Complementing Cereal Grains with Pulse Grains to Enhance the Nutritional and Environmental Sustainability Profiles of Manufactured Foods in Canada and the United States

Christopher P. F. Marinangeli, PhD, RD[1]
Pulse Canada, Winnipeg, MB, Canada

ABSTRACT

The interplay between environmental sustainability and reduced risk of chronic disease with dietary choices is often underpinned by the source of protein within a given dietary pattern. This review discusses opportunities to use pulses to increase the proportion of plant protein in manufactured foods to promote dietary patterns that simultaneously promote nutritional adequacy and environmental sustainability. Although consumption of pulses remains relatively low in Canada and the United States, there is a profound opportunity to use pulses to incorporate high levels of plant protein into dietary patterns and, when combined with cereals, provide a sufficient quantity of all of the indispensable amino acids. Increasing the demand for pulses as a food and food ingredient has the potential to expand their production in North America and lower the environmental impacts of modern agriculture. Sourcing cereals from sustainable cropping systems that incorporate pulses can also facilitate higher yields, enhance soil organic carbon, soil biomass, and nitrogen and water use efficiencies and permit the adoption of environmentally conscientious technologies such as zero tillage. The use of pulses in combination with cereal grains could assist the food industry with providing staple foods and food innovations that align with global health and environmental targets.

Population growth, increased incidence of preventable chronic diseases, and the concurrent effects of diet on climate change have spawned discussions and approaches that encourage the consumption of diets that incorporate more foods from plants. The interplay between environmental sustainability and reduced risk of chronic diseases with dietary choices is often underpinned by the source of protein within a given dietary pattern (64). This is due to the environmental pressures, particularly greenhouse gas emissions, generated by the production of livestock and the associations between high consumption levels of animal protein and risk factors for chronic diseases (70). Increasing the consumption of plant-derived proteins has been identified as a primary strategy to bridge the nutritional gap between protein production and the environmental sustainability of diets. This has been reflected in the newest iterations of dietary guidelines and principles from around the world, including Canada, Brazil, Germany, the Netherlands, Nordic countries, and Qatar (24,25, 30,49,54,67), as well as global modeling analyses focused on production strategies for concurrently meeting the nutritional requirements of humans while meaningfully reducing the effects of dietary choices on climate change (71,83).

Similar to other regions, cereal grains are staple foods in North America. Agricultural production of cereals, particularly wheat, corn, barley, rice, and oats, is widespread. Combined with robust supply chains within Canada and the United States, production is able to meet the demands of industry. Cereals have been consumed by humans for thousands of years (45), and their use has grown considerably during the development of the modern food and feed industries and the technological revolution in food manufacturing that has occurred over the last century. With few exceptions, most cereals undergo some form of processing prior to their consumption by humans. The processing of grains can include a wide variety of techniques, from sprouting and milling to more sophisticated processes, such as extrusion. As sources of dietary fiber and various micronutrients, consumption of cereal grains, particularly whole grain cereals, has been consistently associated with healthy dietary patterns and reduced risk for chronic diseases (4,65,66). For these reasons, whole grain cereals are included in food-based dietary guidelines.

Cereal grains typically contain 6–15% protein (45). When incorporated into whole or refined cereal foods, such as breads, pasta, breakfast cereals (including oatmeal), and crackers, protein levels range between 1.7 and 4.1 g/serving (61). Given that cereal grains are ubiquitous in Western dietary patterns, it is not surprising that they represent a significant source of plant protein consumed by humans despite being relatively low in protein. For example, analyses of the National Health and Nutrition Examination Survey (NHANES) in the United States have demonstrated that between 2003 and 2010 yeast breads and rolls were the primary sources of plant protein and represented 5.6–6.4% of daily plant protein consumption (57,58). Compared with nondairy animal protein (46%), plant protein intake represented ~30% of daily protein consumption, of which yeast breads, rolls, and buns contributed ~18% of plant protein/day (58). Similar results from France's Second Individual and National Study on Food Consumption Survey (INCA2) demonstrated that 30% of total daily protein consumption was from plants, with 21.5% from cereals (12). In the United Kingdom, the National Diet and Nutrition Survey (NDNS) demonstrated that 23–24% of protein in adult diets was from cereal and cereal products (20).

Plant-based protein foods are generally lower in one or more indispensable amino acids (IAA) when compared with human requirements, which necessitates that a variety of plant proteins

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[1] Director, Nutrition Science and Regulatory Affairs, Pulse Canada, 920-220 Portage Ave, Winnipeg, MB, R3C 0A5, Canada. Tel: +1.905.330.0514; E-mail: cmarinangeli@pulsecanada.com; ORCID: https://orcid.org/0000-0002-0881-9921; LinkedIn: www.linkedin.com/in/chris-marinangeli-phd-rd-690b2126; Twitter: @DrCMarinangeli

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be consumed daily to complement any IAA shortfalls. As an example, cereals generally have lower levels of the IAA lysine, as well as tryptophan, or threonine (26). As global conversations propose that dietary patterns shift to derive more protein from plant foods, reliance on a single taxon to fill a possible IAA gap created by displacing some animal protein from diets could present nutritional challenges. However, leveraging the nutritional attributes of cereal grains with other plant protein foods, such as pulses, presents an opportunity to simultaneously enhance the nutritional density and environmental sustainability of diets.

