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Plant-Based Proteins: The Good, Bad, and Ugly

William R. Aimutis

North Carolina Food Innovation Lab, North Carolina State University, Kannapolis, North Carolina, USA; email: bill_aimutis@ncsu.edu

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Abstract

Our global population is growing at a pace to exceed 10 billion people by the year 2050. This growth will place pressure on the agricultural production of food to feed the hungry masses. One category that will be strained is protein. Per capita protein consumption is rising in virtually every country for both nutritional reasons and consumption enjoyment. The United Nations estimates protein demand will double by 2050, and this will result in a critical overall protein shortage if drastic changes are not made in the years preceding these changes. Therefore, the world is in the midst of identifying technological breakthroughs to make protein more readily available and sustainable for future generations. One protein sourcing category that has grown in the past decade is plant-based proteins, which seem to fit criteria established by discerning consumers, including healthy, sustainable, ethical, and relatively inexpensive. Although demand for plant-based protein continues to increase, these proteins are challenging to utilize in novel food formulations.

INTRODUCTION

The rise in popularity of plant-based (PB) foods in recent years is attributed to the consumer's increasing demand for alternatives to animal-based (AB) products. This trend is driven by increasing awareness of the healthiness of PB foods compared to AB foods, negatively perceived animal husbandry practices, and the impact livestock has on our environment. Consumers also express concern over high-cholesterol intake from AB diets, lactose intolerance, and increasing levels of animal protein allergenicity. Therefore, with the rise in PB food popularity has come an increasing demand for protein concentrates and isolates that function in PB formulations with properties similar to animal proteins (**Figure 1**). However, few consumers actually understand PB diets, often associating the term with vegetarianism and veganism (Faber et al. 2020). Despite this, a rise in consumer social consciousness has prompted a change in eating habits across all generations and now a growing percentage of eaters self-identify as flexitarians (reduced meat consumption without total elimination) (Rosenfeld 2018, Spencer 2018).

Demand for soy protein isolates actually preceded the PB demand because food formulators a decade earlier were frustrated with the cyclical price and supply demands of dairy proteins. Earlier this century, manufacturers of dairy protein concentrates and isolates were launching numerous new and improved protein products. The utilization of intact and hydrolyzed soy, whey, and milk protein concentrates and isolates allowed food formulators an option to leverage the functional properties of those products in recipes for healthy, nutritious, and clean-label products. Foods higher in protein carried a "halo effect," with consumers seeing them as healthier and more nutritious. This led to consumers further pressuring manufacturers for protein-fortified products. As often occurs in a supply-and-demand environment, prices and supply of high-protein dairy products began rising and decreasing, respectively. Food manufacturers then began reformulating with soy protein isolates that had many functional characteristics of dairy-based proteins (Kinsella 1979). Similarly, this pressured the supply and prices for soy proteins and presented new opportunities for PB protein (PBP) products.

This review examines the positive and negative attributes of several PBPs. There has been a flurry of activity from several perspectives to launch novel PBPs for inclusion in PB products. Only a small percentage of these have relative supply chain availability and research and/or commercial information available, and therefore this review is focused on the commercially

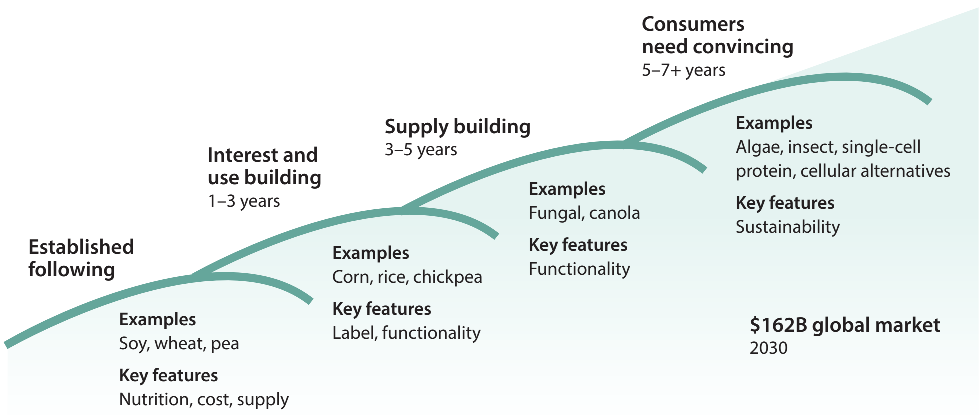

Figure 1

Protein evolution in the marketplace.

relevant products, namely soy, wheat gluten, yellow pea, rice, and chickpea protein concentrates and isolates. For the readers' understanding, we refer to protein concentrates and isolates as having a protein concentration greater than 60% and 85%, respectively.

