Plant-based egg alternatives: Optimizing for functional properties and applications

Miranda Grizio, M.S.
Research Fellow,
The Good Food Institute

Liz Specht, Ph.D.
Senior Scientist,
The Good Food Institute

Executive summary

Demand for plant-based alternatives to meat, egg, and dairy products has grown significantly in recent years across many food categories and applications. This trend has been driven by many factors including allergenicity, sustainability, and consumer shifts towards flexitarian diets. This paper serves as a resource for those developing new plant-based egg alternatives and for those seeking to incorporate egg alternatives into a variety of food products. It provides a roadmap of the various alternatives that exist, the functional properties they provide, and the relative importance of these functionalities across various applications. While many options with attractive economic and performance impacts exist at commercial scale for replacing eggs in food product categories ranging from baked goods to beverages to condiments, there is still room for additional innovation to expand the functional palette of these egg alternatives. For example, cost and scale are still limiting factors preventing more mainstream adoption of stand-alone plant-based products that seek to recapitulate the full functionality and sensory experience of eggs. The molecular insights underpinning the functional properties of eggs outlined in this paper inform opportunities to address these needs utilizing novel plant-based sources, as well as for drawing inspiration from other biological domains such as algae and fungi. We anticipate that demand for plant-based egg alternatives will only continue to grow, and food manufacturers will be well positioned in this shifting market landscape if they proactively embrace plant-based egg alternatives across their product offerings.

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1 Introduction

The global plant-based egg alternative ingredients market is projected to reach over $1.5B by the end of 2026 and grow 5.8% from 2016 to 2026.[1] In 2016, North America accounted for 48% of this market. The growing interest in and use of egg alternatives by the food industry is driven by many factors including consumer demand, allergen reduction, improved food safety, healthier nutritional profiles, easier handling and storage, improved functionality, lower price and reduced price volatility, and environmental sustainability.

These are the same motivations that have driven other rapid market shifts from animal products like milk to plant-based alternatives. Notably, in both eggs and milk, food allergies drive a robust and loyal population of early adopters of plant-based alternatives. The plant-based milk market grew from virtually nonexistent to capturing over 10% of all fluid milk sales in the United States in the span of about 15 years, and the plant-based egg alternatives market is poised to do the same. The category has already experienced some of the early harbingers of plant-based milks' meteoric rise, such as placement of egg-free mayonnaise and dressings alongside their conventional counterparts in the grocery store.

Other substitutions in processed foods have been more subtle from the perspective of the consumer and are driven more by the food manufacturers. For example, pricing volatility and supply chain stability concerns precipitated by recent avian influenza outbreaks have accelerated the shift from eggs to egg-free alternatives in many processed foods. Plant-based alternatives exhibit both consumer and producer benefits that circumvent fundamental problems with eggs, and these alternatives are often cheaper. In many cases, larger-scale adoption of plant-based egg alternatives is simply a matter of initiative on the part of food manufacturers to perfect the reformulation; once implemented, these new formulations are likely to pay long-term dividends. Thus, the potential market size for egg alternatives is most accurately reflected not by the current state of the category but by the total size of the egg market as a whole, which often approaches $10 billion annually in the U.S. alone.

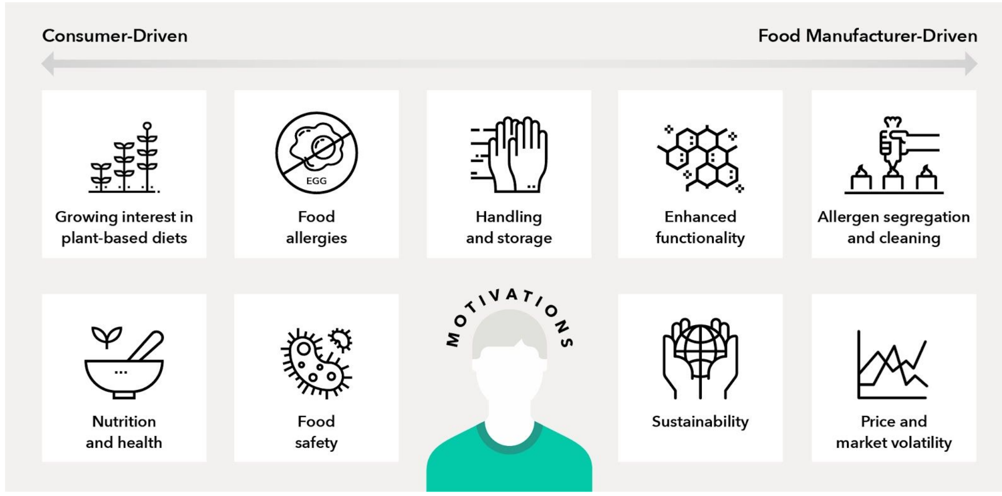
This paper details eggs' functional properties and the importance of these properties for various applications, and it presents a range of available plant-based alternatives that are suitable for replacing eggs in these applications. Opportunities for further research and product development are also identified. This primer is intended for plant-based food manufacturers and food manufacturers currently using eggs who wish to reduce or eliminate eggs in their products. This knowledge is also useful to both established and start-up ingredient companies interested in selling plant-based egg alternatives.

2 Motivations for using egg alternatives

Shifting products from eggs to plant-based egg alternatives is motivated by multiple factors, including some considerations that are more pertinent to consumers and others that are of particular importance to food manufacturers. While many of these factors are arguably important to both groups, they have been organized into predominantly consumer-driven considerations and predominantly food manufacturer-driven considerations below. Notably, there are virtually no consumers who seek out egg as an ingredient in processed foods, while there are many categories of consumers who specifically seek out egg-free labels.

[1] Future Market Insights, 2016. Egg replacement ingredient market: Global Industry Analysis and Opportunity Assessment, 2016-2026.

Figure 1: Motivations for switching to plant-based egg alternatives



Trends toward replacing eggs with plant-based alternatives that provide equivalent or superior functionality are driven by many motivations. Many of these factors are relevant for both consumers and food manufacturers who currently use eggs to endow their products with particular functional, sensory, and nutritional appeal.

2.1 Consumer-driven considerations

Growing consumer interest in plant-based diets

Consumer demand for plant-based foods drove plant-based food sales to $3.1 billion in 2017 in the U.S. alone, with a growth rate of 8.1% that year.[2] With 39% of Americans trying to include more plant-based foods in their diets[3], replacing eggs with plant-based egg alternatives represents an opportunity for food manufacturers to align their products with consumers' needs. In general, plant-based foods are associated with positive health effects and sustainability. Consumers may seek egg-free options in particular to avoid cholesterol and egg allergies and also to support a sustainable and animal-friendly product, brand, or company.