Similar to cereal grains, pulse grains have also been consumed by humans for thousands of years (47). As part of the Leguminosae (Fabaceae) family, pulses are a subset of legumes broadly identified as various genera of dry beans, lentils, peas, and chickpeas (15). They too are represented in dietary guidelines as nutrient-dense foods with substantial levels of various nutrients, including, fiber, folate, iron, and potassium. Unlike cereals however, pulses are often identified as a protein food (31); in their raw and dry forms they contain 20–30% protein. Similar to cereal grains, increased incorporation of pulses into dietary patterns has also been associated with reductions in cardiometabolic risk factors (78). Healthy dietary patterns associated with reduced chronic diseases, such as the Mediterranean Diet and Nordic diets, derive significant amounts of protein from pulses (1,11,51). In addition, given their high lysine content, pulses can be used as a complementary protein source to cereal grains to help address possible IAA gaps as diets shift to include more plant-derived proteins (55).

Despite the rich history of pulses as part of human diets, consumption of pulses as a protein food remains relatively low in many developed regions, including Canada and the United States (50,52). In the United States, NHANES 2007–2010 showed that legumes in general represented 2.8 and 1.3% of total daily protein and plant protein intakes on any given day, respectively. In France, INCA2 showed that 1% of plant protein was from legumes, and, in the United Kingdom's NDNS, legumes were not specifically identified as a source of plant protein (12, 20). In addition to their nutritive aspects, pulses are considered to be environmentally sustainable from the perspective of agricultural production.

The reliance on cereal grains as a primary source of plant proteins in Western diets is not intentional. It is partially an artifact of the historical use of cereal grains as a nutritious dietary staple for humans. In essence, humans eat a lot of cereal grains. Cereal grains also have other applications, such as for animal feed. Familiarity and tradition have nurtured the expansive growth and knowledge regarding the functional attributes of cereals grains relative to other grains in manufactured food products. This has helped cultivate an environment with less diversity in the use of noncereals by the food industry. As demonstrated in Figure 1A and B, the harvested area and production of cereal grains has traditionally, and continues, to far surpass that of pulses in Canada and the United States (16). From this, one can rationalize the high use of cereals across the Canadian and American food value chains. However, production of pulses in Canada and the United States has been increasing, particularly over the last three decades. Between 1961 and 1992, the average area (±SD) and production yield (±SD) for U.S. and Canadian pulses were 0.77 ± 0.1 million ha and 0.17 ± 0.16 million ha and 1.18 ± 0.25 million tonnes and 0.26 ± 0.25 million tonnes, respectively (Fig. 2A and B) (16). Since that time (1992-2018), average pulse production has grown to 1.11 ± 0.31 million ha and 2.05 ± 0.58 million tonnes in the United States and 2.28 ± 0.85 million thousand ha and 4.29 ± 1.82 million tonnes in Canada. The intrinsic physiological attributes of pulse crops, including their ability to fix atmospheric nitrogen and relatively low water requirements, highlights their ecological benefits for cropping systems in North America. Moreover, the use of pulses, predominantly peas and lentils, has been shown to have profound effects on environmental sustainability of diversified cropping systems by reducing the need for summer fallow, while also enhancing the yield, water use efficiency, and fertilizer use efficiency of cereal crops grown in rotation with pulses (5,21,73).

Concerns over health and climate change are challenging the industry to provide foods that drive an increase in protein consumption from plants. The purpose of this review is to discuss the opportunities to use pulses to increase the proportion of plant protein in manufactured foods to promote dietary patterns that simultaneously support nutritional adequacy and environmental sustainability. While the nutritive and environmental aspects of pulses will be highlighted, opportunities for nutritional and environmental complementarity between pulses and cereals by the food industry in manufactured food products will

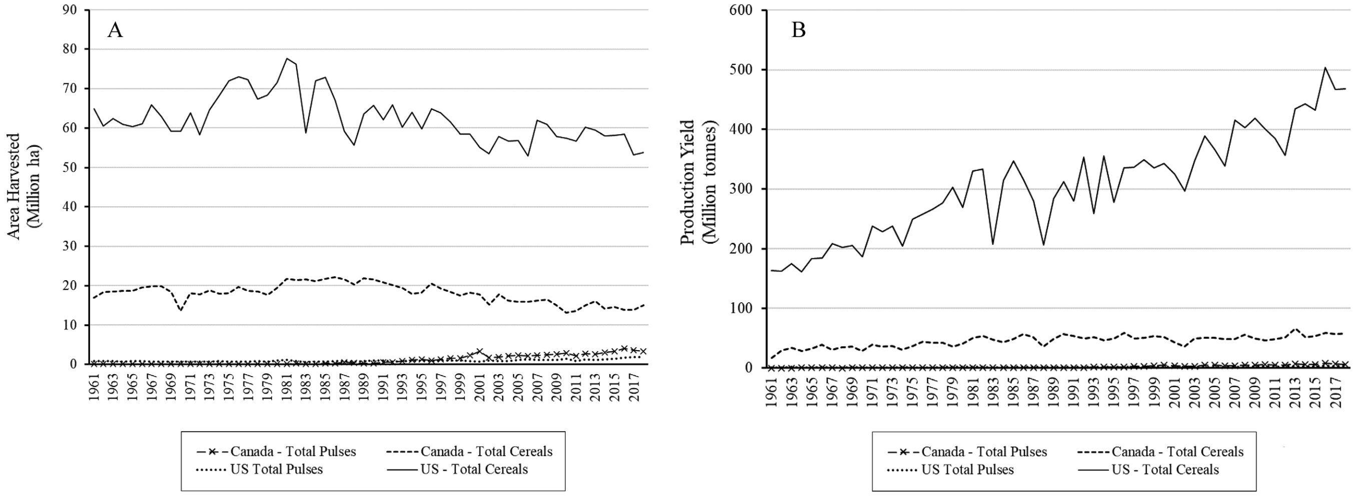

Fig. 1. Comparison of total cereal grain and total pulse grain production in Canada and the United States from 1961 until 2018. **A,** Area harvested (million ha); and **B,** production yield (million tonnes). Data source: FAO (16).