ROLE OF PROTEINS IN FOODS

Food systems are multicomponent matrices mostly dominated by protein, fat, and carbohydrate for their structural, mechanical, and other physicochemical properties. In turn, the interaction of principal food components contributes to the sensorial attributes (flavor, aroma, and tribology), structural texture, physical equilibria, and nutritional value as well as consumer enjoyment (**Table 1**). Proteins are essential for life, as the human body has large demands for amino acids supplied by exogenous protein sources for many physiological functions, including synthesis and repair of bodily tissues, that ultimately contribute to our skeletal framework and metabolic reactions. These metabolic factors are necessary to accomplish those processes and serve as messengers to transport critical molecules within the human body to maintain homeostasis. Proteins are also building blocks for molecules like hormones, antibodies, blood, and other related fluids. Human demand for protein is primarily satisfied via dietary intake (Gorska-Warsewicz et al. 2018), and this is primarily of animal origin (Henchion et al. 2017).

Most living species must ingest protein to sustain life, but proteins also function as structural building blocks for foods. Food chemists have extensively studied the physical functionality of proteins from a variety of sources. Historically, these functional properties are nonnutritive and include emulsifying ability and stability, foaming, and gel formation (Foegeding 2015). More intensive research has demonstrated food-based proteins, regardless of AB or PB, also function at the nano/molecular level to function in flavor binding, color, allergenicity, and digestibility (Foegeding 2015, Zhao et al. 2020). Ultimately, food proteins can constitute the complex structures we recognize as food and may be associated with hedonic properties and nutrient and bioactive bioavailability (Foegeding & Davis 2011).

Sufficient protein intake maintains the body's nitrogen balance for key bodily functions. Over the past three decades, there has also been growing interest in peptides derived from in vivo gastric

Table 1 Benefits of the use of food proteins

Category	Benefits
Functional (criteria used by consumers to evaluate food)[a]	
Appearance	Emulsifying, foaming, water/oil binding, and organoleptic (color/taste/smell)
Flavor	Proteolysis, sweetness, saltiness, accentuation, and solubility
Texture	Water binding, gelation, viscosity, heat stability
Powder characteristics	Dispersibility, wettability, flowability
Nutritional (physiological properties linked to protein bioactives)[b,c]	
Angiotensin-converting enzyme 1 (ACE-1) inhibitor peptides	Blood pressure lowering
Analgesic peptides	Relaxation, pain relief, and sleep inducers
Immunomodulatory peptides	Immune system stimulation
Antimicrobial peptides	Antagonism or inhibition of pathogenic bacteria
Insulin-like peptides and alpha amylase inhibitors	Blood sugar reduction and control

[a]Key metrics: nitrogen solubility index and protein primary and secondary structures.
[b]Key metrics: bioaccessibility and bioactivity via digestion.
[c]Li et al. 2017, Patil et al. 2020.

digestion and in vitro enzymatic hydrolysis to produce amino acid epitopes that have bioactivity beyond nutrition in the human body. Bioactive peptide sequences from AB proteins (ABPs) have been well characterized for their biochemical and physiological properties for the promotion of health and prevention of diseases and health conditions (Madureira et al. 2007, 2010; Silva & Malcata 2004). Some of the known bioactivities include blood pressure lowering, antithrombosis, dental caries prevention, opioid effects, and antimicrobial and immunomodulatory influence (Aimutis 2004). PBPs also have physiological activity (Lonnie et al. 2020). Soy protein was perhaps the first commercially available PBP to make a health claim for its bioactivity (FDA 1999). Consumption of 25 grams of soy protein per day along with a healthy diet reduces cholesterol (Anderson et al. 1995). Additionally, recent research also describes the role of plant protein peptides in traditional agriculture for weed control and as pesticides, fungicides, and herbicides (Christians et al. 2010).

The food industry has focused on deep knowledge building of soybean (Barraquio & Van de Voort 1988, Kinsella et al. 1985, Rizzo & Baroni 2018) and wheat gluten (Rustgi et al. 2019) protein functionality. Consumers' and food formulators' concerns over these proteins' flavor, allergenicity, and other physiological effects have caused food manufacturers to begin looking for alternative protein sources (Shevkani et al. 2015). To be considered as alternatives to soy and wheat gluten, the alternative proteins should be nonallergenic, have a well-balanced amino acid composition, be in plentiful global supply, be capable of being manufactured into concentrates and/or isolates, and contain no antinutrition factors (Boland et al. 2012). Higher digestibility and biological value are also important nutritional factors to consider when identifying possible alternative proteins (Amagliani et al. 2017). PBPs are often deficient in one or more amino acids, especially lysine and tryptophan (Day 2013, Shevkani et al. 2015), and blends of proteins are becoming more commonplace when replacing ABPs.