Food allergies

Egg is one of the most common food allergens. Egg allergies affect an estimated 0.5 – 2.5% of young children, with symptoms ranging from mild rash to anaphylaxis.[4] According to the Food Allergen Labeling and Consumer Protection Act (FALCPA), as one of the eight major food allergens, egg must be disclosed on a food product's allergen information statement or on its ingredient statement to alert consumers to its presence. The presence of this one ingredient can deter consumers seeking allergen-free options. Though only one family member may have a food allergy, it is common for the entire family to follow the restricted diet.

[2] PR Web, 2017. Plant-based foods sales experience 8.1 percent growth over past year.
[3] Nielsen Insights, 2017. Plant-based proteins are gaining dollar share among North Americans.
[4] RJ Rona et al., 2007. The prevalence of food allergy: a meta-analysis.

Food safety
Chickens can carry Salmonella bacteria, which can be transmitted to eggs even before the shells have formed. Salmonella causes an estimated 1 million cases of foodborne illness in the U.S. annually.[5] Moreover, antibiotic treatment of egg laying hens has been linked with the development of antibiotic-resistant strains of Salmonella. Liquid egg products are typically pasteurized to kill pathogens before they are sold, but they pose a risk nonetheless due to their high potential for bacterial contamination and because they exhibit a moisture level and nutrient profile that support bacterial growth.

Nutrition and health
Eggs contain significant levels of cholesterol, unlike plant-based ingredients, which are naturally cholesterol-free. While saturated fat is likely a bigger contributor to total blood cholesterol levels, dietary cholesterol is still of concern, especially to certain groups of people such as those with familial hypercholesterolemia.[6] Since a food product's cholesterol content must be labeled on the U.S. Nutrition Facts panel and is thus always visible to consumers, removing the cholesterol by replacing eggs with a plant-based egg alternative can render products significantly more attractive to health-conscious consumers.

2.2 Food manufacturer-driven considerations

Handling and storage
Liquid egg products are commonly used in the food industry but are highly perishable and have a short shelf life and thus must be quickly used once the container has been opened, thereby increasing the waste associated with using liquid egg products. Moreover, refrigeration is required for liquid egg products and frozen storage is required for frozen egg products. Dry egg replacers comprise the largest share of the egg replacer market and are projected to be the fastest growing format of egg replacers since they are easier to handle, have a longer shelf life, and do not exhibit special storage requirements.[7]

Allergen segregation and cleaning
Allergens can be especially challenging for a food manufacturer since allergen-containing products must be segregated from other products to prevent cross-contact. This can complicate production scheduling and cause production delays due to stringent cleaning and allergen testing requirements between product runs. Warehousing is also complicated by requirements for segregated storage and special signage for egg ingredients. Moreover, allergenic ingredients must be accounted for in a company's food safety plan. Replacing eggs with plant-based egg alternatives streamlines scheduling, production, and warehousing, saving time and money.

Enhanced functionality
In some applications, egg alternatives provide better functionality than eggs. For example, the better binding, emulsification, foam stabilization, and flavor enhancement of certain egg alternatives may be particularly useful in bakery and confectionery applications. Functional properties of eggs are described in detail in Section 4 and options for plant-based ingredients that recapitulate each of these functionalities are outlined in Section 6.

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[5] E Scallan et al., 2011. Foodborne illness acquired in the United States - Major pathogens.
[6] Berkeley Wellness, 2014. The role of dietary cholesterol.
[7] Markets and Markets, 2017. Egg Replacers Market by Ingredient, Form, Source, Application, and Region - Global Forecast to 2022.

Price

The price of shell eggs (i.e., eggs still in their shells) is inherently volatile due to their limited shelf life and inventory, compounded by fluctuating demand that is linked to seasonal consumption of egg-containing food products. This volatility has been notably exacerbated by recent outbreaks of avian influenza. To control the spread of Highly Pathogenic Avian Influenza (HPAI) that affected U.S. egg-laying flocks from 2014 to 2015, 33 million egg laying hens were killed, ultimately causing egg prices to increase by 36%.[8] Price spikes and price uncertainty have driven many food manufacturers to consider the use of egg alternatives. Fluctuating price and availability also makes securing supplier contracts challenging. In addition, there has been an increase in the use of specialty egg products, such as organic and cage-free eggs, which cost more. The high cost of specialty egg products is due to the higher cost of production and limited supply paired with growing consumer demand. In some states, new laws requiring increased space per hen or even mandating cage-free production are in effect or under consideration, indicating that even non-specialty egg products may soon become more expensive.

Sustainability

The majority of egg production in the U.S. is characterized by intensive confinement systems, high water and feed usage, and high waste output. The U.S. corn belt includes some of the most productive cropland in the world, but the grain grown there is currently used for animal feed, with roughly 7 million tons consumed by laying hens each year. The confined conditions of intensive, industrialized farm operations also concentrate animal wastes. For each ton of chicken eggs, layer hens produce multiple tons of manure. Ammonia emissions from this waste is a health and safety concern on farms, and water pollution from waste used as fertilizer is a major contributor to biodiversity loss in streams and ocean dead zones across the United States.

Many food manufacturers are instituting self-imposed sustainability metrics as part of broader sustainability metrics, and a switch from eggs to plant-based alternatives can help food manufacturers meet these goals – thus garnering attendant positive press.

3 Current egg usage and considerations

The current high level of egg consumption in the U.S. represents an enormous untapped market for egg alternatives. Eggs are consumed in more than 90% of households and are served at three out of four foodservice establishments.[9] There has been an expansion in egg consumption beyond the breakfast meal, which has been facilitated in part by restaurant offerings, such as all-day breakfast menus. Breakfast sandwiches and breakfast burritos, available at restaurants and supermarkets, are increasingly popular ways to consume eggs.

Eggs are used in a variety of ways. Eggs may be scrambled, fried, hard-boiled, used in egg-based dishes, such as omelettes or quiches, or used as a minor ingredient in foods requiring a specific functionality, such as binding or emulsification. Understanding the need within a given food product is important to understanding what is required in an egg alternative. A quick-service restaurant may be looking for an egg-free scramble, whereas a mayonnaise manufacturer may only be looking to replace the emulsification function of eggs;

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[8] USDA Economic Research Service, 2016. Retail Egg Price Volatility in 2015 Reflects Farm Conditions.

[9] Packaged Facts, 2015. Egg Market Trends and Opportunities in the U.S.

a household may want the flexibility to use an egg-replacer in a variety of ways.

Pack size and format options

Eggs are available in various formats that comprise different fractions of the market for consumers, foodservice, and food manufacturers. Note that this section refers to typical formats and volumes for U.S. markets and standards may vary internationally.

