including the desire to diversify one's diet, the perception of greater lightness and digestibility of these products, and their appealing taste.



Fattori che determinano il consumo di prodotti plant-based da parte degli italiani

Fonte: lodefood (https://lodefood.com/prodotti-vegetali-in-gdo)

A study conducted by Bva Doxa on a sample of 300 consumers provides a more detailed insight into Italians' increasing preference for this emerging dietary trend. The findings offer valuable information for stakeholders in the food and beverage industry, enabling them to adapt and develop products that align with evolving consumer needs (*26)*.



Comportamento d'acquisto degli italiani davanti gli scaffali con i prodotti plant-based

Fonte: Iodefood (https://iodefood.com/prodotti-vegetali-in-gdo)

3.1 Availability and limited product variety

The availability of plant-based products in supermarkets, cafés and restaurants remains limited compared to their animal-based one. This is primarily due to relatively low consumer demand, which restricts the range of options offered.

In many restaurants and cafés, finding vegan alternatives can be challenging, especially outside of major cities or specialized establishments. While larger urban centers tend to have a wider selection, plant-based choices are still far from being as easily accessible as traditional meat-based options.

The availability of most plant-based meat products came from chilled products, which accounted for nearly 70% of the total sales volume. Frozen options followed at 30.1% in 2023, while shelf-stable (ambient) products made up just a tiny fraction at 0.2% *(27).*

When it comes to product formats, plant-based burgers were by far the most popular choice, making up 61.5% of total sales. Whole cuts, such as plant-based steaks or fillets and smaller pieces like strips, cubes and sticks each accounted for 13.3% of sales (in year 2023). These figures highlight consumer preferences, with a clear lean toward familiar and convenient options like burgers *(27).*

3.2 Prices

Between 2021 and 2023, the average price per kilogram of plant-based meat in Italy rose by 12%. However, in early 2024, prices saw a slight decline reflecting broader trends in food market inflation. This suggests that the plant-based sector is not immune to the economic factors influencing the overall food industry *(27) (Figure 4)*.

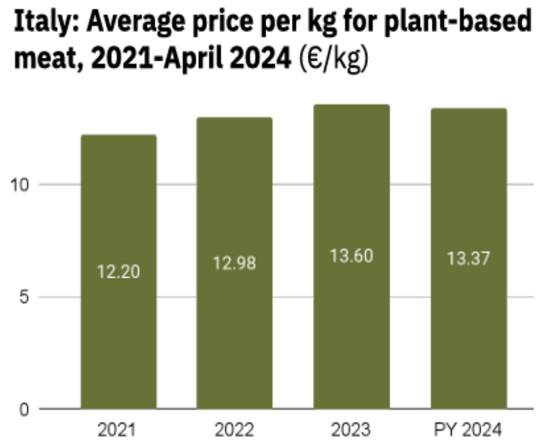


Figure 4: EN - Italy plant-based food retail market insights (October 2024)

According to Nielsen data, plant-based meat remains significantly more expensive than its traditional counterparts. On average, it costs twice as much as beef, more than four times the price of chicken and over three times the price of pork per kilogram. However, this price gap is expected to shrink as production volumes of plant-based alternatives continue to grow.

Price plays a crucial role in consumer purchasing decisions. This puts plant-based meat at a disadvantage, as it remains more expensive than conventional meat options. With rising inflation, fewer consumers are willing to pay a premium for plant-based products. In fact, the willingness to pay extra for plant-based meat has dropped by nine percentage points since 2021 and remains lower than the willingness to pay more for high-quality fresh traditional meat *(28).*

The higher price of plant-based options remains a major barrier, particularly for undecided consumers who are open to change but hesitant due to cost concerns.

3.3 Cultural aspects

Psychological and social motivations, such as personal values and beliefs, play a crucial role in shaping consumer demand of plant-based meat. Social factors like ethnicity, religion, class and gender significantly influence dietary choices, as they directly impact an individual's experiences, psychological perspectives and social identity. However, research suggests that personal values and beliefs tend to be more influential in the decision to adopt a vegetarian diet than demographic or economic factors *(29).*

Individuals who regularly consume animal products tend to have strong positive associations with meat, often linking it to luxury, status, taste and good health, as well as to festive and celebratory occasions. Conversely, positive reactions toward plant-based meat alternatives are most observed among those who are already accustomed to consuming them.

Research suggests that plant-based meat is consumed more frequently by women than men. One possible explanation is that cultural factors play a significant role in shaping dietary choices, with men being more resistant to adopting vegan and vegetarian products in favor of traditional meat-based options *(30)*.

The link between masculinity and meat consumption has deep historical and sociological roots.

In this context, men may consume meat not only for its taste or nutritional value but also to reinforce their masculine identity, particularly when it is threatened.

While plant-based diets are gradually gaining acceptance among men, societal stigma remains strong. This is particularly evident in Italy, where environmental and plant-based dietary awareness lags behind other European countries.

The perception of plant-based meat as a "vegetable product" and, therefore, "not masculine enough" remains prevalent, especially among young men. Studies indicate that some men feel discomfort or even shame when purchasing or consuming plant-based meat in the presence of others.

However, as societal expectations shift, an increasing number of men are beginning to challenge traditional dietary norms, signaling a gradual but meaningful change in attitudes toward plant-based eating.

3.4 Taste

Flavor plays a pivotal role in consumers' decisions to choose plant-based meat products. The success of these alternatives heavily depends, as already mentioned, on their ability to replicate the taste, texture and aroma of traditional meat, making flavor a critical factor in consumer acceptance.

One of the primary challenges in developing plant-based meats is mimicking the unique flavor profile of animal meat. Traditional meat flavors develop through complex chemical reactions, such as the Maillard reaction, which are challenging to replicate with plant-based ingredients. To overcome this, manufacturers incorporate flavor additives to both impart the desired taste and mask any undesirable flavors from plant proteins. For instance, the introduction of soy leghemoglobin, a molecule like heme iron, has been utilized to effectively mimic the color and flavor of meat.

Achieving a taste that closely resembles traditional meat is essential for consumer acceptance and market success. In particular, the umami taste plays a significant role in the acceptance of plant-based meats. Umami, often referred to as the "fifth taste," is essential for mimicking the savory depth of animal-based meat. This taste, which is naturally present in meat due to amino acids like glutamate, is a critical factor in creating plant-based alternatives that appeal to consumers *(31) (Figure 5).*