PBPs are quickly becoming a participant in the global transition toward a sustainable economy (Aiking & Boer 2020). The United Nations 2030 Agenda for Sustainable Development (UN 2015) has identified the need for a multidisciplinary approach to a global transition from diets primarily AB to diets primarily PB for both food security and sustainability. The need for change must occur at several levels within our global population, including a reduction in total caloric and protein consumption in most developed countries. Unfortunately, experts cannot agree if it is possible for PBPs to be produced in quantities with the same nutritious profiles as ABPs (Aschemann-Witzel et al. 2020). To meet future protein demands for a growing global population, all protein supply sources, including those in development, will need to be escalated to sustain human sustenance. Plant protein manufacturers and food formulators must thoroughly understand the properties and limitations of this group of proteins to meet consumer expectations.

PBPs must demonstrate equivalent or superior nutritional, functional, and physiological properties compared to existing protein sources. There are four major PBPs (soy, rice, pea, and wheat gluten) presently offered in global commerce and an emerging fifth (chickpea). Soy and wheat gluten proteins have been marketed for more than five decades, and there is in-depth knowledge about their consumer acceptance and protein functionality. The other three aforementioned proteins are in their early commercial lives, and the knowledge around their nutritional, physiological, flavor, and functional characteristics is accumulating. Food formulators are seeking answers to enable them to partially or entirely replace existing proteins in new and existing products. The trials and tribulations in formulating PBPs have uncovered several benefits and disadvantages of using them. New protein manufacturers have likewise encountered positive and negative aspects of commercializing new PBPs. The perspectives offered in the remainder of this review are an examination of advantages and disadvantages (or challenges) beyond protein classes, major functionalities (gelling, foaming, gelation, etc.), and distinctive nutritional characteristics of the five

PBPs. Information on these topics can be found in excellent reviews published on each protein: see Ashaolu (2020), Monteiro & Lopes-da-Silva (2019), Rizzo & Baroni (2018), and Tang (2017) on soy; Boukid et al. (2021) and Lam et al. 2018 on pea; Amagliani (2017) and Romero et al. (2012) on rice; Anjum et al. (2007) and Rustgi et al. (2019) on wheat gluten; and Boukind (2021) on chickpea.

FACTORS INFLUENCING PLANT-BASED PROTEINS

Plant Genetics

The nutritional and functional properties of PBPs can be improved through classical breeding and biotechnology approaches (gene cloning and editing) to meet the growing global demand for these products. Novel screening technologies for studying the proteomics of plant cultivars enable quick determination of protein properties and mitigation of time-consuming field propagation, protein isolation, and characterization (Luthria et al. 2018). Many commercial PBP manufacturers claim to be using nongenetically modified cultivars for their concentrates and isolates, with the exception of soy. Fortunately for the industry and consumers, there are numerous cultivars for screening. Consumers are becoming more accepting of genetically modified and genetically edited products (Butkowski 2017). This will offer geneticists the ability to remove or edit the genes responsible for negative properties (discussed below).

Several studies have screened pea (*Pisum sativum* L) cultivars to quantify functionality, flavor, and color after manufacturing pea protein concentrates and isolates. Protein solubility and emulsification capacity vary between cultivars (Arteaga et al. 2021). Powder color was also significantly different. Arteaga et al. (2021) reported similarities in sensory characteristics (aroma and flavor) among the cultivars and protein isolates, except for the attributes of pea-like and bitter, which varied depending on the cultivar used for protein isolation. Other studies reported that the aroma of pea seeds changes significantly with cultivar, harvest year, and processing conditions (Azarnia et al. 2011, Cui et al. 2020b); foaming properties are more affected by extraction method than cultivar (Stone et al. 2015); and higher alkaline extraction pH impacted foaming functionality (Cui et al. 2020a).

Wheat cultivars may be the most studied crops for commercial protein concentrates and isolates. The baking industry relies on protein–protein interactions to form structure in baked goods. This important functionality has been extensively studied in durum wheat (Fois et al. 2011, Tosi 2005) and semolina (Kaur 2014). The protein functional properties for meat analogs and meat alternatives are gelation, binding, adhesion, emulsification, water binding, and structure building (Asgar et al. 2010). Gluten functional properties are unique among other PBPs in their ability to form a cohesive blend with viscoelastic properties once gluten has been heat-set or plasticized (Singh & MacRitchie 2001). Many meat alternative products have used this unique property to their advantage in forming structured meat alternatives and jerky products.