Consumers commonly buy shell eggs and liquid egg white products, which are pourable products containing egg whites, color, flavor, spices, thickeners, vitamins, and minerals. Liquid egg white products are typically available in 16- and 32-oz pour spout cartons. Shell eggs are sold in egg cartons containing from ½ to 2 ½ dozen eggs.

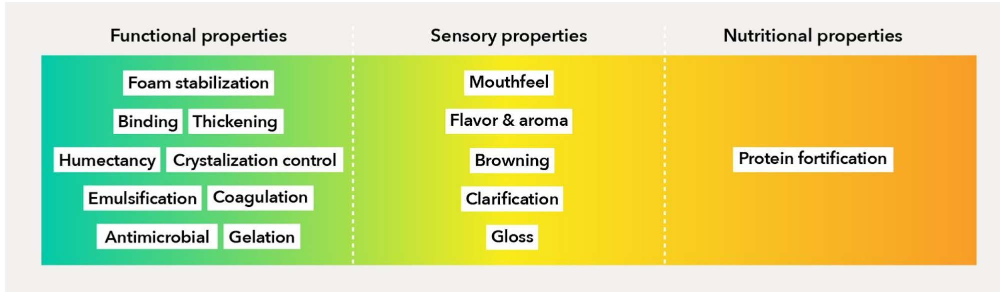
The foodservice industry, which includes restaurants, schools, hospitals, senior and child care facilities, and prisons, has a wider array of options. Egg products for foodservice include liquid whole eggs, liquid egg whites, liquid egg yolks, and liquid scrambled egg mixes. These products are also available frozen. Liquid egg products are commonly sold in pack sizes of 15x2-lb cartons, 20-lb bag-in-box, and 30-lb bag-in-box formats, while frozen egg products are available as 6x5-lb cartons and 30-lb pails. In addition, precooked scrambled eggs, egg patties, omelettes, and hard cooked eggs can be purchased. Scrambled eggs can be purchased in units of 20 lbs, while patties and omelettes are often sold 70 to 240 per container. Hard cooked eggs are sold in a range of pack sizes from 6 dozen (vacuum packed) to 25-lb pails (brined).

Food manufacturers can purchase liquid egg and frozen egg formats, as well as dried products including dried whole egg, dried egg white, and dried egg yolk. Manufacturers benefit from the lower cost, easier handling, and longer shelf life of dried eggs. Dried whole egg has many of the same functionalities as liquid whole egg but is more concentrated. Dried egg yolk is often used in bakery mixes to impart color and retain moisture, whereas dried egg white can be used for foam stabilization in angel food cake and to provide surface shine on breads. Liquid egg products are typically available to food manufacturers in 30-lb pails, 2000- or 2500-lb totes, and 49,000-lb tankers. Frozen egg products are commonly sold in 30-lb pails. The standard pack sizes for dried eggs are 50- and 55-lb bag-in-box formats.

4 Functionalities and molecular properties of eggs

Due to the composition and molecular properties of eggs, they provide a number of functionalities as ingredients in other food products. In some cases, one molecular property is responsible for multiple functionalities. While many of these properties contribute to multiple aspects of the consumer experience, they tend to segregate into categories around functional, sensory, and nutritional properties. Figure 2 provides a qualitative means of visualizing the relative roles these distinct properties of eggs contribute to various aspects of the final product.

Figure 2: Functionalities and molecular properties of eggs



Eggs impart many distinct attributes to food applications as a result of their molecular properties. These attributes contribute in varying degrees to many aspects of the consumer experience of the final product, including the nutritional attributes of the product, the functional properties it exhibits, and sensory qualities, such as taste, texture, and appearance.

4.1 Functional properties

Emulsification

Emulsifiers are molecules with one hydrophilic end and one hydrophobic end. This allows them to bind simultaneously to water and oil, thus stabilizing oil and water mixtures (such as mayonnaise) to help prevent them from separating. Emulsifiers reduce surface tension that, with proper mixing and ingredient proportions, enables one phase to be suspended as tiny droplets in the other phase, producing either an oil-in-water emulsion or a water-in-oil emulsion. Eggs naturally contain compounds that work as emulsifiers, including phospholipids and lipoproteins in the egg yolk and albumin proteins in the egg white. The most important emulsifier in eggs is the phospholipid lecithin. Cholesterol in egg yolk also acts as an emulsifier.

Coagulation

Coagulation occurs when a protein's three-dimensional structure unfolds, thereby exposing the protein's hydrophobic regions, which are then strongly attracted to the hydrophobic regions of other unfolded proteins. The unfolding process is called denaturation and can be triggered by heat, acid, salt, alcohol, or mechanical forces, like beating an egg. An egg contains over forty different proteins; when denatured, these proteins bind to each other and the egg coagulates. This irreversible process transforms the egg from a fluid to a semi-solid or solid state, which can be used to trap and bind other foods that are added during the coagulation period to create products, such as omelets.

Gelation

A food gel is characterized by its viscoelasticity and can be made from polysaccharides or proteins. Eggs can form a protein gel, a three-dimensional network of protein and water that creates the texture and structure typical of certain foods, like custards. As with coagulation, heat or other triggers are required to induce the denaturation required for gelation. Unlike coagulation, gelation is associated with a smooth texture from the incorporation of additional water by mixing. The gel sets to a cuttable texture, as opposed to a creamy texture, indicating an ordered protein-water matrix. The gel properties depend on the degree of denaturation and the protein concentration.

Thickening
Coagulation causes raw egg to change from a fluid into a semi-solid or solid. In this way, egg can act as a thickener in a variety of products, such as puddings and sauces. In addition, eggs can provide thickening through emulsification – for example, in batters – since emulsions are more viscous than the oil and water from which they are made.

Binding
Eggs can be used to bind ingredients together. Binding, or adhesion, is an effect of the coagulation and gelation of eggs. Surface applications include binding the breading to breaded foods and binding poppy seeds to bagels. Eggs are also used for their binding properties in meat products, such as sausages, and in a wide variety of bakery products.

Humectancy
Humectancy is the property of retaining moisture, and the water-binding capacity of egg white and egg yolk proteins renders them effective humectants. This property is especially useful in bakery products since moisture retention is vital to delaying staling and extending shelf life. Eggs can help to produce and maintain a moist crumb, which is seen as an indicator of quality and freshness in bakery products.

Foam stabilization
Eggs, particularly the egg white proteins ovalbumin and ovomucin, are notable for their ability to stabilize foams. This process is often called foaming or aeration and is critical for certain products, such as meringue and nougat. Mechanical agitation, such as whipping, is key to making foams. Whipping incorporates air into the food and also denatures the egg proteins, causing them to bind to each other, thus trapping the air bubbles inside.