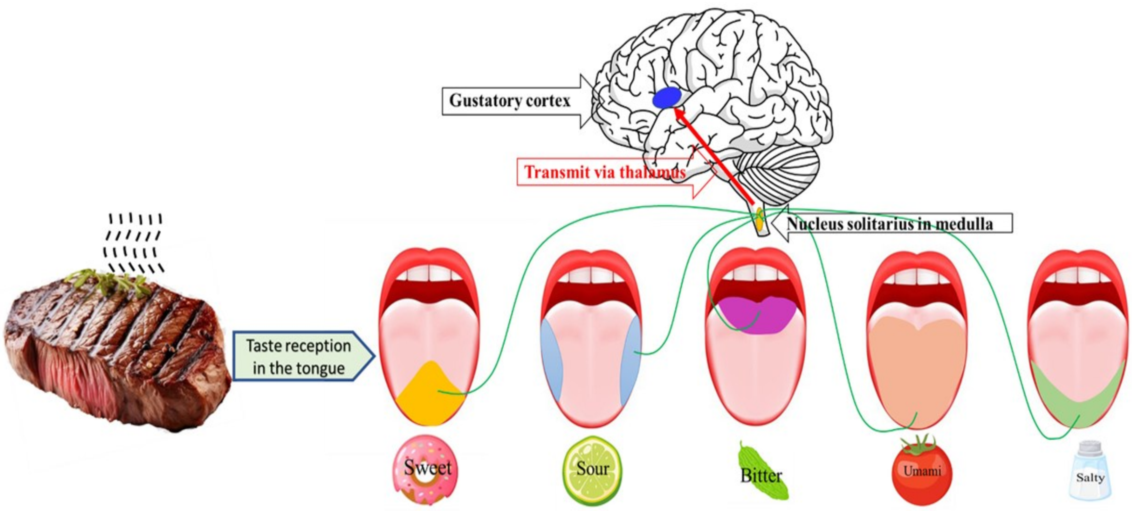


Figure 5: Umami reception site in tongue

CHAPTER IV: UMAMI

One of the biggest reasons we eat is for enjoyment. When we enjoy what we eat, it can contribute to both mental and physical well-being, as long as we maintain a balanced diet.

The primary components of meals are meant to provide essential nutrients and energy, but they also need to be enjoyable to eat. People's perceptions of deliciousness can vary depending on their upbringing and cultural background, but there's a common thread across global cuisines: the presence of umami.

Umami-related compounds like glutamate, inosinate and guanylate are widely found in tasty dishes across different regions, ethnic groups and culinary traditions, suggesting they play a crucial role in making food more appealing.

Even though umami is widely recognized for making food more enjoyable, little research has been done to truly understand why it has this effect. While many food scientists believe umami itself plays a key role, there's still much to uncover. By diving deeper into how umami enhances the palatability of food, we can improve the taste of modern food products, such as plant-based burgers and cultured meats.

4.1 Definition of umami taste

Umami's story dates to about 110 years ago, in 1908, when a Japanese chemist named Kikunae Ikeda made a groundbreaking discovery. Ikeda, a professor at the Imperial University of Tokyo, had spent two years studying in Germany, where he worked in the laboratory of chemist Friedrich Wilhelm Ostwald. At the time, scientists only recognized four "pure" tastes: sweet, sour, salty and bitter.

Ikeda was particularly intrigued by the flavor of *dashi*, a Japanese seaweed broth. He noticed that it contained a unique taste that didn't fall under the traditional categories. He believed this taste was different from sweet, salty, sour or bitter and that it could be found not only in *dashi* but also in meat and fish dishes. To investigate further, Ikeda aimed to isolate the main taste compound from *Laminaria japonica*, the seaweed used in *dashi*. After conducting numerous procedures like aqueous extraction, removing contaminants such as mannitol and sodium, and lead precipitation, Ikeda successfully isolated pure crystals of a substance he identified as glutamic acid *(32)*.

Ikeda gave this new taste the name *umami*, derived from the Japanese word *umai*, meaning "delicious." He noted that the flavor of glutamic acid crystals was distinct, lingering after the sourness faded. The salts of glutamic acid (sodium, barium, calcium and potassium) have strong umami flavor. This was a significant moment in food science, as it confirmed the existence of a new, previously unrecognized basic taste.

So, umami began a "basic" taste.

One of the most widely accepted sets of rules came from Kurihara, who shared them during the *Umami: A Basic Taste* symposium *(32)*. Here's what he said a basic taste should have:

1. It should show up in a lot of different foods.
2. It can't be a mixture of other basic tastes.
3. It needs to stand on its own, which means it should be proven to be independent from the other tastes in scientific studies.
4. There needs to be a specific receptor for it.

Since *umami* ticks off all these boxes, we can definitely call it the fifth basic taste.

4.2 Role of monosodium glutamate (MSG)

Ikeda's research revealed that glutamate was particularly powerful in small amounts. The recognition of threshold (concentration at which it is first detected) for Monosodium Glutamate (MSG) was much lower than that for sucrose (sugar) or salt. But as more glutamate was added, the taste intensity increased only slightly, unlike other tastes, which become stronger at higher concentrations.

Ikeda also speculated that our preference for umami might have an evolutionary purpose. Since glutamate is found in protein-rich foods, he suggested that humans may have developed a preference for umami to help identify nutrient-rich food sources. This theory implied that umami could signal the presence of valuable protein, encouraging us to consume more protein-rich foods.

Glutamate, the ionic form of L-glutamic acid, is an amino acid found in many proteins. In the production of monosodium glutamate (MSG), bacteria ferment molasses or starch hydrolysates to produce L-glutamic acid, which has a naturally sour taste due to its acidic nature. To neutralize this acidity, sodium hydroxide is added, converting it into sodium L-glutamate: the form responsible for the well-known umami taste *(32).*

4.3 Perception of umami

Additional support for umami being a distinct basic taste comes from molecular studies on taste receptors. The first biochemical evidence of an umami taste receptor appeared in 1980, when researchers using bovine taste papillae discovered that the binding of glutamate to these papillae was enhanced significantly when nucleotides were added.

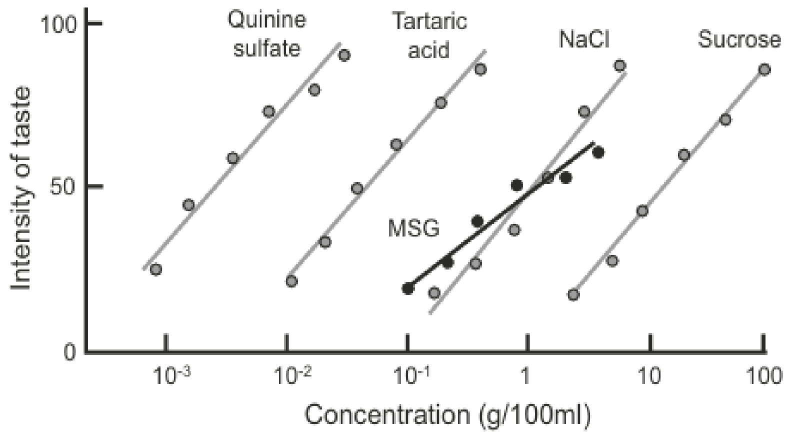
Starting in the early 2000s, molecular research on taste receptors began to identify specific receptors for each of the basic tastes. In 2000, G-protein-coupled receptors called taste 2 receptors (TAS2Rs) were identified as the receptors for bitter tastes. The following year, TAS1R3 was identified as a sweet taste receptor, working in conjunction with TAS1R2.

Later, a combination of receptors, TAS1R1 + TAS1R3, was identified as another candidate for detecting amino acid umami tastes. Additionally, a variant of mGluR1 was also reported as a potential receptor for umami.

This growing body of molecular studies has led to the identification of specific receptors for all five basic tastes: sweet, salty, sour, bitter and umami. The identification of distinct umami receptors further supports the idea that umami is a separate basic taste *(32).*

4.3.1 Intensity

The various umami-enhancing molecules have been identified *(Figure 6)*, yet evaluating their umami intensity remains complex due to the challenges involved in quantifying taste perception.