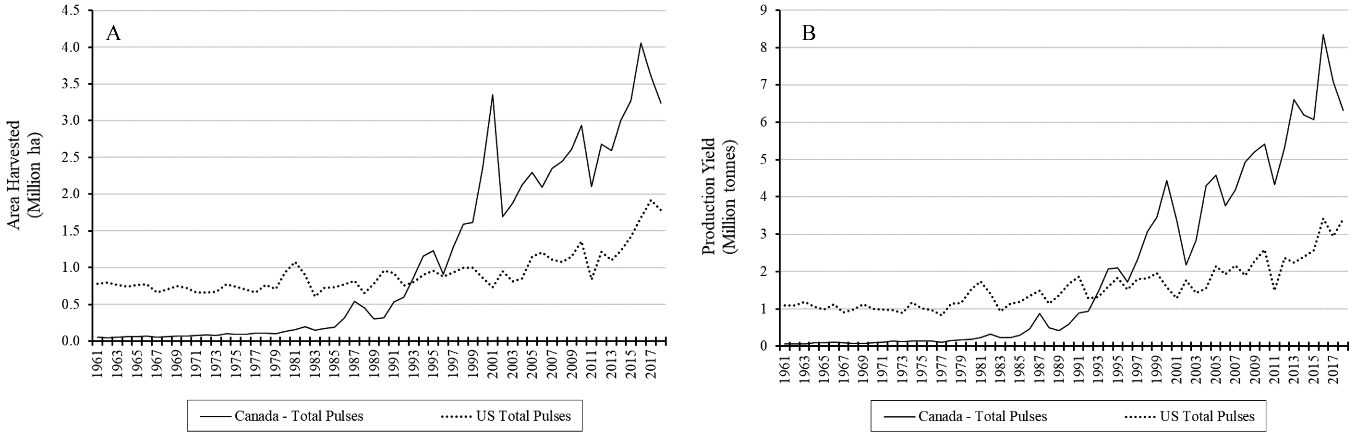

Fig. 2. Comparison of total pulse grain production in Canada and the United States from 1961 until 2018. **A,** Area harvested (million ha); and **B,** production yield (million tonnes). Data source: FAO (16).

Table I. Nutritional composition (per 100 g) of a subset of cooked and raw pulses

Pulse (FDC ID)[a]	Energy (Kcal)	Protein (g)	Carbohydrate (g)	Fiber (g)	Lipid (g)	Fe (mg)	K (mg)	Folate (µg)
Cooked pulses[b]								
Black beans (173735)	132	8.86	23.71	8.7	0.54	2.1	355	149
Navy beans (173746)	140	8.23	26.05	10.5	0.62	2.36	389	140
Pinto beans (175200)	143	9.01	26.22	9.0	0.65	2.09	436	172
Kidney beans, all types (173740)	127	8.67	22.8	6.4	0.5	2.22	405	130
Lentils (172421)	116	9.02	20.13	7.9	0.38	3.33	369	181
Split peas (172429)	118	8.34	21.1	8.3	0.39	1.29	362	65
Raw pulses								
Black beans (173743)	341	21.6	62.36	15.5	1.42	5.02	1,483	444
Navy beans (173745)	337	22.33	60.75	15.3	1.50	5.49	1,185	364
Pinto beans (175199)	347	21.42	62.55	15.5	1.23	5.07	1,393	525
Kidney beans, all types (175193)	333	23.58	60.01	24.9	0.83	8.2	1,406	394
Lentils (172420)	352	24.63	63.35	10.7	1.06	6.51	677	479
Chickpea (173756)	378	20.47	62.95	12.2	6.04	4.31	718	557
Peas, split green (172428)	364	23.12	61.63	22.2	3.89	4.73	852	15

[a] FDC: FoodData Central. Source: U.S. Department of Agriculture Standard Reference Legacy Database (76).

[b] Analysis from pulses boiled without salt.

also be discussed. Examples will focus on lentil and pea production as they represent the greatest proportion of pulse production in Canada and the United States.

An Overview of Nutritional and Environmental Sustainability Attributes of Pulses

Nutritional Composition of Cooked and Raw Pulses. The primary attributes of pulses that differentiate them from other legumes is that they are harvested as a dry grain and they contain insignificant levels of lipids (15). Thus, soybeans and peanuts are not pulses. The low level of lipids is a positive attribute that can broaden the application of pulses within the food innovation pipeline, since lipids can interfere with some processing technologies, such as extrusion (59). This can permit unfractionated, nutrient-dense pulse flours to be used in a wide variety of food platforms.