In bakery products, foam stabilization is involved in leavening. This is especially important for imparting volume and structure to light cakes, like angel food cake. Gas incorporation into the batter or dough is the result of baking soda, yeast, steam, and mechanical agitation. In baking, egg proteins combine with wheat proteins (gluten) to form a strong, elastic network of entrapped air bubbles that can expand during heating. This protein network helps the bakery product to retain its height and shape when cooled.

Crystallization control
Some food components are prone to crystallization under certain conditions. For example, the dissolved sugar used in confections can recrystallize during storage, especially under conditions of fluctuating temperature and humidity. This change can lead to a white surface haze and a grainy mouthfeel, reducing the product's quality and shelf life. Eggs can act as an interfering agent to delay or prevent crystallization. This is related to the role of egg proteins in binding, but can also be linked to the emulsification and foam stabilization effects of eggs, depending on the type of confection. Crystallization control is important in fudge, truffles, nougat, and fondant.

Likewise, eggs can control ice crystallization in frozen foods during the freeze-thaw cycles that occur during distribution and storage. Due to minute temperature fluctuations, frozen foods are in the constant process of thawing and refreezing. After many cycles, the ice crystals can become quite large, changing the product's texture. Eggs can be used to minimize crystal growth. In a product like ice cream, this helps to maintain its smooth and creamy mouthfeel.

Antimicrobial

Certain egg white proteins have antimicrobial properties. Lysozyme is one with commercial significance. As an enzyme, its ability to hydrolyze the cell walls of gram-positive bacteria makes it useful to the cheese and wine industries. Although chicken egg is the primary source of commercially available lysozyme, synthetic lysozyme is also available.

4.2 Sensory properties

Mouthfeel

Eggs can add mouthfeel to certain food products. Mouthfeel refers to the sensations in the mouth and throat produced by foods and beverages. Eggs can provide a rich and creamy mouthfeel to mayonnaise and sauces as an effect of emulsification and thickening. However, in a product like custard, in which eggs provide gelation, the mouthfeel is characteristic of a gel. The product is cohesive and has a distinct "break" in the mouth, which is associated with its cuttable texture. The gel can range from weak to strong, with a mouthfeel ranging from slightly creamy to firm.

Flavor and aroma

At least 115 volatile flavor compounds have been identified in eggs.[10] Overall, eggs tend to have a mild or bland flavor. However, eggs are characterized by the slight taste and aroma of sulfur due to the presence of the sulfur-containing amino acids cysteine and methionine, found mainly in the egg white. In addition, egg yolks contribute fat that impacts flavor perception when used as an ingredient in other foods. Eggs also contribute to Maillard reaction flavors if used in foods exposed to the high temperatures of baking. These cooked flavors, known as brown flavors, have been described as toasty and malty.

Color

An egg yolk's yellow-orange color is derived from carotenoids, primarily xanthophylls but also small amounts of carotenes. Since birds cannot synthesize carotenoids, the carotenoids present in eggs come from the diet. This can include yellow corn and alfalfa, as well as marigold and paprika extracts. Yellow and red carotenoids are typically added to chicken feed to ensure the golden yolk color preferred by consumers.[11] Producers monitor egg yolk color with yellow-to-red color swatches known as egg yolk fans, which allows them to adjust the feed and feed additives to achieve their target egg yolk color.[12] Carotenoids commonly found in egg yolks include lutein, zeaxanthin, canthaxanthin, citranaxanthin, apo-carotene-ester, and cryptoxanthin. Organic eggs do not contain canthaxanthin, citranaxanthin, or apo-carotene-ester since synthetic carotenoids are prohibited in organic feed. Most carotenoids are oil-soluble.

Clarification

Since egg proteins can be coagulated, they can be used to clarify liquids, such as broth and wine. To make a clear broth, like consommé, egg white can be added. As it coagulates, it captures tiny particles in the broth and floats to the top where it can be skimmed off. Similarly, egg white or refined albumen is used as a fining agent to bind excess tannins in wine. In this case, the precipitate settles to the bottom leaving behind a clarified wine. The reduction in tannins produces a wine with less bitterness and astringency and better overall flavor. Filtration is an alternative to the use of egg for the clarification of soup and wine.

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[10] AJ Macleod and SJ Cave, 1975. Volatile flavour components of eggs.
[11] JA Coutts and GC Wilson, 2007. Optimum egg quality: A practical approach.
[12] DSM, 2016. DSM launches new Egg Yolk Pigmentation Guidelines and YolkFan.

Browning
Egg proteins can contribute to browning via the Maillard reaction. This chemical reaction occurs when amino acids and particular types of sugars, known as reducing sugars, are heated together at high temperatures. Browning is an important feature of baked goods; it especially affects the surface of the food, where the temperature is the highest. The Maillard reaction also produces a variety of flavor compounds that combine to give baked goods their characteristic taste.

Gloss
An egg wash applied to the surface of bakery products prior to baking imparts shine to the finished product. This is commonly done for pie crusts, soft pretzels, and challah. The fat content of the egg yolk is responsible for the glossy finish. In addition to providing gloss, an egg wash creates a golden or brown color through the Maillard reaction.

4.3 Nutritional properties

Protein fortification
The protein content of eggs can make them useful in protein fortification applications, such as protein bars and shakes. While one large egg contains about 12.5% protein (or slightly more than 6 grams), dried egg formats contain significantly more protein at 48% for dried whole eggs and 81% for dried egg whites.[13]

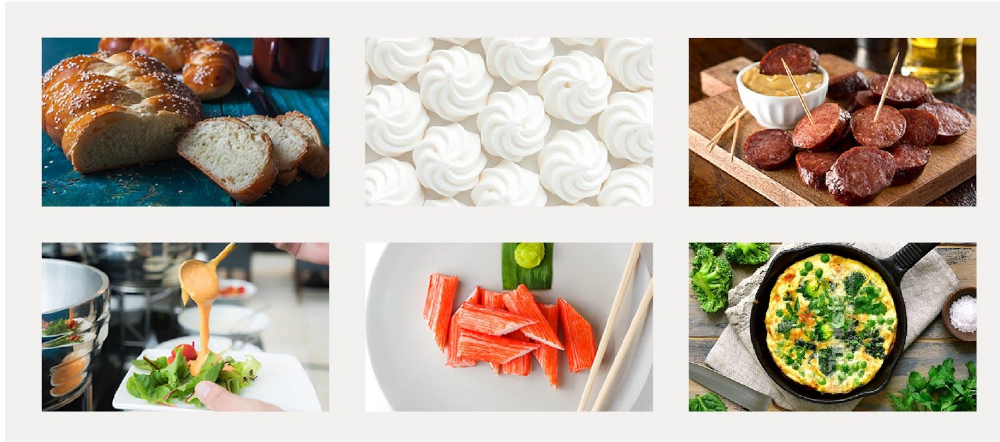
5 Applications

Since eggs provide different functionalities to different products, the key to successful egg replacement is to understand what functional properties the eggs are providing in a particular product. In this way, an egg alternative ingredient can be chosen that exactly fits the need, whether it is emulsification in egg-free mayonnaise, foam stabilization in angel food cake, or crystallization control in a frozen dessert.