The primary PBP for decades has been soy protein. Soybean genetics is extensively studied because of this crop's importance in feeding livestock and edible oil extraction. Literally thousands of cultivars exist that are both non-genetically modified and genetically modified. Nonetheless, soybean genetics that influence protein functionality has not been characterized as extensively as that of wheat and pea proteins. Both of the latter proteins have more commercial significance that relies on their protein functionality. There are numerous references in the literature (Zhang et al. 2021) indicating that cultivars higher in production of glycinin and β-conglycinin are important for structure building in tofu, but little information has actually focused on improvement of functional properties such as foaming and gelation. We do know glycinin has a significant role in gel formation because of its numerous disulfide bonds, and a lesser role in emulsifying and foaming (Nishinari et al. 2014).

Food chemists have studied rice cultivars in relation to starch functionality (Patindol & Wang 2002) and nutritional properties. Protein functionality has not received much attention because rice proteins are large in molecular size and, as a result, demonstrate poor aqueous solubility. Most functional properties rely on the hydrodynamic properties of the proteins (Foegeding 2015). Nonetheless, a limited number of studies have identified the impact of cultivar on protein functional properties for this globally important food crop (Rafe et al. 2016). The Tarom cultivar was reported to have better functional properties, specifically solubility, emulsifying, and foaming, than the Shiroodi cultivar (Esmaeili et al. 2016). Waxy rice cultivars form stable emulsions at neutral pH (Mun et al. 2016). The results from these three studies indicate rice cultivars should be more closely examined to identify those important for protein isolates.

Similar to rice, chickpea starch functionality of different cultivars has been more extensively studied than protein functionality (Milán-Noris et al. 2016, Withana-Gamage et al. 2011). The use of chickpea as a PBP is rising, and more future studies will focus on cultivar selection in relation to its protein functionality. Commercial companies manufacturing chickpea protein concentrates and isolates have conducted a large amount of cultivar research but have not published this work because it offers them a competitive advantage. However, from the limited amount of published work, chickpea cultivars differ in their water-holding and oil absorption capacity. Gelling and emulsifying properties also appear to be different among cultivars.

The key takeaway from this genetic discussion is the following: Genetics does have an impact on protein functionality. With the exception of soybean and wheat, there have been very few in-depth studies on the impact of genetic control on protein functionality. This creates a "gray space" for research. Pea protein isolate is being extensively studied, as it has risen to prominence in commercial usage, and will continue to be studied given the number of new manufacturing plants being constructed for this PBP. Chickpea and rice cultivars are also being screened to optimize protein synthesis and functionality. Most of this research is being conducted by industrial research groups, and they hold their findings as proprietary.

Supply Chain Challenges

The growing demand by consumers for more PB foods has created opportunities for entrepreneurial companies to launch new PBP concentrates and isolates from multiple raw materials. Proteins are a main constituent of many agricultural commodities, and protein manufacturers have used this to offer innovative ingredients to food formulators for improving product nutritional values, physical functionalities, and/or physiological bioactivity. Outside of the global major crops (wheat, rice, corn, and soy), farmers have not produced the vast quantities of other crops to fulfill supply chain needs as a new protein entrant moves into commercial markets. Take, for example, yellow pea. A decade ago, most yellow pea was grown along the Canada–United States border; a minor amount was also grown in Europe. A majority of the crops grown in the Western Hemisphere were shipped to Europe for processing into pea starch and fiber. As consumers began pushing the industry to find alternatives to AB products for ethical and sustainability reasons, meat and dairy alternatives were formulated based on several different botanical sources, including soy, almond, rice, oat, and yellow pea. Global agronomic production has increased to meet the new demands of food formulators. However, larger acreage cultivation of crops does not rapidly occur. Commercial plant breeding is a complicated process. Seed stock to increase plant acreage requires extensive plant selection practices to identify top-performing candidates to produce the desired agronomic characteristics while maintaining crop yield and resistance to weeds and pests (Glenn et al. 2017). Once candidate hybrids are identified, it can take several growing seasons in both the northern and southern latitudes to obtain enough seed stock for farmers to plant the acreages required to supply raw material to protein manufacturers.

Sustainability

Increased consumption of beef and chicken as humans' main sources of protein over the past 75 years has placed pressure on global food security. This nutritional preference shift has led to substantial growth in intensive animal production for industrialization (Grigg 1995) and, in turn, concern for environmental issues such as soil erosion, generation of greenhouse gases, and water pollution. The animal meat industry is heavily criticized for these effects as well as for the perceived unethical treatment of animals. These factors have contributed to the rise in popularity of PB meat alternatives over the past decade. But are PBPs environmentally favorable?

Scientists, journalists, celebrities, and activists have outspokenly encouraged consumers to transition from AB foods to PB foods for both healthier eating and to save the environment (Gates 2021, Willet et al. 2019). However, PB products are expensive, nutritionally inadequate, and may not be as good for the environment as often touted (Adesogan et al. 2020). There has been much publicity about the supposed environmental and nutritional advantages of PB foods compared to AB foods. Many of the scientific publications studying the environmental consequences of PB foods rely on modeling studies that do not thoroughly examine all variables about dietary substitutions and nutritional adequacy (Ridoutt et al. 2017). Most studies make unsubstantiated assumptions about the interactions between food source, processing, human nutrition, and environmental impact. To undeniably claim PB foods are environmentally favorable, a shared-knowledge framework should be designed to guide future models and research on diet and environmental interaction (Ridoutt et al. 2017).