The nutritional composition for some pulses for a subset of nutrients and fiber is summarized in Table I. For the most part, pulses are most often promoted and consumed as whole cooked seeds that are prepared by boiling in water from their dry form or from a can. Nutritional data for traditionally prepared pulses shows they contain high levels of plant-derived protein, ranging from approximately 8 to 9 g of protein/100 g, as well as high levels of fiber, iron, potassium, and folate, ranging between approximately 6 and 9 g/100 g, 1.3 and 2.4 mg/100 g, 355 and 436 mg/100 g, and 65 and 181 µg/100 g, respectively. Fiber, iron, potassium, and folate have been identified as nutrients of concern in specific age and sex groups in Canada and the United States (29,77). Traditionally cooked (i.e., boiling) and canned pulses are primarily captured in national nutritional survey data where, compared with nonconsumers, the highest levels of pulse consumption have been shown to increase intakes of dietary protein, fiber, folate, zinc, and potassium (50,52). Higher consumption of pulses has been linked to reductions in risk factors for chronic diseases, including lower LDL cholesterol levels and blood pressure and improvements in weight management (6,27,34,37,39,78). Pulses have also been shown to be effective for blood glucose management (60,69). However, results from the EAT-*Lancet* Commission indicate the consumption of legumes, across all regions analyzed, fail to meet proposed levels of intake corresponding to the commission's Planetary Health Diet eating pattern (83).

Historically, traditionally prepared or canned pulses have been the primary vehicle for incorporation into diets as either standalone foods or as ingredients in prepared dishes. However, given their inherent nutritional composition and the global movement to increase the proportion of plant protein in Western dietary patterns, there is increased interest in pulses as ingredients in manufactured food products. While largely rooted in their ability to bolster the protein levels of these foods, other nutritional enhancements can also be realized. As an ingredient, losses of nutrients from whole milled pulses are nominal, which can create an alluring nutritional value proposition for the food industry. As outlined in Table I, protein levels of dry pulses range between 21 and 25%, which can be attractive as a high-protein, plant-based ingredient. Currently, peas and, to some extent, lentils represent the primary pulses used as ingredients in manufactured foods in North America, which is secondary to their composition, availability, cost, and accessibility to infrastructure to process into usable applications across food platforms.

Although Table I provides a nutritional snapshot of pulses, similar to other crops, their nutrient levels can vary annually depending on genetic and environmental factors. Genetic variation in the protein content of lentil seed from around the world has ranged between 23 and 36% (36). From 2009 to 2019, the mean protein of Canadian peas and lentils ranged between 22.0 and 23.9% (mean 22.8%) and 25.6 and 28.0% (mean 26.7%), respectively (80,81). As interest in pulses as sources of protein increases, research and supply chains are becoming increasingly refined, in which compositional and functional properties of specific varieties of crops are being identified and developed. For example, lentil variety and protein levels have been shown to affect dehulling efficiency and, perhaps, functionality in food products (79). Recent genomic analyses of 135 accessions for field pea identified single-nucleotide polymorphisms associated with seed protein concentrations, which could assist in developing future varieties of field pea with protein attributes that have nutritional and functional benefits across food applications (22).

Pulses and Environmental Sustainability. The environmental sustainability of food systems is extremely complex. It is not only dictated by inputs and methods used throughout the food value chain, but socioeconomic drivers of production and dietary patterns within regions must also be considered. Food production has been identified as the largest contributor to environmental change, which includes greenhouse gas emissions, freshwater use, land use, and terrestrial and marine life and biodiversity depletion (83). Analyses by Springmann et al. (70) predicted that the environmental pressures imposed by food production and consumption from greenhouse gas emissions, cropland use, blue water use, phosphorous application, and nitrogen application are projected to increase by 87, 67, 65, 54, and 51%, respectively, by 2050 if current models remain as the status quo. With respect to greenhouse gas emissions, the production of animal products represented the highest environmental pressure. The same study predicted that the adoption of dietary patterns that emphasize a reduction in animal protein and higher consumption of plant-based foods, including legumes, predicted a decrease of 29–56% in the projected environmental pressure of greenhouse gas emissions by 2050 (70).

From a production standpoint, pulses are considered an environmentally sustainable crop. One of the most discussed attributes of pulses has been their ability to extract, or fix, atmospheric nitrogen by way of a symbiotic relationship between the plant and bacteria that reside in the root nodules of legumes. The ability of pulses to fix nitrogen can significantly reduce the need for synthetic nitrogen fertilizer. The production and application of nitrogen fertilizers generates significant CO_2 and N_2O emissions, which contribute to climate change (73). Pulses also can help to maintain soil quality by increasing soil organic carbon by way of returning carbon, nitrogen, and biomass to soil (73).

A meta-analysis of life-cycle analysis (LCA) studies of various fresh food categories corroborates the low carbon footprint of legumes and pulses: 16 LCA studies for legumes and pulses generated a mean and median carbon footprint of 0.51 kg of CO_2 eq/kg of produce and 0.66 kg of CO_2 eq/kg of produce, respectively (10). The global warming potential of legumes and pulses was considerably lower than other protein foods, such as nuts and various animal products (1.20–26.61 kg of CO_2 eq/kg of produce or bone-free meat) (10). The meta-analysis included legumes that are not considered pulses, such as peanuts and groundnuts, and thus, there is further opportunity to inform and leverage the sustainability of pulses grown in specific jurisdictions that have implemented sustainable production practices, particularly in North America. For example, a carbon footprint analysis of Canadian production of lentils (Alberta and Saskatchewan) that considered changes in soil carbon, direct and indirect N_2O emissions, emissions associated with seed, pesticide, and fertilizer production, and direct on-farm energy use demonstrated a negative weighted average global warming potential of –108.1 kg of Co_2 eq/tonne (62). This was largely secondary to the adoption of agricultural tools that foster significant levels of soil carbon sequestration (–328.3 kg of CO_2 eq/tonne of lentils) (62). A similar carbon footprint analysis on Canadian peas grown across Alberta, Saskatchewan, and Manitoba generated a low weighted average carbon footprint of 36.1 kg of CO_2 eq/tonne; substantial soil carbon sequestration was also demonstrated (–207.5 kg of CO_2 eq/tonne) (63).