It should be noted that in the U.S., certain food products that traditionally contain eggs have standards of identity considerations that should be taken into account when labeling products. Examples include mayonnaise, spoonable salad dressings, and frozen custard, all of which have egg content requirements. Many companies use alternative terms that are recognizable and informative for the intended application. For example, egg-free mayonnaise products on the market include Just Mayo Spread & Dressing, Vegenaise Dressing and Sandwich Spread, and Hellmann's Vegan Carefully Crafted Dressing & Sandwich Spread.

[13] USDA Food Composition Databases, USDA Agricultural Research Service (accessed 2018).

Figure 3: Various applications of eggs



Different properties of eggs are important for different applications. Because of the unique role eggs play in various products, the intended application informs which plant-based egg alternatives are most appropriate in a given context.

5.1 Grain-based products

Bakery products

Eggs are especially valuable to the baking industry since they provide a wide variety of relevant functionalities. Binding, humectancy, and browning are important for breads, cakes, muffins, cookies, pancakes, pastries, and many more. Browning imparts color to bread crusts and pastry surfaces and also contributes the cooked flavors characteristic of baked goods. Eggs may also impart a yellow color to the finished product. Foam stabilization is a key functionality for meringues but also affects many other bakery products, such as cakes and some breads, through its role in leavening. Eggs also contribute emulsification to baked goods, such as cinnamon rolls and cheesecake. Moreover, an egg wash can create gloss on the surface of pastries and pie crusts and can bind poppy seeds and sesame seeds to the surface of bagels.

Pasta and noodles

Egg is used in egg pastas and egg noodles to impart both flavor and color.

Breaded foods

Egg is commonly used in making the breading for breaded foods. It acts as a binder, allowing the bread crumbs to adhere to the surface of other foods.

Nutrition bars

Dried whole egg or dried egg whites are sometimes used to provide protein fortification to nutrition bars, though soy protein and whey protein are more commonly used.

5.2 Creamy and semi-solid foods

Mayonnaise and salad dressings

Mayonnaise and spoonable salad dressings use egg yolks or whole eggs for emulsification and thickening. Egg in these products also imparts an egg flavor, a yellow color, and a rich and creamy mouthfeel to the products.

Sauces, dips, and creamy soups
Eggs can be used for emulsification and thickening of sauces, dips, and creamy soups. Eggs provide a rich and creamy mouthfeel and can also contribute a yellow color to products, like Hollandaise sauce.

Custards and puddings
Custards are egg-set desserts that include crème brûlée, flan, and cream pies. Eggs provide gelation, which creates the set, giving the characteristic cuttable texture and cohesive mouthfeel of a custard. In certain traditional puddings, like rice pudding, egg is used to create a very weak gel; while the egg contributes thickening that produces an overall creamy texture in the pudding, the texture is also slightly cuttable due to gelation. A cuttable texture is one that retains its structure when cut or spooned out, rather than filling back in. Eggs can offer a spectrum of textures from creamy to cuttable; thickening and emulsification are associated with a creamy texture, while gelation is associated with a gel texture. Depending on competing flavors and colors in the custard or pudding, egg may also contribute egg flavor, yellow color, and browning.

Confections
Egg is used as an ingredient in certain confections for binding and crystallization control. This is important to the quality of fudge, truffle fillings, fondant, and nougat. Egg acts as an interfering agent to prevent the growth of sugar crystals which, left unchecked, leads to a white surface haze and grainy mouthfeel. The water-binding ability of eggs also provides humectancy, helping to keep soft fillings soft. In nougat, egg plays a key role in foam stabilization.

5.3 Frozen foods

Frozen desserts
For frozen desserts, like ice cream and frozen custard, eggs are useful for emulsification and crystallization control. Eggs' ability to emulsify facilitates the suspension of tiny droplets of milkfat evenly throughout the product, which results in a creamy texture and mouthfeel. Their ability to control the growth of ice crystals during freeze-thaw cycles helps to maintain the product's smooth, creamy texture and mouthfeel throughout the distribution chain. A frozen dessert without adequate freeze-thaw stability can develop a crunchy, icy texture by the time it reaches the consumer.

Frozen prepared foods
Eggs can also provide crystallization control to frozen prepared foods, such as frozen microwaveable meals. Unchecked ice crystal growth during freeze-thaw cycles can lead to the formation of large ice crystals that can puncture frozen foods. Upon heating, this structural damage becomes evident by the food's soggy texture. Egg can help keep crystal size small to ensure proper texture in frozen prepared foods, keeping pasta firm and vegetables crisp.

5.4 Beverages and liquid food products

Broth
Clarification is an egg functionality that can be important in broths, such as consommé. When egg white is added to broth, it coagulates, entrapping food particles. This complex rises to the surface of the broth, where it can easily be skimmed off, leaving behind a translucent broth.

Wine
Egg white or, more typically, refined albumen can be used as a fining agent in wines. It provides clarification by binding to particulates in the wine. The precipitate falls to the bottom, and the clarified wine can be poured off. It also binds to excess tannins, which reduces bitterness and astringency in the wine to improve the flavor. The egg white enzyme lysozyme is another egg ingredient used in winemaking. As an antimicrobial, lysozyme can prevent spoilage by lactic acid bacteria, such as Oenococcus, Pediococcus, and Lactobacillus. In addition, it is used to prevent premature malolactic fermentation, a type of fermentation that is often desirable but one that must be carefully controlled.

Eggnog
Egg provides emulsification, thickening, color, and a creamy mouthfeel to eggnog. It is also responsible for eggnog's characteristic eggy taste.

Protein shakes
Egg can be used for protein fortification of ready-to-drink protein shakes and shake mixes.

5.5 Meat, cheese, and stand-alone egg products

Meat patties, sausages, and imitation crab meat
Meat products, in particular meat patties and sausages, may use egg to help bind the ingredients together. Moreover, egg can be used to increase the gel strength of meat and fish protein gels, which improves the structure and texture of sausages and imitation crab meat (surimi).