Relationship between taste intensity and concentration. (Modified from Yamaguchi (1987))
Figure 6

Several methods are used to evaluate umami taste intensity *(32)*, such as:

- Two-Alternative Forced Choice (2-AFC) and Three-Alternative Forced Choice (3-AFC)

These are discrimination testing methods where a participant is given a set of samples and must choose the one that meets a specified criterion.

- In 2-AFC, the participant is presented with two samples and must select the one that has a particular attribute (e.g., "Which sample is sweeter?").
- In 3-AFC, the participant is given three samples, with one being different from the others, and must identify the odd sample or the one with the specified attribute.

- Quantitative Descriptive Analysis (QDA)

A sensory evaluation technique where trained panelists use descriptive terms to quantify the intensity of different sensory attributes (e.g., sweetness, bitterness, texture). It involves structured scaling and statistical analysis to provide a detailed sensory profile of a product.

- Taste Dilution Analysis (TDA) and Comparative Taste Dilution Analysis (cTDA)

  - TDA is a method used to determine the minimum concentration at which a taste compound is detectable in a given solution. It helps identify the potency of taste-active compounds.
  - cTDA is a variation of TDA that compares different compounds or formulations to evaluate their relative taste dilution thresholds.

- Taste Recognition Threshold Concentrations (TRTC)

The lowest concentration of a taste compound at which a person can correctly identify its taste (e.g., the minimum level at which sweetness or bitterness is recognizable). This is an important measure in sensory science to understand human taste perception sensitivity.

Despite the advantages of trained taste panels, this approach has limitations, such as subjectivity due to psychological and physiological factors. A more standardized, reliable and reproducible protocol for measuring umami intensity is necessary for accurate evaluation in product development *(32).*

4.3.2 Long-lasting

One of the most unique aspects of umami taste is how long-lasting it is, often described as its persistence or aftertaste.

The long-lasting aftertaste of umami is tied to its concentration: the more of the umami substance you have, the longer that aftertaste sticks around. This could be because of how umami signals are processed not just in the mouth but also in the throat.

Interestingly, when both MSG (monosodium glutamate) and IMP (inosine 5′-monophosphate) were used together, their combined effect in the pharynx was simply the sum of their individual effects. This suggests there's no synergy between MSG and IMP in this part of the throat, implying that the way umami is detected may differ between the mouth and the throat *(32).*

So, the lingering umami aftertaste likely comes from signals in both the mouth and throat, but there's still much more to learn about how exactly these signals work and what other factors might influence them.

4.3.3 Mouthfullness

Characteristic descriptions of umami taste often include such word as mouthfullness.

The same word is elicited by the addition of some flavor compounds named kokumi, a Japanese word literally meaning "rich taste." Kokumi is characterized by thickness, continuity and that satisfying sense of fullness in both flavor and texture.

In humans, the addition of glutathione to a solution of MSG + IMP + NaCl not only increased the umami intensity but also made the kokumi qualities more prominent.

As for the receptor that detects kokumi, it's believed to be the calcium-sensing receptor (CaSR). Research has shown that the activation of CaSR correlates well with the intensity of kokumi flavors. Interestingly, CaSR is found in a subset of taste cells that do not express the typical umami receptor component TAS1R3 *(32).*

While the exact interaction between the umami and kokumi pathways remains unclear, these findings open an exciting avenue for future research. Understanding how these two taste qualities interact will likely reveal more about how complex taste sensations are processed and experienced by the human sensory system.

4.3.4 Satisfaction

Another term commonly used to describe the flavor of MSG is “satisfaction”. This sensation is not just limited to what we feel in the mouth; it may also be influenced by signals from the throat and the gastrointestinal tract.

Some neural information about glutamate comes from the pharynx and larynx, regions that contain taste buds and specialized cells. One such cell type is called the solitary chemosensory cell (SCC), which exists not just in the throat but also in the nasal epithelium and trachea. SCCs can detect chemical substances, much like the taste receptor cells we find on the tongue. These cells also express the umami receptors TAS1R1 + TAS1R3, though how they respond to glutamate specifically is still unclear (*32)*.

When SCCs are activated, they release acetylcholine, which stimulates sensory fibers in the trigeminal nerve. These fibers then send signals to the brain, possibly contributing to sensations like persistence and satisfaction after consuming MSG. This connection hints that glutamate doesn't only impact our taste buds but also interacts with somatosensory fibers, which contribute to more physical sensations beyond taste. Moreover, after swallowing, glutamate could travel down to the gut, where it might also activate umami receptors in the digestive tract *(32)*.

Additionally, glutamate might stimulate both umami receptors and cholecystokinin (CCK) in the intestine. CCK is a hormone associated with feelings of fullness and can suppress appetite *(32)*.

In short, the feeling of satisfaction from MSG may involve a complex interaction of taste and neural signals throughout the body, from the mouth to the gut, and possibly even activating reward pathways in the brain.

4.4 Process to obtain umami taste

The development of vegan meat flavors requires a deep understanding of the mechanisms responsible for flavor formation in animal meats. This process typically involves the breakdown of major components like proteins, fats and carbohydrates, which interact during cooking, producing various volatile and non-volatile compounds that contribute to the meat's flavor and aroma.

Key to mimicking these flavors in plant-based foods are two main techniques: thermal treatments and the use of flavoring agents such as yeast extracts and hydrolyzed vegetable proteins (HVPs).

This flowchart *(Figure 7)* represents a process for developing a processed meat-like flavor using fermented plant-based proteins and specific microorganisms (*Bacillus subtilis* or *Bacillus natto*) *(33).*

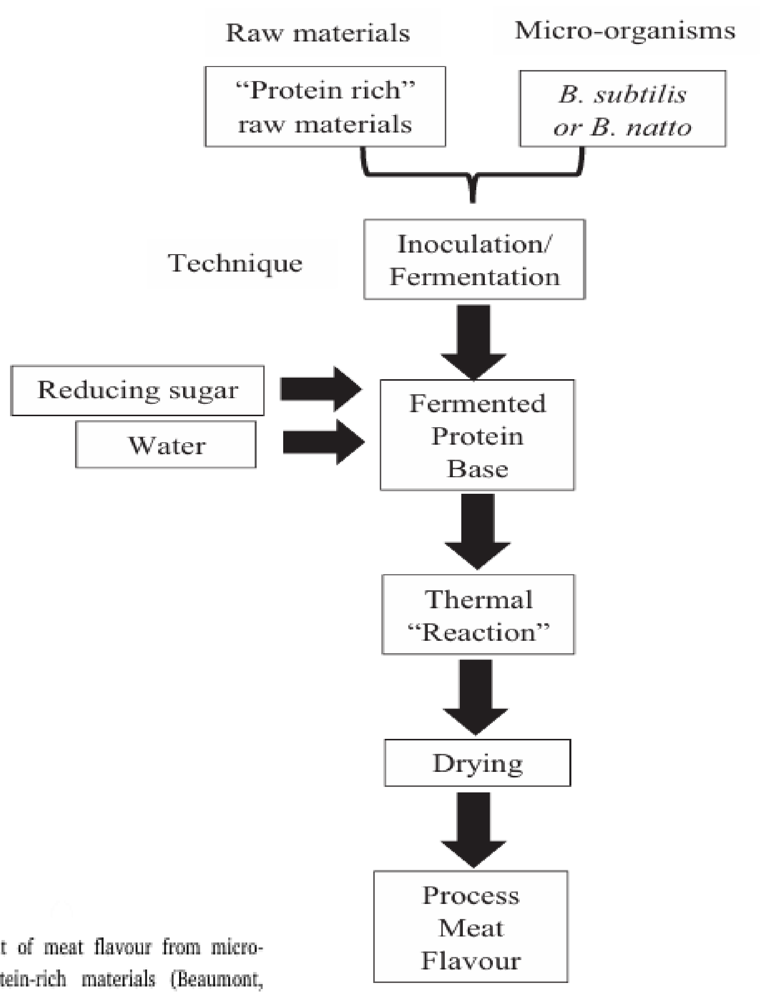


Fig 7 Development of meat flavour from micro-organisms and protein-rich materials (Beaumont, 2002).