Plant-Based Protein Manufacture

Protein extraction from their native environments is a difficult task. PBP extraction is no exception (Kumar et al. 2021). Current methods are capital intensive, not very efficient, and often produce sidestreams and wastewater that are difficult and costly to further process. As a result, PBP manufacturers must often command prices higher than do ABP manufacturers.

Conventional PBP extraction techniques use alkalization and acidification technologies as part of their unit operations, but these methods are only efficient at removing approximately 50% of the protein present in the plant biomass (Karki et al. 2010, Kasai & Ikehara 2005). PBPs are difficult to extract from biomass because cellulose and hemicellulose fibers entrap protein molecules in their molecular structure. Some manufacturers further solubilize proteins from the initial extraction stages using conventional protein solubilizing by "salting out" the molecules from the alkalized solution. This method involves using appreciable amounts of sodium chloride that must be removed downstream where wastewater is further treated before release to the environment or municipalities (Kumar et al. 2021). Further inefficiencies in these extractions include sidestreams high in starches and fiber fractions that must be further concentrated and processed to develop products suitable for commerce to recover costs associated with raw material procurement. From a sustainability perspective, it is important to utilize every available fraction from PB raw materials.

Newer methods of PBP extraction are being scaled from laboratory and pilot plant developments that improve protein extraction efficiency, digestibility, and functionality (Kumar et al. 2021, Rahman & Lamsal 2021). An additional benefit is the reduction of environmentally unfriendly waste streams. Unfortunately, these technologies can be capital intensive, require more area in a manufacturing plant, and are limited in scale at this point. Nonetheless, these technologies will become more cost-effective in time and offer more innovative PBP products in an environmentally favorable way.

Aside from extraction technologies, PBP manufacturers face other challenges to offer these products as food ingredients. Few new green-field manufacturing facilities have been built for

PBPs; most companies have retrofitted existing manufacturing facilities. Other challenges include raw material segregation and storage, inadequate facility hygiene design to prevent cross-contamination among allergens, lack of food safety knowledge regarding these products, and an overall lack of process design knowledge to maximize efficiency. These factors are further complicated by a lack of subject matter experts in food science and process innovation, especially as related to PBPs.

Nutritional Value of Plant-Based Proteins

Protein malnutrition (a.k.a. severe acute malnutrition) exists in many parts of the world and is the leading cause of death globally in children under two years of age (UNICEF/WHO/World Bank 2021). Proteins are one of three macronutrients (lipids and carbohydrates are the others) that humans rely on for health and longevity. Most PBPs also contain small percentages of other nutrients such as fiber, starches, minerals, and other sugars. The most important aspects of any protein source are its total and essential amino acid content, digestibility, and overall composition. Dietary protein, upon digestion, provides amino acids as precursors for de novo muscle protein synthesis. Therefore, from a nutritional perspective, we should also consider gastrointestinal digestion leading to optimal biological function (Jiménez-Munoz et al. 2021).

The nine essential amino acids are especially important, as human cells cannot synthesize these at sufficient rates to meet metabolic demand, and therefore humans must obtain them through their diet. PBPs have relatively low amounts of essential amino acids and leucine contents compared to ABPs (Gorissen et al. 2018). Additionally, some PBPs are low in lysine, cysteine, and/or methionine. In fact, a single plant protein in a formulated food product is not sufficient to provide the consumer an appropriate daily dietary source of amino acids (Day 2013). Fortunately, most people consume several different protein sources in their daily diet in sufficient quantities to meet metabolic demands for muscle synthesis (Balandrán-Quintana et al. 2019).

The past half-century has witnessed a concerted effort by scientists to genetically improve the main protein crops: wheat, corn, and soy. The levels of essential amino acids (including those containing sulfur) have improved (Kumar et al. 2020). However, lysine remains a challenge. Traditional genetic and breeding approaches are not sufficient to change the highly regulated lysine metabolic pathway in most plants without detrimental consequences to crop yields and plant growth (Galili & Amir 2013). Two genetically modified cultivars have been successfully introduced for increased lysine content. One encodes for the enzyme responsible for the first step in lysine biosynthesis, and the other increases free lysine content (Kumar et al. 2020). Genome editing was successfully used in soybeans to increase the levels of branched-chain amino acids in synthesized proteins (Li et al. 2015). Genetic modification and editing of plants in the future will improve PBP quality, nutritional value, and functionality, but the bioefficacy and biosafety will need confirmation, as nutritionists have questioned whether PBPs are digested in a manner similar to ABPs.