Cheese
The egg white enzyme lysozyme can be used as an antimicrobial agent against gram-positive bacteria in low-acid hard and semi-hard cheeses. It can control microbial outgrowth of the gram-positive Clostridium tyrobutyricum, which is the main cause of a cheese defect known as late-blowing defect. If left unchecked, C. tyrobutyricum undergoes fermentation, leading to the production of gas and off-flavors and odors in the cheese. Late-blowing defect is a type of cheese spoilage characterized by irregular eyes and cracks in the cheese as a result of the unwanted production of gas bubbles. Swiss-type cheeses, such as Emmentaler and Swiss, and Dutch-type cheeses, such as Gouda and Edam, are particularly susceptible.

Scrambles, omelettes, and quiches
Coagulation is the egg functionality responsible for creating the unique texture of scrambled eggs and related dishes, such as omelettes and quiches. Eggs also provide color, flavor, and often a gelled mouthfeel to these dishes.

6 Plant-based egg alternatives

The options for plant-based egg alternatives include individual ingredients as well as ingredient blends, which facilitate a broader range of functional properties. Furthermore, recent progress has been made toward developing stand-alone egg alternatives that can provide all the functionalities of egg as well as function as whole eggs in foods like scrambles and omelettes. Tables 1-3 list manufacturers and distributors of single-ingredient egg alternatives (typically used in commercial food production) and retail products intended for direct consumer use.

6.1 Plant-based egg alternative ingredients

Colorings
Colorings can be used to mimic the yellow-orange carotenoid-based color of egg yolks. Natural colors include lycopene, annatto, turmeric, and paprika extracts. Another option is the use of color-rich ingredients, such as red palm oil, which naturally contains beta-carotene. Synthetic colorings may also be an option. For example, FD&C Yellow #5 and #6 can be blended with FD&C Red #3 to achieve a variety of yellow and orange shades. Vitamin B2 (riboflavin) can also be used to impart a yellow color. Brown colorings, such as caramel color, can be used to mimic the browning effect of eggs, for example, in bakery products. The composition of the food product will determine whether an oil-soluble or water-soluble coloring is most suitable.

Spices
Spices, such as turmeric and paprika, can also be used to add yellow or orange color to foods. Turmeric is commonly used in home cooking to make tofu scramble yellow, so that it more closely resembles the color of scrambled eggs.

Flavorings
Flavorings that closely match the flavor of egg are available from flavor companies. Impressive advancements have been made in this area over the past decade in response to the growing demand for eggless versions of traditional egg products. These flavors are referred to as egg-type flavors. It is important that the product developer describes the intended product application to the flavor company representative to ensure proper flavor selection. An egg-type flavor best suited for an eggless scramble may not work well for an eggless custard or mayonnaise. Flavor companies maintain databases of product applications and recommended usage levels for each of their flavors. If the cooked flavor associated with bakery products is desired, flavor companies can also provide so-called brown flavors.

Himalayan black salt
Himalayan black salt (kala namak) can be used to impart an egg-like sulfur flavor to foods and is especially valuable for home use, where commercial flavorings are not available. Its natural sulfur content has made it popular for making tofu scramble taste more like scrambled eggs.

Lecithins
Plant-derived lecithins, such as soy lecithin, can be used to provide emulsification. Sunflower and canola lecithin are also available. The choice of emulsifier depends upon several considerations, such as the relative ratio of water and oil in the end product, the temperature at which the emulsion will be formed, the salinity of the food matrix, and other factors that contribute to the hydrophilic-lipophilic difference (HLD). Often various emulsifiers with different properties are blended to match the average HLD with that of the intended food product.

Legume proteins, flours, and aquafaba
Legume protein isolates and concentrates offer a number of the same functionalities as egg proteins, such as binding, foam stabilization, emulsification, gelation, and humectancy. Since protein isolates have a higher protein content than protein concentrates, they are generally more effective although more expensive. Soy protein isolate (also called isolated soy protein or ISP) and soy protein concentrate are widely available. Some soy protein hydrolysates that have been enzymatically modified, often to improve solubility, are especially effective at foam

stabilization. Other legume proteins that have more recently become commercially available are black bean, chickpea, fava bean, lentil, navy bean, pea, and mung bean proteins. In many cases, only protein concentrates are available. Legume proteins can also provide thickening and freeze-thaw stability (crystallization control), though gums and starches are more typically used for these functions. Legume proteins can also contribute to the Maillard reaction to provide browning and can be used for protein fortification.

Legume flours, such as soy flour, contain much less protein than their isolate and concentrate counterparts but can still contribute to binding and thickening in part due to their starch and fiber content. Pea flour and peanut flour may provide similar functions.

The liquid in which legumes are cooked, known as aquafaba (which means bean water), contains sufficient protein, starch, and fiber to function as an egg replacer and succeeds in some of the most difficult applications, such as emulsification in egg-free mayonnaise and foam stabilization in meringues. A common replacement strategy is 1 tablespoon of aquafaba per egg yolk, 2 tablespoons per egg white, and 3 tablespoons per whole egg.

Tofu

Tofu is a product made by coagulating the soluble soy proteins in soymilk with salts or acids. The result is a white to off-white coagulated block with a viscoelastic structure. This protein gel contains water, fat, and carbohydrates, and the gel structure can range from weak to strong, depending on the water content. The two major categories of tofu are filled tofu (e.g., silken tofu) and pressed tofu (e.g., soft, firm and extra firm tofu). For filled tofu, the packaging tray is filled with a mixture of soymilk and coagulant that sets in the tray, yielding a smooth, delicate, high-moisture tofu with a weak gel texture. Silken tofu is often used as an egg-alternative to provide binding and humectancy in home baking. For pressed tofu, the set is broken, mixed, pressed, and cut prior to packaging, resulting in a firm tofu with an internal texture resembling the coagulated texture of scrambled eggs. Like filled tofu, pressed tofu can be mixed with other ingredients to contribute binding and humectancy. Tofu's protein content also allows it to participate in the Maillard reaction for browning. Tofu's mild flavor can be easily modified with flavors or seasonings.

Cereal proteins

Like egg proteins, cereal proteins can provide the functionalities of binding, thickening, humectancy, gelation, and browning. The proteins in wheat, collectively called gluten, are critical to baking for this reason. Wheat protein isolate is also an effective emulsifier and foam stabilizer, and there is some evidence that barley and rice proteins may have similar effects. Cereal proteins can also be used for protein fortification and may contribute to freeze-thaw stability.