The food industry is increasingly aware of the environmental sustainability of food offerings, and it is often woven into their innovation platforms and social responsibility commitments. Thus, regionally specific environmental data, as demonstrated for Canadian peas and lentils, could be a valuable asset to supply chains as use of pulses as a source of protein by the food industry becomes increasingly relevant. In 2018, the Alberta Pulse Growers Commission acquired an Environmental Protection Declaration (EPD) for Alberta-grown peas (74). EPD is a third-party certification based on the International Organization for Standards' published standard for environmental labels and declarations (ISO 14025:2006) (33,75). The EPD provides an open and transparent platform for communicating the LCA of Alberta peas for use and comparison. The availability of regionally specific LCA on the production of pulses and other commodities could drive the development and adoption of sustainable agricultural production as the environmental food market becomes increasingly competitive. For example, the Canadian agricultural sector has successfully adopted practices that have enhanced the environmental profile of production. This has included the adoption of conservation tillage technology: between 1981 and 2011 zero tillage use in the Canadian Prairies increased from 3 to 10% of cropland to up to 70% in some regions (5). These practices, alongside the widespread adoption of cropping systems without fallowing (5), are what largely generated the net carbon sequestration values in soil for the production of Canadian peas and lentils discussed previously (62,63). This will be discussed in more detail in the latter sections of this article.

Finally, the ability for some pulses, such a pea, lentil, and chickpea, to be grown in semiarid conditions, such as the northern

Great Plains of Canada and United States, and their resistance to water-stressed conditions, can also enhance their utility as a sustainable source of plant proteins (2).

Finding Complementarity between Pulses and Cereals to Enhance the Nutritional and Sustainability Profiles of Foods

Nutritional Complementarity of Pulses and Cereal Grains. Both pulses and whole grain cereals are nutrient-dense foods. When combined together, the fiber, folate, iron, potassium, and other micronutrients from pulses can complement the nutritional profile and health benefits of whole grain cereals. Combining cereal grains with pulse grains is a viable strategy for ensuring IAA adequacy if dietary patterns are to rely more heavily on plant protein sources. Pulse grains contain 50 to ≥100% more protein per 100 g, dry weight, than cereal grains, making them practical foods for increasing the proportion of plant protein in diets. If the relative amounts of dietary plant proteins are to increase at the expense of animal sources of protein, it is critical that recommended IAA requirements are met. The risk of not meeting IAA requirements when replacing animal proteins with plant proteins is dependent on 1) daily protein consumption levels; 2) the relative intake of plant protein compared with animal protein; and 3) the foods used to supply IAAs.

It is well recognized that plant protein foods, as sole protein sources, can be deficient in one or more IAAs. When compared with cereal grains, pulses generally contain higher levels of lysine but lower levels of sulfur amino acids (methionine and cysteine) and/or tryptophan (55). Conversely, cereals grains tend to have higher levels of methionine but lower levels of lysine. In the context of human and animal IAA requirements, nutrition science has adopted the doctrine of IAA complementation when advising the implementation of diets that rely heavily on plant protein sources. The food industry may also explore strategies to deliver a complete protein source using complementary plant proteins when developing foods. Using IAA complementarity, plant protein sources can be combined such that the IAA profile of one food complements the IAA of the other and vice versa.

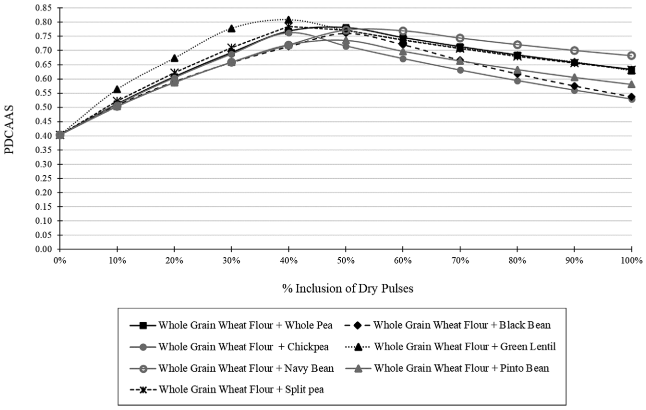

Fig. 3. The effect of adding whole dry pulses to whole grain wheat flour on the protein digestibility corrected amino acid score (PDCAAS). The amino acid composition of whole grain wheat flour was determined from the U.S. Department of Agriculture Standard Reference Legacy Database (FDC ID 168893) (76). The true fecal nitrogen digestibility coefficient for whole grain wheat flour was assumed to be 0.86 (17). Amino acid composition and true fecal nitrogen digestibility coefficients for dry cooked pulses were from Nosworthy et al. (56). The level of protein in whole yellow pea flour was assumed to be 22.8 g/100 g from the Canadian Grain Commission and based on the average protein content from 2009 to 2019 (81). The ratio of indispensable amino acids (IAA) to total protein in cooked dry split peas was from Nosworthy et al. (56) and was used to estimate IAA levels in whole yellow peas.