Let's break down each step in more detail and explain how they contribute to the creation of umami and meat-like flavors in plant-based products:

1. Raw Materials: "Protein-Rich" Raw Materials

- The starting materials are plant-based proteins such as soy, wheat, pea, or other legume-derived proteins. These proteins provide the amino acid building blocks necessary for umami flavor development.

2. Microorganisms: *Bacillus subtilis* or *Bacillus natto*

- These bacteria are commonly used in fermented foods (e.g., natto, tempeh, miso) and help break down plant proteins.
- Through fermentation, they produce enzymes (proteases, peptidases) that hydrolyze proteins into free amino acids, including glutamic acid, a key umami compound.
- They also generate secondary metabolites like pyrazines, which contribute to roasted and nutty flavors, enhancing the complexity of plant-based meat analogs.

3. Inoculation/Fermentation

- The microorganisms are introduced to the protein-rich raw materials in controlled conditions.
- Fermentation breaks down proteins into smaller peptides and free amino acids, particularly glutamate, which is essential for umami taste.
- Other volatile compounds formed include ketones, aldehydes, and esters, which contribute to meaty and savory aromas.

4. Addition of Reducing Sugar and Water

- Reducing sugars (such as glucose or ribose) are added to facilitate Maillard reactions in the later stages.
- Water ensures proper enzymatic activity and fermentation consistency.
- The combination of reducing sugar and free amino acids will later undergo a thermal reaction to generate complex meat-like flavors.

5. Fermented Protein Base

- After fermentation, the protein-rich material has already developed a savory, umami-rich profile.
- It contains high amounts of glutamic acid, peptides, and other taste-active compounds that enhance the perception of meatiness.

6. Thermal "Reaction" (Maillard & Strecker Degradation Reactions)

- The Maillard reaction occurs when reducing sugars and amino acids react under heat, leading to the formation of:
    - Aldehydes (e.g., 2-methylbutanal, 3-methylbutanal) → contribute to roasted and caramelized notes.
    - Pyrazines (e.g., 2,5-dimethylpyrazine) → add nutty, roasted, and grilled aroma.
    - Thiazoles and sulfur compounds → provide meaty and brothy flavors, mimicking the taste of cooked meat.
- Strecker degradation further breaks down amino acids into volatile compounds that resemble cooked meat aromas.

7. Drying

- This step stabilizes the fermented and thermally processed protein, ensuring a concentrated umami and meat-like flavor.
- The dried product can be used as a flavoring ingredient in plant-based meat alternatives.

8. Processed Meat Flavor for Plant-Based Products

- The final product is a highly concentrated, umami-rich meat flavoring derived from plant proteins.
- It is used in plant-based burgers, sausages, and other meat analogs to improve savory depth and complexity.
- The combination of fermentation, enzymatic hydrolysis and Maillard reactions ensures that the flavor mimics traditional cooked meat.

4.5 Techniques to re-create vegan meat flavor

The development of authentic meat-like flavors in vegan meat alternatives requires a thorough understanding of the chemical processes responsible for flavor formation in conventional meat.

One approach involves the thermal processing of plant-based raw materials, such as yeast extract (*ex. in Figure 8*) and hydrolyzed vegetable protein, which generates compounds that mimic the sensory attributes of animal meat. Flavor, along with texture and aroma, is a critical sensory attribute in food products and plays a significant role in consumer acceptance *(34)*.

Figure 8

Aromatic active compounds in yeast extract giving meaty flavour (Lin et al., 2014).

Compounds	Flavour property
2-Methyl-3-furanthiol	Meaty
2-Furan methanethiol	Roasted meaty
Dimethyl disulfide	Meaty, sulphur
2-Methyl-5-(methio)-furan	Roasted meaty
2,3-Butanedione	Butter creamy
Acetic acid ethenyl ester	Wine, fruity
2-Acetyl-1-pyrroline	Roast, sweet
4-Methyl-5-thiazole ethanol	Beef, nutty

The primary contributors to meat flavor formation are carbohydrates, proteins and fats, as they contain essential flavor precursors.

Upon heat application, these precursors undergo chemical transformations, leading to the generation of numerous volatile compounds, including alkenes, alcohols, aldehydes, ketones, ethers, esters, carboxylic acids and sulfur-containing compounds. These compounds contribute to both the taste and aroma meat *(34).*

4.5.1 Acid Hydrolysis

Acid hydrolysis is commonly used to create hydrolyzed vegetable protein (HVP), a flavoring agent used in plant-based meat products. This technique involves breaking down proteins using an acid (often hydrochloric acid, HCl) under high temperatures. Here's how the process works:

- **Method:** The protein is incubated with 4–6 M HCl at temperatures ranging from 100–130°C for 4 to 24 hours. Afterward, the mixture is neutralized using sodium hydroxide (NaOH) *(35)*.
- **Outcome:** The result is a dark brown liquid with a strong savory flavor due to the breakdown of proteins into amino acids, small peptides, and other flavor precursors. These can undergo the Maillard reaction (non-enzymatic browning) to create more complex meat-like flavors.
- **Challenges:** This process may produce carcinogenic compounds, such as chloropropanols, so it's better to use weaker acids and milder hydrolysis conditions.

4.5.2 Enzymatic Hydrolysis

Enzymatic hydrolysis is a gentler alternative to acid hydrolysis. It uses enzymes to break down proteins into peptides and amino acids, which can then contribute to flavor development, particularly through the Maillard reaction.

- **Method:** Enzymatic hydrolysis requires a lower temperature (50–55°C) and a controlled pH (usually 5–7). The process typically takes 10 to 24 hours (*35)*.
- **Enzymes Used:** Various proteases (Flavourzyme, Alcalase, Papain and Bromelain) are commonly employed to break peptide bonds and generate desirable flavor precursors *(36).*
- **Benefits:** Compared to acid hydrolysis, enzymatic methods produce fewer carcinogenic by-products and offer more precise control over flavor development. The resulting hydrolysates are rich in savory and meaty flavors, making them ideal for plant-based meat products.

- **Applications:** Enzymatic hydrolysis is used to produce flavors that resemble chicken and beef, with the potential to create specific flavors using enzyme combinations tailored to the desired profile (e.g., for chicken or beef-like flavors).

4.5.3 Extrusion Cooking

Extrusion cooking is a thermomechanical process that takes ingredients to high pressure and temperature. This method is widely used in the production of texturized vegetable proteins, which serve as the base for plant-based meat analogues *(37).*

- **Method:** Raw ingredients are mixed with water, and the mixture is forced through a die under high pressure and temperature, which causes the water to vaporize, creating a final product with desired functional and textural properties.
- **Flavor Development:** During extrusion, complex chemical reactions, including lipid oxidation, Maillard reactions, and amino acid transformations (e.g., deamidation of glutamine and asparagine), contribute to the development of meaty flavors.
- **Challenges:** One of the key challenges is the loss of volatile flavor compounds during the extrusion process due to high temperatures, leading to less intense flavors in the final product. However, researchers are exploring ways to retain or enhance flavor by modifying extrusion parameters like temperature, moisture content and screw speed.