Gums

Gums, also called hydrocolloids, are used widely throughout the food industry for thickening, binding, and mouthfeel. Their extraordinary capacity for binding water makes them effective at very low usage levels. A variety of gums are available; some are plant-based, while others are synthetic or produced through microbial fermentation. Certain gums can provide gelation. Gel formers include agar, sodium alginate, pectin, and carrageenan. Xanthan gum used in conjunction with locust bean gum, tara, or konjac can also form a gel. The mouthfeel and texture produced by gums depends on the gum and can range from creamy to gelled. Other commonly used gums are gellan gum and guar gum. Gums are also effective at controlling ice crystallization in frozen foods: for example, carrageenan is used in frozen desserts to provide freeze-thaw stability. Furthermore, gum arabic (acacia gum) is a gum that can double as an emulsifier. Some gums require a heating step to be effective, so they can be used in applications that require heat processing. Gum manufacturers can recommend the best gum and usage level for a particular application.

Starches

Like gums, starches are also used throughout the food industry for thickening, binding, mouthfeel, and control of ice crystallization. As polysaccharides, both starches and gums have high water binding capacities; this is the basis for their functionalities. Unlike gums, starches are used at much higher concentrations, which allows them to add body to food products. (As their name suggests, there is a limit to the amount of gum that can be added to a product before it becomes gummy). Most starches require heat activation, though there are a few cold-swelling starches. Corn starch is the most commonly used starch in the U.S., but potato starch, rice starch, tapioca starch, and wheat starch are also available. Some modified starches are available that can provide gelation or emulsification. Moreover, a mixture of corn starch in water can be used to add gloss to the surface of baked goods. It should be applied immediately after baking, rather than before baking, to prevent overbrowning. A commercially available example is Bake Sheen Liquid Egg Wash Substitute (Par-Way Tryson Co.).

Fibers

The functionalities of fiber include binding, thickening, and mouthfeel. Insoluble fibers can also provide bulk or body to products, while soluble fibers can contribute to gelation. Plants usually contain a mix of soluble and insoluble fibers. Commercially available fibers include apple fiber, citrus fiber, and oat fiber. Cellulose derivatives, such as carboxymethyl cellulose (CMC) or hydroxypropyl methylcellulose (HPMC), can be used as thickeners or emulsifiers.

Fruit purees

Some fruit purees are used as egg replacers in home baking. Applesauce and banana puree provide binding and humectancy, most likely due to their fiber content.

Sugars, syrups, and dextrins

Sugars, syrups, and dextrins are commonly used to provide humectancy. Examples include corn syrup and maltodextrin. Corn syrup can also be used to add gloss to bakery products when applied immediately after baking.

Vegetable oils

Vegetable oils can be used to impart gloss when applied to the surface of bakery products prior to baking in place of an egg wash.

Sulfites

Synthetic sulfites, such as potassium metabisulfite, or sulfur dioxide gas can replace many of the antibacterial functions of egg lysozyme in winemaking.

Flax and chia seeds

Ground flax seed is a popular egg replacer used in home baking, especially for cookies, muffins, and quick breads. A common recipe for a “flax egg” is 1 tablespoon of flaxseed meal mixed with 3 tablespoons of water. When allowed to sit for 15 minutes to an hour, the consistency becomes sticky and gelatinous. This flax solution is effective at binding and providing humectancy to baked goods and can be used in a 1:1 replacement for eggs. Like egg, flax seed contains multiple components, including protein (at 20-30%), oil (at 35-45%), and soluble fiber. The protein and soluble fiber may be responsible for the binding and humectancy functionalities. Some home cooks use ground chia seeds in the same way for egg replacement.

Algal flours

Like flax seed, algal flour is a complex food made up of multiple components. It naturally contains protein, oil, fiber, and starch. It also contains monoglycerides, diglycerides, and phospholipids, which act as emulsifiers. This variety of functional components allows algal flour to be used for emulsification, humectancy, freeze-thaw stability, and mouthfeel. AlgaVia (Corbion) is an example of a commercially available algal flour marketed for use as an egg replacer.

Table 1. Ingredient suppliers offering egg alternatives. This resource is not exhaustive but provides several suppliers for each egg alternative ingredient category described above. These suppliers often have minimum order requirements but may send samples upon request for pilot-scale formulation runs. While this list was created with the U.S. market in mind, many of these suppliers offer their ingredients globally. (*) denotes that these companies may be able to supply lower-volume quantities.

Category	Suppliers	Category	Suppliers
Algal flours	Corbion	*Himalayan black salt*	Pride of India
Lecithins	Archer Daniels Midland Cargill DuPont	*Fruit purees*	SunOpta Tree Top
Cereal proteins	Archer Daniels Midland Manildra Group USA MGP Ingredients	*Fibers*	Cargill Fiberstar Grain Millers TIC Gums
Colorings	Chr. Hansen DSM Kalsec Naturex Sensient Technologies	*Starches*	Archer Daniels Midland Cargill Ingredion Tate & Lyle
Flavorings	Bell Flavors & Fragrances* Target Flavors* Firmenich Givaudan Symrise	*Spices*	Fuchs North America McCormick Flavor Solutions The Food Source International
Fibers	Cargill Fiberstar Grain Millers TIC Gums	*Tofu*	Nature Soy Northern Soy Pulmuone WestSoy
Legume proteins and flours	Archer Daniels Midland BI Nutraceuticals Devansoy DuPont Ingredion SunOpta World Food Processing	*Gums*	AEP Colloids Cargill CP Kelco DuPont FMC Corporation Ingredient Solutions TIC Gums

Table 2. Ingredient distributors offering egg alternatives. Distributors supply a wide variety of ingredients and may have lower minimum order quantities than ingredient manufacturers, such as those listed in Table 1.

Distributors	Accurate Ingredients Batory Foods Brenntag Essex Food Ingredients Fincher Food Associates	Jungbunzlauer Pangaea Sciences Pocantico Resources Prinova Univar

6.2 Plant-based egg alternative ingredient blends and stand-alone plant-based egg replacers

Since egg alternative ingredients tend to provide only one or a few of eggs' many functionalities, more versatile alternatives often utilize a combination of the ingredients detailed above. Some retail ingredient manufacturers sell ingredient blends marketed specifically as egg alternatives to address the wide range of consumer needs for egg replacers in their cooking and baking at home. Their ingredient lists provide insight into the multiple functionalities these products provide.

Table 3. Plant-based egg alternative ingredient blends and stand-alone egg replacers available for retail sale.