IAA complementarity can be demonstrated using measures of protein quality, which refers to the ability to use dietary IAA from the protein in a food for growth, maintenance, and metabolic work (48). Protein quality is dependent on the levels of IAA within the protein fraction of a food and the ability to digest the protein and absorb and assimilate IAAs (44). Although various methods exist, the protein digestibility corrected amino acid score (PDCAAS) is the most commonly used measure of protein quality and is integrated into the U.S. regulatory system for making protein nutrient content claims on foods (19,43). A summary of the PDCAAS methodology has been published elsewhere (17). In essence, the PDCAAS is a correction factor that adjusts the protein level by accounting for the true nitrogen digestibility and levels of IAA of a protein relative to IAA requirements of a reference population. Figure 3 is a theoretical representation of IAA complementarity when dry pulses and whole grain wheat flour are combined. When whole grain wheat flour was partially replaced with 30–60% dry pulses, the PDCAAS increased from 0.40 to up to 0.81. Given their different IAA profiles and digestibility coefficients, various pulses demonstrate different levels of complementarity at different rates of inclusion.

Chaudhary et al. (9) examined the effects of partial replacement of 15, 53, and 30% of refined wheat flour in pan bread, breakfast cereal, and pasta, respectively, with Canadian whole yellow pea flour. Using the nutrient balance score (18), which is a measure of nutrient density across 27 nutrients, reformulation with whole yellow pea flour increased the score by 11% for pan bread, 70% for breakfast cereal, and 18% for pasta (9). For perspective, the levels of iron, potassium, fiber, and protein increased by 63, 125, 150, and 14%, respectively, when whole pea flour was used to partially replace refined semolina in pasta (unpublished data). The PDCAAS across foods was increased by 41–111% when reformulated with yellow pea flour (Fig. 4). Using the data from the Chaudhary et al. (9) study, Figure 4 also demonstrates the capacity for protein quality (PDCAAS) to in-

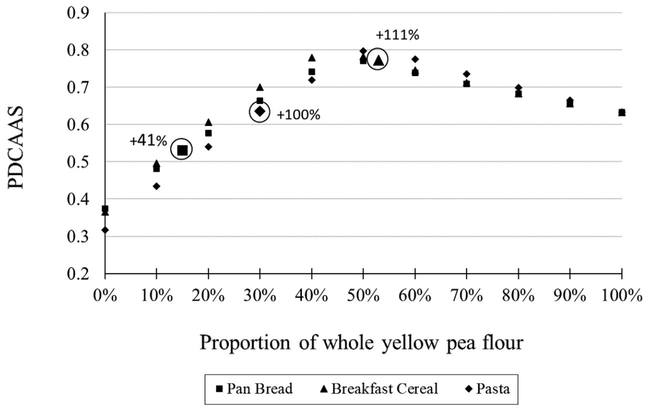

Fig. 4. Protein digestibility corrected amino acid score (PDCAAS) for pan bread, breakfast cereal, and pasta reformulated with Canadian whole yellow pea flour. (Adapted from Marinangeli et al. [43]) Enlarged and circled markers represent tested reformulated foods where a proportion of the total refined wheat flour in the formulation was replaced by whole yellow pea flour (15% for pan bread, 53% for breakfast cereal, and 30% for pasta [dry]). PDCAAS was calculated based on methods outlined in the "Joint FAO/WHO Expert Consultation: Protein Quality Evaluation" (17).

crease when whole pea flour is used at increasing levels as an adjunct to cereal grains in cereal-based staple food products (43).

Environmental Complementarity for Pulses and Cereal Grains. As discussed previously, nitrogen fixation, reduced synthetic nitrogen requirements, and water efficiency of pulses are attractive environmental attributes that underscore the attention pulses have received as a high-protein plant food that supports international efforts toward climate change mitigation. The integration of pulses into diversified cropping systems can complement the environmental production footprints of other crops, including cereals, by decreasing environmental pressures while increasing production levels. As demonstrated in Figure 3A and B, until the early 1990s, production of pulses in the United States far surpassed that of Canada. Thereafter, Canadian production of pulses began to surpass the United States when their benefits in sustainable cropping systems were realized and employed (2).

Fallow, also known as summer fallow, is the practice of not planting crops on land for a growing season to permit soil moisture to recover and the opportunity for soil nitrogen mineralization to occur (5,8); all of which increases the performance and yield of subsequent crops grown. However, fallowed land requires tillage, which can affect air quality and perpetuate soil erosion (35,38,68). In monoculture cropping systems, to produce cereals for example, fallow remains as a common practice. However, farmers around the world, including in Canada and the United States, continue to diversify cropping systems to include pulses, which enables the adoption of a zero-tillage practice. By preceding cereals with pulses in a diversified cropping system, improvements in soil biomass, nitrogen fertilizer efficiency, water efficiency, and reduced pressure from weeds and disease are incorporated into the system and can improve yields and environmental footprints of subsequent cereal crops, especially in arid and semiarid growing regions.

The benefits of using pulses as part of diversified cropping systems has gained momentum around the world, including in Canada and the United States. Analyses of 12 years of data from five different no-till cropping systems in Saskatchewan demonstrated that systems that included pulses (wheat–canola–wheat–pea) consistently increased the production of wheat grain (kg ha/year) by 14–38% and wheat protein (kg ha/year) by 33–66% compared with monocultured wheat systems and systems that included fallow (72). Monocultured wheat and wheat from fallowed systems also consistently produced lower yields across high and low producing sites. Fertilizer application was 20% less in the diversified pulse system versus monocultured wheat. With higher levels of wheat production in combination with pulse rotations, grain fertilizer use efficiency was 44% higher than monocultured wheat systems and 1.2–14% higher than systems that included fallow (72). A similar study over 5 years examined production attributes of durum wheat in 3 year cropping systems where durum (year 3) was preceded by wheat in year 1 and either a pulse (pea, lentil, or chickpea) (no till), a cereal (barley or spring wheat) (no till), or summer fallow (3–4 tillage operations) in year 2 (23). In dry and normal-to-wet conditions, rotations with pulses increased the yield of durum compared with monoculture cereal rotations by 6 and 0.6%, respectively. Compared with cereal monoculture systems, pulse rotations required 49.9 and 45.5% less synthetic nitrogen fertilizer and improved fertilizer grain nitrogen use efficiency for grain yield by 99.0 and 86.6%, respectively (23). Compared with rotations that included summer fallow in year 2, pulse rotations increased the yield of durum wheat by 36.7% in dry and 34.3% in normal-to-wet conditions. Although fertilizer application rates were similar between the two systems, grain nitrogen use efficiency of durum was increased by 36.6% (dry conditions) and 29.3% (normal-to-wet conditions) when pulses were included in the crop rotation compared with fallow (23).