4.5.4 Fermentation

Fermentation is another important technique in developing vegan meat flavors. It involves the breakdown of organic compounds, such as proteins and sugars, by microorganisms (like bacteria, yeast, or fungi). This process is widely used in the production of fermented foods, including soy-based products like tempeh and miso, which have a savory, meat-like flavor *(38).*

- **Microbial Activity:** Certain strains of bacteria, like Bacillus species, are particularly effective in producing meaty flavors through their hydrolytic activities. These microorganisms break down proteins into peptides and amino acids, which can then contribute to savory flavor profiles.
- **Flavor Development:** The fermentation process not only generates flavor precursors but also enhances the overall aroma and taste of plant-based products, making them more meat-like. After fermentation, heat treatment further enhances the flavor by allowing the Maillard reaction and other chemical processes to take place.
- **Consumer Preference:** Fermentation is gaining attention due to its sustainability, as it offers an eco-friendly way to replicate meat flavors without relying on animal products.

CHAPTER V: PROS AND CONS IN PLANT-BASED MEAT AND MEAT

The traditional practice of raising animals for slaughter to produce meat has come under increasing regard in recent years due to several concerns. These concerns can be broadly categorized into three primary areas:

1. personal health risks,
2. ethical considerations,
3. ecological/environmental impact.

First, the consumption of meat has been linked to a variety of health issues, such as cardiovascular diseases and certain forms of cancer.

Second, from an ethical standpoint, the killing of animals for food raises serious questions about the humane treatment of animals, particularly as they are often subjected to inhumane conditions during their lives.

Third, the production of traditional meat is known to have significant negative effects on the environment, including deforestation, excessive water consumption and the emission of greenhouse gases.

One potential solution to address these issues is for individuals to reduce or eliminate meat from their diets. However, this approach presents significant challenges. This alternative offers a promising way to mitigate the negative effects of traditional meat production while still meeting consumer demand for products that mimic the taste and texture of conventional meat *(39)*.

5.1 Nutritional intake

Our bodies rely on protein digestion to get the essential nutrients we need to stay healthy. Before our bodies can use dietary protein, it must first be broken down and absorbed through the intestines. This process happens in the digestive system, where enzymes called proteases break food proteins into smaller peptides and free amino acids in the stomach and small intestine. Around 20% of the amino acids are absorbed in their free form, while 80% are taken up as dipeptides and tripeptides. Inside the small intestine, some amino acids are oxidized by intestinal cells (enterocytes), while others are broken down by bacteria in the gut.

Amino acids are transported into the body through two main systems: the sodium-dependent system, which carries about 60% of free amino acids, and the sodium-independent system, which transports the remaining 40%.

Proteins from food are the primary source of nitrogenous nutrients we need for growth, development, reproduction and overall health. However, producing pure protein on a large scale is costly, so we rely on plant- and animal-based foods to meet our protein needs *(40).*

To improve the quality of plant proteins, various pre-processing methods such as roasting, dehulling, blanching, soaking, frying and sprouting can be used. These techniques help improve texture and flavor while reducing harmful anti-nutrients like protease inhibitors. However, some anti-nutrients, like phytates, are highly resistant to heat and can't be completely removed even at 100°C. In such cases, fermentation can be used to produce enzymes called phytases, which break down phytates into more digestible forms *(41).*

Developing plant-based foods that are free from anti-nutrients and provide all essential amino acids is an important step toward better. By combining different plant protein sources (grains and legumes) people can create meals with a more balanced amino acid profile nutrition.

Currently, soy is one of the most accessible and widely used plant proteins. Researchers are also exploring new ways to enhance plant-based nutrition, including microbial fermentation, increasing the protein content of dairy alternatives and using microalgae as a protein source *(41)*

Also nutrients such as vitamins and minerals that are deficient in a plant-based diet must be replaced through fortification (Figure 9, next page).

Nutrient fortification in plant-based foods.

Nutrient	Current Sources and Processes	New Sources and Fortified Products
Protein	Plant-based protein sources include soybeans, chickpeas, and other legumes.	■ Protein can be increased through microbial fermentation using both mono- and mixed-culture bacteria. ■ Protein Source :Microalgae ■ Developing products with all essential amino acids and fewer inhibitors to improve bioavailability.
Vitamin B_{12}	Fortified foods include morning cereals, non-dairy milk, and yogurt replacements.	■ Fortification by lactic fermentation using naturally occurring bacteria that produce vitamin B_{12}. ■ Lupin tempeh* is made by fermenting lupin. ■ Crops can be grown hydroponically, directly in water that has been fortified with vitamin B_{12}.
Vitamin D	Milk, eggs, plant-based beverages, cereal for breakfast, and mushrooms are examples of fortified foods. Supplemental lichens D_3.	■ Eggs biofortified with vitamin D. ■ UV radiation of baker's yeast and mushrooms. ■ Lichens: Research and assessment are required before using them in food.
Iron	Salt, sugar, cereal-based goods, milk, and other dairy products are examples of food fortification.	■ Biofortification. ■ Enrichment of Ferritin content. ■ Reduction of Phytic acid (Eg. adding phytases during baking). ■ Iron fortification is microencapsulated before being added to food. ■ Addition of ascorbic acid.
Omega-3	Sources of ALA include walnuts, wheat germ, chia seeds, flaxseeds, hempseeds, and their derived oils, as well as leafy green vegetables.	■ Microalgae cultured ■ Fish oil or algae is added to the diets of cows and hens to biofortify dairy and eggs.
Calcium	Plant-based beverages and breakfast cereals are examples of fortified food.	■ Fermentation technique: growth of mixed microorganisms ■ Consumption of *Spirulina*

Source: Alcorta et al., 2021.

Figure 9 in article: Future trends in plant-based meat: Consumer perception, market growth and health benefits

Janifer Raj Xavie, Sahana Hevlin Shashikumar, Dimple Vats, Om Prakash Chauhan

An example of nutrient composition of Plant-Based Meat Alternatives of different firms:

Product	Carbs (%)	Lipids (%)	Proteins (%)
Beyond	6.2%	12.4%	17.7%
Impossible	8%	12.4%	16.8%
Morning Star	12.5%	7.8%	25%
Boca	8.5%	5.6%	18.3%
Gardein	9.4%	5.3%	16.5%
Beef	0%	31.7%	14.1%

This table compares the macronutrient composition (carbohydrates, lipids and proteins) of plant-based meat alternatives from different brands and traditional beef. It highlights significant variations in nutrient distribution among these products. Notably, beef contains no carbohydrates and has the highest lipid content (31.7%), while plant-based alternatives contain varying amounts of carbohydrates and lower lipid levels. Morning Star has the highest protein content (25%), whereas Gardein and Impossible have protein levels similar to beef. This comparison underscores the differences in nutritional profiles, which may influence consumer choices based on dietary preferences and health considerations *(42).*

5.2 Health

Plant-based diets have been shown to offer significant health benefits, particularly in managing conditions like type 2 diabetes, obesity and hypertension. They are also known to support heart health.