The nutritional equivalency of PBPs to ABPs is questioned because PBPs have less of an anabolic effect because of their lower essential amino acid content, digestibility, and levels of lysine and sulfur amino acids. The human species directs plant-derived amino acids toward oxidation rather than muscle protein synthesis (Pencharz 2016). In healthy, younger individuals, this does not present much of a problem, as their metabolism compensates to maintain muscle homeostasis. However, older individuals develop resistance to postprandial amino acid absorption and subsequently do not replace muscle loss (Berrazaga et al. 2019, Traylor 2018).

ABPs are more digestible than PBPs (FAO 2011). This is partially explained by the greater amounts of β-sheet pleating in PBP secondary structure (ABPs either have no secondary structure or are mostly in a helical conformation). β-sheeting molecular conformation interferes with host digestive enzymes to access and digest native proteins (Carbonaro 2012). Digestion is further complicated by the fact that PBPs are intercalated with plant fibers causing steric hindrance and essentially burying enzyme attack points (Nguyen 2015). Digestibility of commercial PBP concentrates and isolates is slightly improved, but they still have lower ileal digestibility (Davies & Jakeman 2020). As more PB foods become popular with consumers, scientists will need to study the bioaccessibility and bioavailability of PBP amino acids.

Research gaps remain in our understanding of PBP digestibility and ultimate nutritional value. Furthermore, PBP manufacturing processes positively and negatively impact the nutritional and functional value of these proteins. Mixed-protein systems (both PBPs and ABPs) appear to be better for both functionality and nutrition, and this emerging area will likely receive considerable attention in the coming years (Gorissen et al. 2018, Jiménez-Munoz et al. 2021).

Physical and Physiological Functionality

The use of PBPs to reduce or replace ABPs in food formulations has steadily increased during the past decade. As this trend evolved, protein manufacturers commercialized more PBP concentrates and isolates beyond the common soy and wheat gluten complexes. Proteins are used in food formulations because their amphiphilic nature interacts with several other molecular compounds found in food products to emulsify, foam, gel, bind oil and water, build structure, and/or form protective films. The interactions occur through hydrophobic interaction, electrostatic interactions, hydrogen bonding, and, occasionally, covalent bonding. In general, proteins interact with each other or other proteins, carbohydrates (including complex carbohydrates such as starches, fibers, and hydrocolloids), and minerals in food systems. Food processing through various unit operations can influence the degree of interaction. Subsequently, storage conditions may also modulate further interactions as water evaporates from the completed food or the inherent vibrant mobility of protein molecules causes undesirable interactions such as firming observed in many nutritional bars.

Many PBPs function similarly to ABPs. Unfortunately, most do not have as complete a functionality repertoire as animal proteins. Food formulators have worked around this by combining different PBP types (mixed-protein systems) to accentuate some functional properties and align them more closely to ABP systems. Mixed-protein systems also allow the development of innovative applications, often with synergistic functional properties (Alves & Tavares 2019). Most research conducted in this area has utilized dairy proteins along with soy and pea proteins. For example, combining whey protein isolate with soy protein isolate and heating the system showed formation of soluble and insoluble aggregates that influenced the final texture of a model food system (Roesch & Corredig 2005). The size of aggregates, and changes in the resulting product texture, could be influenced by varying the ratio of whey protein isolate to soy protein isolate. This offers food formulators a means to increase protein in a food system without impacting the final product texture. Similar results were reported with pea protein isolate and the whey protein β-lactoglobulin (Chihi et al. 2016). The authors noted a reduction in aggregate size when these proteins were heated together in a model food system, and the food texture was different when either protein was heated alone (Chihi et al. 2016). Other functional properties influenced by mixing PBPs and ABPs include increasing the resistance of gas bubbles from coalescing in foams, increasing emulsion and gel firmness, reducing gel syneresis, increasing the protein concentration of gels without affecting gel strength, and increasing thermal stability of proteins (Alves & Tavares 2019).

Consumer Acceptance

Consumer acceptance of PBPs is ambivalent, but their acceptability of PB foods is rapidly growing. The only proteins consumers have expressed negativity toward are wheat gluten and soy.

Gluten intolerance only occurs in 0.5–1.0% of the population, but in recent years a global fad has implied gluten as a culprit protein in numerous human illnesses (Gujral et al. 2012). This has caused many consumers to avoid gluten in all foods, despite most not being clinically diagnosed with a gluten intolerance (Croall 2019). Soy protein flavor has been criticized because protein concentrates and isolates first appeared nearly 50 years ago. Obviously, soy (and other PB) protein manufacturers have improved flavor by modifications across the entire seed genetics to food preparation spectrum, but many consumers still express flavor sensitivity. Additionally, researchers expressed concern about soy isoflavones having estrogenic activity, but others have demonstrated this activity is very low and tissue specific (Rizzo & Baroni 2018). Other positive health attributes such as reduction of inflammation, oxidation, and, ultimately, cardiovascular disease outweigh this concern.