A recent systematic review and meta-analysis that included 26 studies evaluated more than 1,900 comparisons of cropping systems with and without a pulse (lentils and peas) rotation in western Canada. Results showed that, compared with oilseed–cereal and cereal–cereal rotations, pulse–cereal rotations increased the yields of cereals by 7 and 16%, respectively (42). Based on these data, modeling analysis demonstrated that if pulses were included in cereal rotations and nitrogen fertilizer application rates were unadjusted the yield of cereal grains would increase from 2,671 to 3,103 kg/ha and reduce system greenhouse gasses by ~13% (42). If nitrogen fertilizer application rates were reduced to levels that maintained production levels of wheat, preceding cereals with pea or lentil reduced greenhouse gas emissions by 65% (42). These results are a snapshot that demonstrates the production and environmental benefits of using pulses, specifically peas and lentils, to enhance the production and environmental sustainability of cereal grains.

The benefits of incorporating pulses into diversified cropping systems also extend to soil water conservation and availability for subsequent crops, especially in arid and semiarid regions. In a study by Gan et al. (23), precipitation for growing seasons in 2006–2010 ranged between 129 and 410 mm, where, during summer fallow rotations, 79% of the water from a soil depth of 0 to 1.2 m was lost. The authors indicate that the water lost during summer fallow could have been used to produce pulses, and, thereby, increase the sustainability and production of the entire system (23). A study by Niu et al. (53) highlights the fact that most of the water used by lentils and peas is from the top layers of soil because of relatively shallow root systems of approximately 40 cm from the surface. This permits the water retained at lower depths to be used by subsequent crops with deeper root systems, such as wheat (14,40,41,53,82). Results from Niu et al (53), showed that, compared with wheat, the incorporation of peas and lentils into diversified cropping systems significantly increased the water use efficiency of wheat (kg/ha/mm of rainwater). The study also demonstrated that significantly more water was found at a soil depth of 60 to 90 cm in cropping systems that included pea and lentil compared with monocultured cereal systems prior to sowing wheat. Also, growing pea and lentil as previous crops increased residual soil nitrogen at lower depths (30–90 cm) compared with wheat monoculture (53). These results were observed alongside an 18 and 26% increase in wheat yields with cropping systems diversified with lentil and pea. The residual water and nitrogen at the time of sowing wheat explained 30% of variation in wheat production between diversified and monoculture systems (53).

Research also supports the potential of pulses to enhance not only the nutrient density of a food but also the environmental sustainability of foods made with pulses. Using the data from MacWilliam et al. (42), the study by Chaudhary et al. (9) showed that partial replacement of refined wheat flours in pan bread (15% yellow pea flour), breakfast cereals (53% yellow pea flour), and pasta (30% yellow pea flour) with Western Canadian whole yellow pea flour decreased the carbon footprint by 4, 11, and 13%, respectively (Fig. 5). This analysis assumed that the wheat was derived from a cereal–cereal monoculture rotation. Using data from the same meta-analysis (42), where the wheat used to manufacture foods was assumed to be preceded by lentil or pea and nitrogen fertilizer rates for wheat were unadjusted (optimized scenario 1), greenhouse gas emissions were decreased by 12% for pan bread, 13% for breakfast cereal, and 21% for pasta (unpublished data). When nitrogen fertilizer application rates for wheat from a pulse-diversified cropping system were decreased to levels that would not negatively affect wheat production (compared with a wheat monoculture; optimized scenario 2), the carbon footprint for pan bread (–37%), breakfast cereal (–24%), and pasta (–51%) was substantially decreased (unpublished data). Evidence demonstrates that pulses complement production of cereals by permitting the adoption of farming practices that help decrease the effects of agriculture on climate change.

Discussion and Considerations

Ongoing dialogue suggests that humans should derive proportionally more protein from plant-based foods to concurrently address chronic diseases and climate change. This review has presented evidence for the nutritional and environmental sustainability attributes of pulse grains, not only as a standalone foodstuffs, but also when produced and eaten in combination with cereal grains.

It is important to be aware that the motivations for a consumer's adoption of dietary patterns that incorporate higher levels of plant protein can vary. In this review, the contribution of pulses to support healthy dietary patterns and environmental sustainability of food production were identified as motivators for the food industry. As discussed in a companion article in this issue of *Cereal Foods World*, data from the International Food Information Council's (IFIC) 2020 Food and Health Survey demonstrated more than 65% of American consumers consider protein from plants to be healthy dietary choices, and 6 in 10 consumers indicated that foods should be produced in an environmentally sustainable manner (32). However, in addition to health and climate change, other motivators such as sensory/taste and heightened concerns over animal welfare are also driving the adoption of plant-based dietary patterns (46). In the IFIC survey, 51% of parents with children under 18 years of age indicated that animal welfare is an important consideration when purchasing food. Compared with some other common plant protein foods, such as soy protein, pulses are non-GMO (genetically modified) and may provide an additional value proposition for industry stakeholders for their use as nutritionally dense and environmentally sustainable proteins. This is supported, in part, by the observation that >40% of adults consider non-GMO as environmentally sustainable (32).