A plant-based diet includes a variety of fruits, vegetables, whole grains, legumes and nuts while reducing the intake of saturated fats and replacing them with healthier polyunsaturated fats.

Research studies, including the Adventist Health Study-2 (AHS-2) and the EPIC-Oxford study, highlight the positive effects of vegan diets. Vegans tend to consume the highest amounts of fiber and the lowest levels of total and saturated fats, leading to better cholesterol levels and healthier body weight.

Since obesity is a key risk factor for type 2 diabetes, plant-based diets can play a crucial role in prevention and management by promoting weight loss, reducing calorie intake, enhancing satiety and lowering inflammation and insulin resistance *(43).*

One major factor linking animal-based diets to insulin resistance is the accumulation of harmful fat metabolites in muscle and liver cells, which interferes with insulin signaling and glucose absorption. This explains why plant-based diets, which naturally contain less saturated fat, can help improve insulin sensitivity.

However, to fully benefit from a plant-based diet, it's essential to maintain a well-balanced and nutrient-rich eating pattern.

Studies also indicate that vegetarian and vegan diets may help lower blood pressure. According to the AHS-2 research, vegetarians and especially vegans, tend to have lower systolic and diastolic blood pressure compared to meat-eaters *(44).*

Beyond these benefits, plant-based diets have been linked to a lower risk of cancer. Systematic reviews and meta-analyses suggest that higher nut consumption is associated with a reduced risk of cancer and lower cancer-related mortality. Similarly, increased intake of fruits, vegetables and whole grains has been shown to lower overall cancer incidence and death rates. Consuming more legumes, such as beans and lentils, is also linked to a reduced risk of gastrointestinal and other cancers. Many plant foods contain powerful phytonutrients with cancer-fighting properties *(44).*

Plant-based meat is often marketed as a healthier alternative to regular meat, but it's not necessarily as good for you as it seems. While it's high in protein, free of cholesterol and not classified as a potential carcinogen like red or processed meats, it's still a highly processed food.

That means it often has nutrients removed and contains added ingredients like salt and saturated fats (usually from coconut, canola, or rapeseed oil) to improve taste and shelf life. Many plant-based meats have over 1.4g of salt per 100g, which is quite high, and consuming too much salt and saturated fat has been linked to health risks like high blood pressure and heart disease *(45).*

In summary, plant-based diets offer a wide range of health benefits, from managing chronic diseases to reducing the risk of cancer. By focusing on nutrient-dense, whole foods, individuals can improve their overall well-being and longevity.

5.3 Quality

Plant-based meat products are a relatively new category in the food industry and when they first appeared on the market, there was no clear agreement on what they should be called. The naming of these products has been a subject of debate, particularly because the livestock industry has repeatedly attempted to prevent the use of terms associated with animal-based products.

In 2017, the European Union ruled that most plant-based beverages could no longer be labeled as "milk," with a few exceptions like "almond milk" and "coconut milk." The same restrictions were applied to terms like "butter," "cheese" and "yogurt" when referring to plant-based alternatives. According to the European Court of Justice, the term "milk" can only refer to products derived from the mammary secretions of animals through milking *(46)*.

By 2020, the European Parliament extended these restrictions, prohibiting terms like "milk substitute" or "milk-type beverage." For example, tofu could no longer be marketed as "vegetable cheese." However, despite these strict regulations on plant-based dairy, the European Parliament ruled in favor of plant-based meat alternatives, allowing terms such as "vegan steak," "vegetable salami" and "meat-free burger" to remain on packaging. Lawmakers determined that labels like "plant-based burger" were unlikely to confuse consumers *(47).*

The Italian livestock industry continues to push for stricter labeling laws. In December 2022, a proposed law (Bill 746) sought to ban the use of terms like "cutlet," "wiener," "cold cuts" or "steak" on plant-based products. Supporters of this legislation argue that these terms could mislead consumers into believing plant-based alternatives have the same nutritional qualities as meat *(48).*

Other reasons given for these restrictions include:

- concerns over additives**:** critics claim that plant-based substitutes contain artificial additives and flavorings, though many processed meat products, such as sausages and breaded cutlets, also contain these ingredients.
- protecting Italian food traditions: proponents of the law argue that banning meat-related terms protects traditional Italian food products. However, this perspective overlooks the fact that many Italian companies are investing in plant-based food production, pouring significant resources into research, development and marketing.

One of the main arguments against restrictive labeling laws is that plant-based products contribute to environmental sustainability. Allowing these products to use familiar meat-related names could make them more appealing to consumers, increasing sales and potentially reducing the demand for animal products, which generally have a higher environmental impact *(49)*.

The research by Messer et al. (2017) highlights that food labels can significantly influence consumer choices, either positively or negatively. On the one hand, food producers use product names to inform consumers and encourage purchases. On the other hand, misleading or restrictive labeling could confuse shoppers or discourage them from trying plant-based options.

Producers of plant-based meat alternatives have learned valuable lessons from the plant-based dairy industry. One key takeaway is that labeling products as "meat-free" can negatively impact sales. For example, when the supermarket chain Sainsbury's changed the name of its vegan mashed dish from "Meat-Free Mash" to "Cumberland Spiced Veggie Mash," sales increased by 76% *(50).*

As a result, many plant-based meat brands now avoid using terms like "vegan" or "vegetarian" on their packaging. They also prefer their products to be stocked alongside conventional meat products rather than in the vegan section of supermarkets, which is typically where non-meat eaters buy tofu, tempeh and other plant-based alternatives.

While using familiar meat-related names (such as "burger" or "meatballs") frustrates the livestock industry, including the word "vegan" in a product name can also be risky. Some research suggests that labeling a product as "vegan" can create a sense of exclusion, making consumers feel judged or hesitant to buy the product *(Demartini, 2022).*

In addition to guaranteeing fair food trade practices, food laws and regulations must be followed to safeguard consumer interests, human life and health. For instance, the EU has classified recently created foods under the Novel Food Regulation, which states that food is defined as having never been consumed or existing in the EU before May 15, 1997, the date of adoption of the first novel food regulation *(51).*

The EU has established three criteria for new food regulations:

- consumer safety,
- correct labelling to prevent deceiving customers,
- adequate nutritional intake, not inferior to food they are meant to replace.