The most important sensory attributes of PBP products are color, flavor, and texture. These factors have a large influence on consumer appeal and acceptance. Bitter flavors are often cited by consumers as a negative attribute of PB foods. The issue of negative flavor perception in PB products is being addressed by flavor companies producing flavor blockers. These molecules target compounds eliciting a bitter flavor (Gaudette et al. 2016). Despite a growing presence of bitter blockers in PB foods, consumers still feel these products are not as flavorful as AB products. The complexity of PBPs' aromas and flavors will be further differentiated in the future by using metabolomics (Pavagadhi & Swarup 2020). This will allow flavor chemists to accurately prescribe blocking agents to prepare more desirably flavored PB foods.

Food scientists are also becoming more familiarized with formulating food dishes that incorporate PBP alternatives to both meat and dairy. Consumers have readily accepted the emergence of PBP meat alternatives for dishes typically utilizing ground meat or sausage in their preparation. Fortunately, consumers view meat, regardless of whether it is an ABP or PBP, as an important component of most meals (Mackenzie & Shanahan 2018). Greater opportunities for PBP meat alternatives will evolve as different "cuts" become available representing multiple species. Furthermore, if research data can support the nutritional equivalency of PB meats to AB meats, more consumers will incorporate these products into their diets.

Climate Change

Consumers often cite that their reason for consuming more PB foods is attributed to the impact on our climate of raising livestock. One metric tracked by atmospheric scientists for indication of climate change is atmospheric carbon dioxide concentration. Global CO_2 has risen from 180 ppm (glacial periods) to 384 ppm in 2009 with a consequential mean temperature increase of 0.76°C (IPCC 2007). The impact of climate change has encouraged plant scientists to identify how it is impacting crop characteristics, including protein concentration and composition.

A meta-analysis (228 studies) summarized the impact of elevated CO_2 concentration on protein concentration and composition in major food crops (Taub et al. 2008). Protein concentration decreased 10–15% in wheat, rice, and barley; 14% in potatoes; and only 1.4% in soybean. More acres will need to be planted to feed our increasing global population if this trend is not reversed. Further investigation into the protein composition of crops being grown in elevated carbon dioxide atmospheres and processed into concentrates or isolates has shown that some amino acids are significantly reduced. More specifically, wheat showed differentiated proportions of glutenin and gliadin protein classes. These proteins are major functionality contributors to dough and bread (Högy & Fangmeier 2008). Similar results were reported in protein subclasses from rice (Terao et al. 2005). Interestingly, barley protein from plants grown in higher CO_2 atmospheres had higher proportions of essential amino acids in their primary sequences (Manderscheid et al.

1995). All these studies have been conducted in potted plants under controlled atmospheres, and future investigations should be conducted under actual field conditions.

By inference, changes in protein concentration and composition could potentially be impacted by climate change. If the proportion of hydrophobic or sulfur-containing amino acids changes, protein physical functional properties (gelation, foaming, emulsification, etc.) may change. Regarding PBP functionality evolving with climate change, we do not have a historical perspective for comparison. Soybean proteins have been studied for more than a half-century, but this time frame may be too short to understand climate change's impact on changes in functionality. We have some evidence from the microbial world that proteins do adapt to increased environmental temperature by a set of imprecise molecular signatures, and there are major roles for solvent accessibility, disulfide bonds, hydrophobicity, hydrogen bonds, and ionic and pi-electron interactions that lead to condensed packing of protein molecules (Barik 2020). Whether PBPs will evolve to improve their thermoresistance for the plant's own survivability is unknown. Any such changes in a plant's molecular signature will be subtle, and it is likely PBPs will retain or improve their physical functionality.

Safety and Allergenicity

Food allergies and intolerances have been increasing globally, and with the increased consumption of PB foods, this trend will likely continue. Allergenic responses to PB foods are usually caused by proteins and pollen cross-reactivity. People with food allergies generally know which of the "Big 9" (wheat, soy, sesame, eggs, fish, tree nuts, peanuts, milk, and shellfish) to avoid. However, with the increased usage of PBPs in many food categories, consumers with allergies, and even individuals that may not have experienced a previous allergic reaction, need to be cautious. For example, individuals with soy or peanut allergies must be especially cautious of foods containing pulse proteins. Some individuals with wheat intolerance or allergy may not be aware they will also negatively respond to barley and rye proteins. The concern about many novel proteins is their allergenicity may not yet be known. Reputable protein manufacturers are analyzing the primary sequences of novel proteins to determine if there are allergenic epitopes in the primary sequences of their protein products. Other proteomic methods are emerging with increased sensitivity to identify allergenic potential (Verhoeckx et al. 2016). Any protein can be allergenic with repeated exposure. The allergenicity of many proteins can be attenuated by processing exposure to heat, enzyme hydrolysis, or high pressure (Johnson et al. 2010, Kasera et al. 2015).