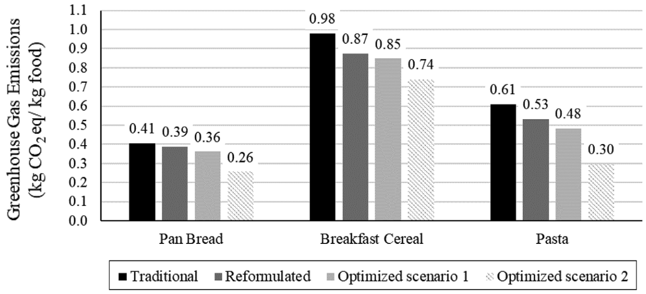

Fig. 5. Greenhouse gas emissions of cereal foods reformulated with whole yellow pea flour. Food formulation and life-cycle analysis (LCA) data from Chaudhary et al. (9). Greenhouse gas emission data from crop rotations was from MacWilliam et al. (42). Traditional foods contained refined wheat flour as the entire flour component of the food. In the reformulated foods, refined wheat flour was partially replaced by Canadian whole yellow pea flour (15% for pan bread, 53% for breakfast cereal, and 30% for pasta [dry]) (9). For traditional and reformulated scenarios, wheat was assumed to be sourced from cereal–cereal rotations (total emissions: 330 kg of CO_2 eq/tonne of wheat). For optimized scenario 1, wheat was assumed to be sourced from a pulse (pea or lentil)–cereal rotation, where the nitrogen fertilizer application rate for wheat was the same as for the cereal–cereal rotation (total emissions: 286 kg of CO_2 eq/tonne of wheat produced). For optimized scenario 2, wheat was assumed to be sourced from a pulse (pea or lentil)–cereal rotation, where nitrogen fertilizer application rates for wheat decreased to levels that would not affect production levels (total emissions: 116 kg of CO_2 eq/tonne of wheat produced). For all scenarios, emissions from the production of peas was assumed to be 188 CO_2 eq/tonne.

This article discusses the use of pulses and cereals in manufactured foods to increase their nutritional and sustainability attributes. However, on its own, "processed food" can have negative connotations for consumers and may affect purchase decisions (32). A recent SWOT (strengths, weaknesses, opportunities, and threats) analysis identified consumers' concerns around processed food as a "threat" to the plant-based food and protein sector (3). During the development stages, a strong focus on nutrition, including plant protein and sustainability, could be leveraged as strengths to help counteract concerns that detract from the consumption of manufactured foods (3). Also, it is important to highlight that the manufacturing process exerts environmental pressures, which also require optimization and refinement to decrease the effects of the food system on climate change.

Finally, recommendations to displace animal protein in the diet do not suggest that the population adopt a strict vegetarian or vegan lifestyle. There are various degrees to which plant proteins can be effectively incorporated into healthy dietary patterns, which helps to increase the demand for plant protein foods that improve the healthfulness and sustainability of dietary patterns. Springmann et al. (71) modeled that flexitarian, pescatarian, vegetarian, and vegan dietary patterns could reduce risk of mortality by 19–22% and decrease combined environmental impacts (greenhouse gas emissions, freshwater use, cropland use, nitrogen application, and phosphorus application) by approximately 115–145%. Furthermore, it is important to consider that, for some individuals or populations, it may not be feasible or nutritionally sound to adopt diets that incorporate more plant proteins, especially for those who are nutritionally vulnerable and/or living in some undeveloped regions (7,13,28).

Conclusions

It is evident that pulses and cereals can play a critical role in helping to enhance the nutritional density and environmental sustainability of dietary patterns in North America and around the world. Although consumption of pulses remains relatively low in Canada and the United States, there is a profound opportunity to use pulses to incorporate high levels of plant proteins into dietary patterns, and, when combined with cereals, provide a sufficient quantity of all of the IAAs. Increasing the demand for pulses as foods and food ingredients has the potential to grow their production in North America and, thus, lower the environmental impacts of modern agriculture. Sourcing cereals from sustainable cropping systems that incorporate pulses can facilitate higher yields, enhance soil organic carbon, soil biomass, and nitrogen and water use efficiencies and permit the adoption of environmentally conscientious technologies such as zero tillage. In an era when diet-related chronic diseases and climate change are concurrently gaining momentum as societal priorities, the use of pulses in combination with cereal grains could assist the food industry in providing staple foods and food innovations that align with global health and environmental targets.

Conflicts of Interest

C. P. F. Marinangeli is an employee of Pulse Canada and former employee of Kellogg Canada.

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Christopher Marinangeli received his Ph.D. degree from the University of Manitoba. He is also a registered dietitian and is currently the director of nutrition science and regulatory affairs at Pulse Canada. Previously, he worked in the consumer-packaged goods industry as a consultant catering to the food and natural health product sectors, the pharmaceutical industry, and the foodservice industry. He has published more than 40 peer-reviewed papers. Chris is an active member of the Scientific Advisory Council for the Canadian Federation of Dietetic Research (CFDR) and previous board member of the CFDR and the International Life Science Institute's Canadian Advisory Committee.