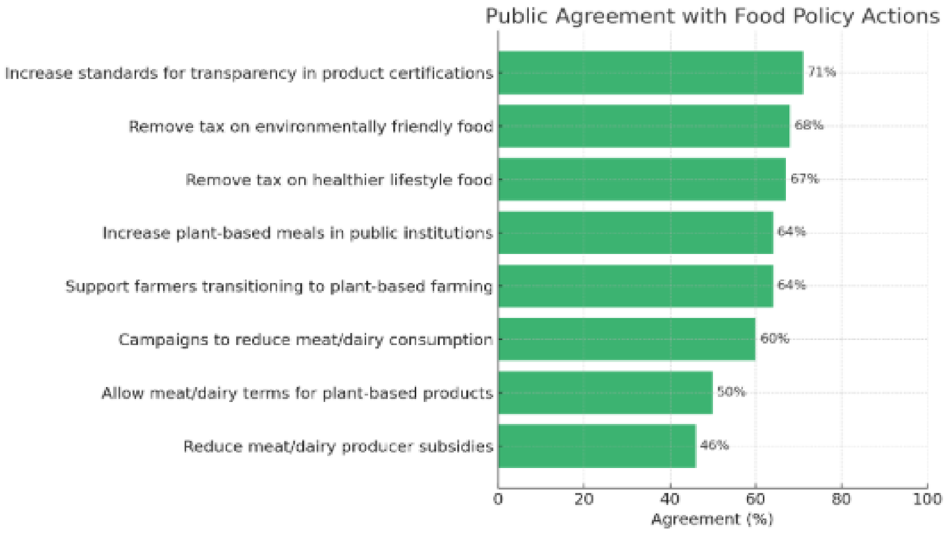


Figure 10 in article: Evolving appetites: An in-depth look at attitudes towards plant-based eating

Italian consumers strongly support greater transparency in product certification (Figure 10), with 71% in favor of stricter standards related to environment, health, welfare and organic labels. Additionally, 68% tax exemptions for food products with a lower environmental impact *(52).*

Interestingly, while environmental concerns are not a primary motivator for individual dietary changes, this broad support for institutional measures suggests that consumers are open to policy-driven incentives that promote sustainable food choices.

5.4 Process-related

The processing of plant-based meats plays a significant role in determining their nutritional profile, sustainability and health benefits.

Here's how processing influences these factors:

- Additives: in highly processed plant-based meats, additives like preservatives, colorants and flavor enhancers are often used to make the product more appealing or to extend shelf life. Some of these additives might have a potential impact on health if consumed frequently.

- Fiber Content: processing often reduces the fiber content found in whole plants, which is a key benefit of plant-based foods for digestive health. The more the plant-based meat is processed, the less likely it is to retain beneficial dietary fiber.

- Whole Food vs. Processed: a significant difference is the comparison between eating whole plant foods (like beans, legumes, and grains) versus processed plant-based meat alternatives. While plant-based meats are generally considered healthier than traditional meats, whole plant-based foods tend to offer more fiber, antioxidants and micronutrients without added fats or sodium.

The table represents a comparison of ingredients used in various plant-based meat burgers from different companies:

Firm	Ingredients
Beyond Meat	Water, Pea Protein, Expeller-Pressed Canola Oil, Refined Coconut Oil, Rice Protein, Natural Flavors, Dried Yeast, Cocoa Butter, Methylcellulose, Potato Starch, Salt, Potassium Chloride, Beet Juice Color, Apple Extract, Pomegranate Concentrate, Sunflower Lecithin, Vinegar, Lemon Juice Concentrate, Vitamins and Minerals (Zinc Sulfate, Niacinamide [Vitamin B3], Pyridoxine Hydrochloride [Vitamin B6], Cyanocobalamin [Vitamin B12], Calcium Pantothenate).
Impossible Foods	Water, Soy Protein Concentrate, Coconut Oil, Sunflower Oil, Natural Flavors, Potato Protein, Methylcellulose, Yeast Extract, Cultured Dextrose, Food Starch Modified, Soy Leghemoglobin, Salt, Mixed Tocopherols (Antioxidant), Soy Protein Isolate.
Morningstar Farms (Kellogg's)	Water, Wheat Gluten, Soy Flour, Vegetable Oil (Corn, Canola and/or Sunflower Oil), Egg Whites, Calcium Caseinate, Cornstarch, Onion Powder, Soy Sauce Powder (Soy Sauce [Soybeans, Salt, Wheat]), Salt, Natural Flavor, Soy Protein Isolate, Garlic Powder, Spices, Sugar, Gum Acacia, Whey, Yeast Extract, Xanthan Gum, Potato Starch, Tomato Paste (Tomatoes), Onion Juice Concentrate.
Boca (Kraft Foods)	Water, Soy Protein Concentrate, Reduced Fat Cheddar Cheese (Pasteurized Part-Skim Milk, Cheese Culture, Salt, Enzymes, Annatto [Color], Vitamin A Palmitate), Corn Oil, Wheat Gluten, Caramel Color, Methylcellulose, Soy Protein, Dried Onion, Cheese Powder (Cheddar Cheese [Milk, Cheese Culture, Salt, Enzymes], Cream, Salt, Sodium Phosphate, Lactic Acid), Salt, Natural Flavor (Non-Meat), Hydrolyzed Soy Protein, Disodium Inosinate and Disodium Guanylate, Sesame Oil, Spices and Herbs, Dried Garlic, Mannitol, Yeast Extract.
Gardein (Pinnacle Foods)	Water, Textured Soy Protein Concentrate, Vital Wheat Gluten, Canola Oil, Onions, Soy Protein Isolate, Methylcellulose, Yeast Extract, Barley Malt Extract, Garlic Powder, Onion Powder, Salt, Potato Starch, Natural Flavors, Sugar, Celery Seed, Smoke Flavor, Spice Extractives, Spices.

The health effects of food additives depend on the quantity consumed and individual sensitivities. Some additives in plant-based meat may raise concerns, particularly if consumed frequently. Here's an analysis of the potential ingredients detected in the table:

1. Methylcellulose (Thickener, Stabilizer)
   - Generally recognized as safe (GRAS), but some people report digestive discomfort, bloating or laxative effects.
2. Caramel Color (Colorant)
   - Some forms contain 4-MEI, a potential carcinogen when consumed in large amounts (especially in artificially processed caramel coloring).
3. Disodium Inosinate & Disodium Guanylate (Flavor enhancers)
   - Often used with MSG (monosodium glutamate) and may cause reactions in sensitive individuals (e.g., headaches, flushing).
4. Lactic Acid (Preservative)
   - Generally safe but if it is in excess it may contribute to acidity imbalances in the body.
5. Yeast Extract (Flavor enhancer)
   - Contains free glutamates, which act similarly to MSG and may trigger sensitivity in some individuals.
6. Annatto (Colorant)
   - A natural dye, but some people report allergic reactions or gastrointestinal discomfort.

Also the processing methods used in plant-based meat production can significantly influence the final product in several ways. Here are some potential consequences:

Processing	Structure	Advantages	Disadvantages
Spinning	Single fibers	• Simple equipment and easy operation • Mass production capacity	• Physical solidification process • Large amounts of waste chemicals
Extrusion	Sponge-like texture and layered fibers	• Improve protein functional properties • Mass production capacity	• Expensive processing equipment • Strict raw material requirements
Shear cell technology	Layered fibrous structure	• Better control of the processing parameters • With the combination of simple shear and heat	• Complex (but somewhat simpler than with extrusion)
3D printing technology	Layered fibrous structure	• Produce customized food • Simple equipment and customized fabrication and tailored nutrition control	• Low production volumes • Postprocessing requirements

1. Texture and Mouthfeel Alterations

- Spinning produces single fibers, which may lead to a less realistic meat-like texture.
- Extrusion creates a sponge-like texture that can sometimes feel dry or rubbery.
- Shear cell technology and 3D printing provide a layered fibrous structure, improving realism but requiring precise control to avoid inconsistencies.

2. Nutritional Changes

- High temperatures during extrusion and shear cell processing can degrade heat-sensitive vitamins and amino acids.
- 3D printing technology allows for better nutrient customization but may require additives to maintain structure.

3. Flavor Impact

- Extrusion can introduce "cooked" or off-flavors due to the Maillard reaction, which might not always be desirable.
- Some processes, like shear cell technology, may require additional flavor enhancers or fat incorporation to mimic the juiciness of real meat.