Product (Manufacturer)	Ingredients
VeganEgg (Follow Your Heart)	whole algal flour, whole algal protein, modified cellulose, cellulose, gellan gum, calcium lactate, carrageenan, nutritional yeast, black salt
The Neat Egg (Atlantic Natural Foods)	chia seeds, garbanzo beans
No Egg Egg Replacer (Orgran)	potato starch, tapioca starch, raising agent (calcium carbonate), citric acid, methylcellulose
Egg Replacer (Ener-G Foods)	potato starch, tapioca flour, leavening (calcium lactate, calcium carbonate, cream of tartar), cellulose gum, modified cellulose
Egg Replacer (Namaste Foods)	tapioca starch, arrowroot starch, citrus fiber, cream of tartar, sodium bicarbonate
Egg Replacer (Bob's Red Mill)	whole soy flour, wheat gluten, corn syrup solids, algin (from algae)
Baking Mix (The Vegg)	pea protein isolate, fortified nutritional yeast, xanthan gum, sodium alginate, guar gum, black sea salt, beta carotene
Not Your Parents' Tofu Scramble (The Vegg)	soy protein, whole algal protein, whole algal flour, fortified nutritional yeast, magnesium chloride, black sea salt
Vegan Egg Yolk (The Vegg)	fortified nutritional yeast, sodium alginate, black salt, beta carotene

7 Conclusions and opportunities for further research and development

An abundance of plant-based egg alternatives exist for most food applications that can make egg-free product development or reformulation relatively simple. However, several key opportunities remain in the egg alternative space.

Although some egg alternatives are very close to providing all the functionalities of eggs, a perfect stand-alone replacement does not yet exist. VeganEgg and JUST Scramble may be the closest due to their ability to coagulate like eggs. (JUST Scramble is currently undergoing testing at one restaurant and is not yet commercially available). Since coagulation typically depends on protein denaturation, a relatively high protein content may be critical for making a stand-alone egg alternative. Soy protein, algal protein, and mung bean protein are among the most promising candidates explored thus far due to their texture when coagulated, but opportunity exists to explore many more plant sources. These products should also be effective at providing binding, humectancy, thickening, gelation, and mouthfeel.

Furthermore, among the products that seek to replace stand-alone eggs, both VeganEgg and JUST Scramble imitate a blended egg (yolks and whites combined) rather than yolks and whites as two distinct components with unique properties. Therefore, these products may struggle to provide the functionality associated specifically with egg whites (e.g., foam stabilization) or with egg yolks (e.g., emulsification). Clara Foods is a cellular agriculture company manufacturing specific egg white proteins using engineered yeast with the goal of mimicking the functionality of conventional egg whites, such as foam stabilization in meringues. (Their product is not yet commercially available).

These blended egg mimics also cannot be used to make dishes like hard-boiled eggs or sunny-side-up eggs where the fractions remain distinct at the point of consumption. Thus far, no commercial product has addressed the two-part nature of eggs in a way that has made a plant-based hard-boiled egg alternative available, though some clever mimics can be devised with patient culinary finesse.[14]

Certainly, a stand-alone egg replacement that could be used for all egg applications and provide all of the functionalities of eggs would be of tremendous value to the food industry and to consumers. This might be achieved through optimization of the ingredient blend concept and supported by plant proteins with unique functionalities, including the ability to coagulate. As new plant proteins are discovered and isolated, these options will increase. One protein that has recently shown promise in producing protein gels with similar properties to egg white gels is ribulose bisphosphate carboxylase-oxygenase (known as Rubisco), a protein found in virtually all plants and green algae.

Intermediate steps toward the goal of a plant-based stand-alone egg replacer might include the development of a stand-alone egg yolk replacer and an egg white replacer, which would each have a relatively broad range of applications and therefore meet the needs of a variety of food manufacturers.

Other potential commercialization opportunities include an egg replacer specifically designed for the baking industry that could be used across all baking applications because eggs provide such a broad range of functionalities in bakery products. Since a bakery may

[14] The Gentle Chef, 2015. "Hard-Cooked" Eggless Eggs.

manufacture a multitude of very different products, this would vastly simplify the product reformulation process required to make products egg-free, in addition to streamlining purchasing and warehousing operations.

Furthermore, opportunity exists for the development of a plant-based alternatives for various enzymatically active ingredients derived from eggs. For example, lysozyme derived from egg white is used in cheese and wine. The selective antimicrobial activity of lysozyme makes it valuable to these industries. Though synthetic lysozyme is available, for manufacturers preferring to use natural ingredients, a plant-based lysozyme may be a key solution. Plant sources of lysozyme include cauliflower, cabbage, and papaya.

It is the aim of The Good Food Institute that in compiling the information on known plant-based egg alternatives and in identifying gaps, the food industry is better positioned to produce egg-free products that meet the demands of today's consumers. The benefits of replacing eggs with plant-based egg alternatives are far-reaching and include issues of health, safety, and sustainability, in addition to improved business processes. As a leader in the advancement of policy, innovation, and industrial development to move the food system away from conventional animal agriculture, The Good Food Institute is actively investigating and pursuing key strategies to expand the field and catalyze further development of the plant-based egg industry for a more healthy, humane, and sustainable food supply.

ABOUT THE GOOD FOOD INSTITUTE

The Good Food Institute is a 501(c)(3) nonprofit organization dedicated to creating a healthy, humane, and sustainable food supply. GFI's team of scientists, entrepreneurs, lawyers, and lobbyists are laser focused on using markets and food innovation to transform our food system away from industrial animal agriculture and toward plant-based and clean meat alternatives. To learn more, please visit GFI.org.

ABOUT THE AUTHORS

Miranda Grizio, M.S.
Science & Technology Research Fellow, The Good Food Institute
mirandag@gfi.org   Miranda at LinkedIn

Miranda is a food scientist working in R&D for the natural foods industry who has won several new product awards, including a *Vegetarian Times* Foodie Award. She holds a master's degree in Food Science from Kansas State University and a master's degree in International Development from Tulane University. Miranda also volunteers at Compatible Technology International providing technical assistance for food processing projects in developing countries to improve the incomes and nutrition of smallholder farmers and their families. At GFI, she supports food entrepreneurs and scientists interested in plant-based foods by researching plant-based ingredient functionality.

Liz Specht, Ph.D.
Senior Scientist, The Good Food Institute
lizs@gfi.org   Liz at LinkedIn

Liz works to identify and address areas of need for plant-based and clean meat scientific innovation and works with funding agencies to prioritize research that moves this field forward. Liz holds a bachelor's degree in chemical and biomolecular engineering from Johns

Hopkins University, a doctorate in biological sciences from the University of California, San Diego, and postdoctoral research experience from the University of Colorado Boulder. Liz is a Fellow with the University of Colorado at Boulder's Sustainability Innovation Lab and has a decade of academic research experience in synthetic biology, recombinant protein expression, and development of genetic engineering tools.