FORMULATING WITH PLANT-BASED PROTEIN

Consumers have used their immense buying power to encourage the food industry to rapidly develop novel PB foods because they are more ethical and ecofriendly than AB foods. However, as food formulators began incorporating PBPs into existing and new recipes, they quickly realized PBPs could not simply be substituted one-for-one for ABPs. These ingredients have been criticized from their very beginnings as having beany, bitter, and astringent sensory characteristics that diminish the positive sensory experience. The flavor and aroma of soy protein concentrates and isolates have improved over the past 50 years, but newer PBPs have not been able to apply technical information gleaned from soy to their botanical sources. Furthermore, many PBPs are not as nutritionally complete and digestible as ABPs, causing food formulators to design foods using protein mixtures to create healthier products that meet consumer nutritional needs (Cossen et al. 2021).

Besides their nutritional properties, proteins are often used as food ingredients for their functional properties. The functional efficacy of proteins is directly correlated to their composition, concentration, and interaction with other ingredients in a food system. As new PBPs enter commercialization, protein scientists continually characterize their protein systems from a primary perspective of physical functionality in a semipurified form (e.g., as concentrates and isolates). However, testing physical functionality in food systems must be validated to confirm any protein, including PBPs, demonstrates functionality. PBPs are functional in several circumstances, but there are some cases in which it is not possible to take advantage of these properties. For example, gelation of PBPs often requires the presence of appreciable sodium chloride levels in the food system. This may not be in the consumer's best interest from sensory and health perspectives.

The emerging popularity of PBPs has encouraged scientists to study the interactions of PBPs with other food polymers to improve the quality and nutritional value of food formulations (Lin et al. 2017). Although PBPs generally display good interactions with other edible polymers, the characteristics of one botanical source may not be demonstrated by another. Furthermore, most of these studies have been conducted only in laboratory biphasic systems, and when translated to multiphasic food formulations, positive interactions observed earlier in the laboratory seem to not directly correlate with lab-observed behaviors. Nonetheless, PBPs interact with themselves and other proteins, as well as edible polymers, to form a variety of complexes with different structures (Lin et al. 2017). These interactions can be advantageously used for fat substitution, encapsulation, and novel emulsion systems (Pickering emulsions) (Hu et al. 2016).

Two important criteria consumers use to judge a product are appearance, when purchasing the product for the first time, and sensorial experience, when deciding whether to repurchase the product. Flavor and aroma are paramount in this consumer evaluation. The scientific literature contains numerous studies on the interactions of volatile flavor compounds with ABPs and PBPs in model systems, but the mechanisms responsible are very ambiguous (Wang & Arntfield 2017). Understanding and evaluating protein–flavor interactions can be challenging. As mentioned earlier in this review, PBPs are often undesirably associated with both volatile and nonvolatile flavors and aromas. It is challenging for food formulators to overcome these properties. Many formula iterations must be tested using various flavor blockers and potentiators. Iterations are costly and time consuming, and food formulators must become familiarized with all PBP offerings to develop the best-tasting products. There are wide variances in product quality among PBP products.

In a haste to launch new products and take commercial advantage of rising trends, many new PB foods were formulated using very complex mixtures of food ingredients and the inclusion of PBPs. These products were quickly criticized by nutritionists, minimalists, and the medical profession, all claiming that many of the products were less healthy than the products they were replacing (Barrett 2020). As food formulators learned more about PBPs, subsequent generations of PB foods have reduced the numbers of ingredients used in their products, and new products boast about their "cleaner label."

CONCLUSIONS AND OUTLOOK

A rapidly increasing global population is impelling scientists to develop novel food ingredients in an environmentally and ethically favorable manner to feed future generations. PBPs are rapidly emerging as suitable alternatives for ABPs in response to these principles. However, food scientists eager to use PBPs in food formulations are often disappointed in their implementation because of off-flavors, poor functionality, or missing key nutrients. There are nearly 400,000 species of vascular plants in the world, and it is believed nearly half of them are edible. Yet we only consume approximately 200 different species. Even fewer are used for protein products. It is apparent not only that scientists will improve the products we commercially produce today but that there is a rather large palate to explore further. The good criteria of PBPs commercialized today will be further exploited, and the bad and ugly characteristics will be minimalized with future generations of PBP products.

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