4. Additive Dependence

- Some methods, such as spinning and extrusion, may require binders, stabilizers, or emulsifiers to maintain structure, potentially increasing the level of processing.
- 3D printing may necessitate the use of hydrocolloids or gelling agents to maintain shape.

5. Environmental and Waste Concerns

- Extrusion and spinning generate chemical waste and require high energy inputs, potentially reducing the sustainability of plant-based meat.
- 3D printing has lower production volumes, limiting its immediate scalability.

5.5 Environmental impact

Climate crisis is no longer a distant threat and its global effects are undeniable. Experts consider global warming to be the biggest public health emergency of the 21st century, impacting not just the environment but also our health and overall quality of life.

Recent data shows that pollution levels are at an all-time high, with greenhouse gases like carbon dioxide, nitrous oxide and methane driving up global temperatures. This warming doesn't just make summers hotter but it disrupts entire ecosystems, affecting the oceans, weather patterns and leading to natural disasters like droughts, floods and extreme temperatures.

When we think about pollution, the first culprits that come to mind are usually cars and power plants burning fossil fuels. While these are indeed major contributors, the food industry, particularly the production of animal-based foods, plays a huge role too. In fact, agriculture is the second-largest source of human-caused greenhouse gas emissions, responsible for about a third of the total. According to a 2020 FAO report, emissions from food production have risen by 9% since 2000, reaching a staggering 16 billion tons of CO2 equivalent *(53).*

Livestock farming is a major driver of these emissions (Figure 11). Raising cattle, for example, generates anywhere from 1 to 20 kg of CO2 per kilogram of beef produced. Even poultry and egg production contribute significantly, with emissions ranging from 1 to 12 kg of CO2 per kg of chicken and 1 to 6 kg of CO2 per kg of eggs. Beyond just emissions, meat production is also incredibly water-intensive: it takes about 2000 liters of fresh water to produce just 1 kg of beef *(54).*

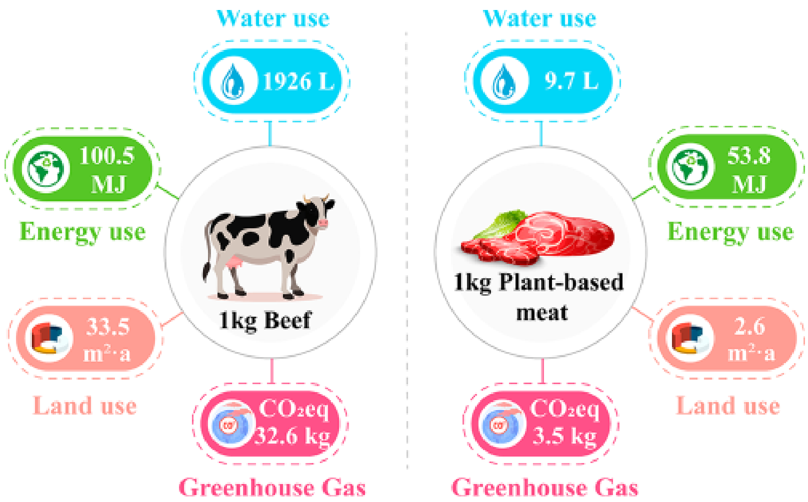


Figure 11: potential resources and environmental advantages of plant-based meat compared to beef. Data adapted from a Beyond Meat life cycle assessment.

In response to these environmental concerns, plant-based meat alternatives have been gaining popularity. These products, which mimic the taste and texture of meat, fit into a plant-based diet where animal products are mostly or completely avoided. While there isn't global data on how many people are adopting this diet, interest is growing rapidly due to health benefits, animal welfare concerns and the desire for a more sustainable food system *(55)*.

However, producing these meat substitutes also requires careful consideration. A 2020 study found that the most common ingredients in these products are soybeans, wheat, peas, chickpeas and beans *(56).* Since these ingredients are grown in different parts of the world, the industry relies on large-scale exports, which come with their own environmental costs, including heavy use of non-renewable resources and emissions from transportation.

So, while plant-based meat alternatives are generally more sustainable than traditional meat, there's still a lot we don't fully understand about their overall environmental footprint. A few important things to consider are that PBMAs (plant-based meat alternatives) are highly processed, so the environmental impact of the energy used in their production can offset the benefits of using plant-based ingredients, which generally have a lower environmental footprint and the sustainability of PBMAs production should include good agricultural practices, such as crop rotation, proper use of fertilizers, plant protection and efficient water management.

CONCLUSIONS

The plant-based meat industry has seen significant growth in recent years, but several challenges remain. These include advancements in:

Production technology: improving plant-based meat production, manufacturers must develop more efficient processes and advanced equipment. There is still a significant gap in optimizing production flow, integrating automated industrial chains and using intelligent production methods.

Regulatory standards: plant-based meat relies heavily on tissue structuring technology, supported by protein extraction and post-processing techniques. However, research is mainly focused on tissue formation and protein extraction, with little attention given to the complete production process. Moreover, the industry lacks highly automated and industrialized manufacturing equipment. Key areas for improvement include plant nutrient extraction and protein recombination technologies. Establishing comprehensive food safety and testing standards is essential for the plant-based meat industry. Despite its rapid expansion, there is no uniform monitoring and management system to regulate product quality.
A major challenge lies in the variation of plant-based meat compositions across different companies. Many research teams are developing new additives to enhance taste and texture, making plant-based alternatives more similar to animal meat *(57)*. However, this raises food safety concerns, emphasizing the need for strict regulatory measures. Additionally, since texture, flavor and color are primarily evaluated through sensory testing, establishing objective and standardized quality control methods is necessary.

Market competition with traditional meat: strengthening the plant-based meat industry, for greater awareness and policy support. While plant-based products that mimic traditional beef flavors have been developed, their higher cost compared to animal meat discourages some consumers from trying them.

Texture and structure improvements: to closely replicate the texture and composition of animal meat, plant-based meat formulations must be optimized at the microstructural level. Although plant-based products are fortified with nutrients to resemble animal meat, they still lack certain essential amino acids.
Protein reconstruction is a critical step in developing plant-based meat. Twin-screw extrusion technology is widely used due to its industrial efficiency, but it still falls short in replicating the exact texture, shape and flavor of animal meat.

Spinning technology, once a key processing method, is now being replaced due to concerns about chemical pollution during production *(59).* A hybrid approach that combines twin-screw extrusion with 3D printing may help address current production challenges by improving the appearance and texture of plant-based meat while maintaining high efficiency *(60).*

Consumer acceptance: plant-based meat has several advantages, including resource conservation, environmental protection, hunger alleviation and improved human and animal welfare. However, some consumers are still hesitant due to differences in appearance, taste, and texture compared to traditional meat. Despite this, consumer acceptance is growing. Additionally, plant-based meat is particularly favored by men, vegetarians and individuals with higher education levels *(61)*.

The rapid expansion of plant-based meat investments signals a promising future, but ensuring food safety and consumer confidence will be crucial. Strengthening regulatory frameworks, improving production technologies, and aligning plant-based meat processing with the taste and texture of animal meat will drive continued industry growth *(62).*

Plant-based meat has the potential to become a mainstream food option, contributing to global sustainability, improved health and better animal welfare. However, ongoing research and technological advancements will be key to overcoming current challenges and maximizing consumer acceptance.

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