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ORIGINAL ARTICLE

Technoeconomic Prospects for Commercialization of *Brassica* (Cruciferous) Plant Proteins

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Abstract *Brassica* oilseed is the second largest oilseed in the world both in terms of seed and meal production. The nutritional value and functional properties of rapeseed/canola (RSC) protein make it a suitable alternative protein in food applications. However, the meal produced from RSC by the current processing technologies undergoes desolventizer-toasting that degrades the nutritional and functional quality of the meal, thus making it unsuitable as a feedstock for protein extraction. Several widely used technologies for advancing the commercial production of RSC protein were studied. These technologies generally involve aqueous extraction followed by adsorption or membrane separation methods, including (1) the alkali extraction of protein and recovery at low pH, (2) protein micelle formation method, (3) chromatographic separation, and (4) meal component fractionation method. This paper reviews challenges in the current *Brassica* oilseed protein value chain related to the development and commercialization of RSC proteins in a market dominated by soybean protein. This work also includes an empirical case study of the recent RSC commercialization ventures. Opportunities for the commercialization of oilseed protein in the market are also presented.

Keywords Rapeseed/canola · Food protein · Protein extraction · Commercialization

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Introduction

The role of plant proteins as a source of high-value nutrients for human consumption has been reignited due to increased global demand. The world population is projected to increase by 33% from 7.3 billion in 2014 to 9.7 billion by 2050, with developing countries, especially in Africa and Asia, accounting for nearly the entire increase (FAO, 2009). This trend has implications on the global food security and sustainability due to the use of arable land for the intensification of livestock production for animal protein (FAO, 2009; National Research Council, 2015). There are also additional drivers related to changing food preferences, in particular, the increased demand for plant protein in Europe and North America and a decline in meat consumption, buoyed by epidemiologic and clinical evidences showing a positive correlation between high consumption of plant-based foods and a significantly lower risk of cardiovascular disease, diabetes, stroke, and cancer (Dinu, Pagliai, & Sofi, 2017; Hu, 2003; Medina-Remón, Kirwan, Lamuela-Raventós, & Estruch, 2018; Patel, Chandra, Alexander, Soble, & Williams, 2017; Rinaldi, Campbell, Fournier, O'Connor, & Madill, 2016; Satija et al., 2017; Vanamala, 2017).

Clearly, these events represent significant market pull for new sustainable sources of proteins, such as *Brassica* proteins. With global production of about 60 million tonnes annum^{-1}, *Brassica* oilseeds are among the world's leading edible oil crops, second only to soybean. In fact, numerous studies have provided technical elucidation of the utility of *Brassica* proteins from various perspectives, including nutritional and functional properties (Aachary & Thiyam, 2012; Alashi, Blanchard, Mailer, & Agboola, 2013; Tan, Mailer, Blanchard, & Agboola, 2011; Wanasundara, 2011). Research has demonstrated that proteins of *Brassica* oilseeds possess well-balanced amino acid profile and technological functionality (Alashi et al., 2013; Bos et al., 2007; Wanasundara, 2011). Advances in the processing technology have successfully extracted and fractionated canola proteins with distinct functionalities (Wanasundara, Tan, Alashi, Pudel, & Blanchard, 2016) for a wide range of food ingredient applications currently dominated by soybean. In this regard, *Brassica* oilseeds (rapeseed/canola [RSC]) are well positioned as a feedstock for protein extraction, given their high production and global adaptation to diverse agronomic environments. Major processors of *Brassica* oilseeds in North America are located in the Canadian Prairie provinces (Saskatchewan, Manitoba, and Alberta), which account for virtually all of Canada's RSC oilseed production (18 million tonnes annum^{-1} and 22% of world's production, ahead of China, India, Germany, France, and Australia) (FAO, 2017a).

Despite their high production (backed by decades of research, regulatory approval, and available technologies for commercial production of RSC proteins), *Brassica* oilseeds continue to be underutilized in high-value food-grade protein markets with very few commercially available canola protein products (Burcon, 2017; TeuTexx, 2015; US Food and Drug Administration [US FDA], 2010; Wanasundara et al., 2016). *Brassica* oilseed protein products have not been very successful in entering the market as ingredients or bulk protein sources for food application. In fact, more than 90% of plant-based proteins are dominated by soybeans for which there are established processing technologies and a wide spectrum of applications for fractionated seed coproducts (Deak, Johnson, Lusas, & Rhee, 2008; Shurtleff & Aoyagi, 2016; Singh, Kumar, Sabapathy, & Bawa, 2008; Thrane, Paulsen, Orcutt, & Krieger, 2016). It is ironic that proteins from the second largest oilseed crop in the world do not even feature among the emerging sources, which now include pea and rice protein (Bomgardner, 2015). Despite new information on the role of RSC proteins as antidiabetic, anorexigenic, hypocholesterolemic, anticarcinogenic, antiviral agents, angiotensin I-converting enzyme-inhibiting agents, and feedstocks for biomaterials, the primary use remains as a feed protein source (Aachary & Thiyam, 2012; Manamperi, Chang, Ulven, & Pryor, 2010; Udenigwe & Aluko, 2012; Zhang, Liu, & Rempel, 2018).

The aim of this paper is to examine technoeconomic and value-chain challenges that have constrained the effective commercialization and market positioning of *Brassica* proteins as an integral part of the innovation chain. Opportunities for the commercialization of RSC proteins are also elucidated. In this regard, this work provides an integrative perspective within the overall context of an innovation value chain (Kline & Rosenberg, 1986) that facilitates understanding of complex, novel processes for converting a research invention into a successful commercial advancement. This includes stages of technology development, such as basic research, technology scale-up, and full-scale commercial adoption. This paper focuses both on technological and economic factors associated with the commercialization of *Brassica* proteins; hence, the term "technoeconomic analysis," which is a widely used concept in studies that integrate the analysis of technology development/innovation and economic feasibility. Throughout this paper, the term RSC is used interchangeably as followed in international commerce and utilization of *Brassicas.* Rapeseed is defined for seeds from the entire *Brassica* genus on the basis of acceptable glucosinolate content (as explained below). Subsequently, the term canola is widely adopted to characterize *Brassica* oilseeds that meet an internationally regulated standard defined by the Canola Council of Canada (2017a) as "Seeds of the genus *Brassica* (*B. napus*, *B. rapa* or *B. juncea*) from which the oil shall contain less than 2% erucic acid in its fatty acid profile and the solid component shall contain less than 30 micromoles of any one or any mixture of 3-butenyl glucosinolate, 4-pentenyl glucosinolate, 2-hydroxy-3 butenyl glucosinolate, and 2-hydroxy-4-pentenyl glucosinolate per gram of air-dry, oil-free solid." Hence, both terms (canola and rapeseed) refer to the same internationally regulated standard defined above.

Brassica Oilseed Processing Technologies

Traditional RSC Oilseed Processing Technologies

The commercialization of RSC proteins for food applications is a function of technologies for the fractionation and extraction of proteins from seed meal. Hence, it is useful to provide the overall context of traditional technologies that characterize the current RSC value chain. Two oil extraction technologies are typically used for RSC: mechanical screw-pressing and prepress solvent extraction. In Canada, there are 14 oilseed processing plants owned by six companies (Archer-Daniels-Midland [ADM], Bunge, Cargill, Richardson, Luis Dreyfus Company, and Viterra). Eleven

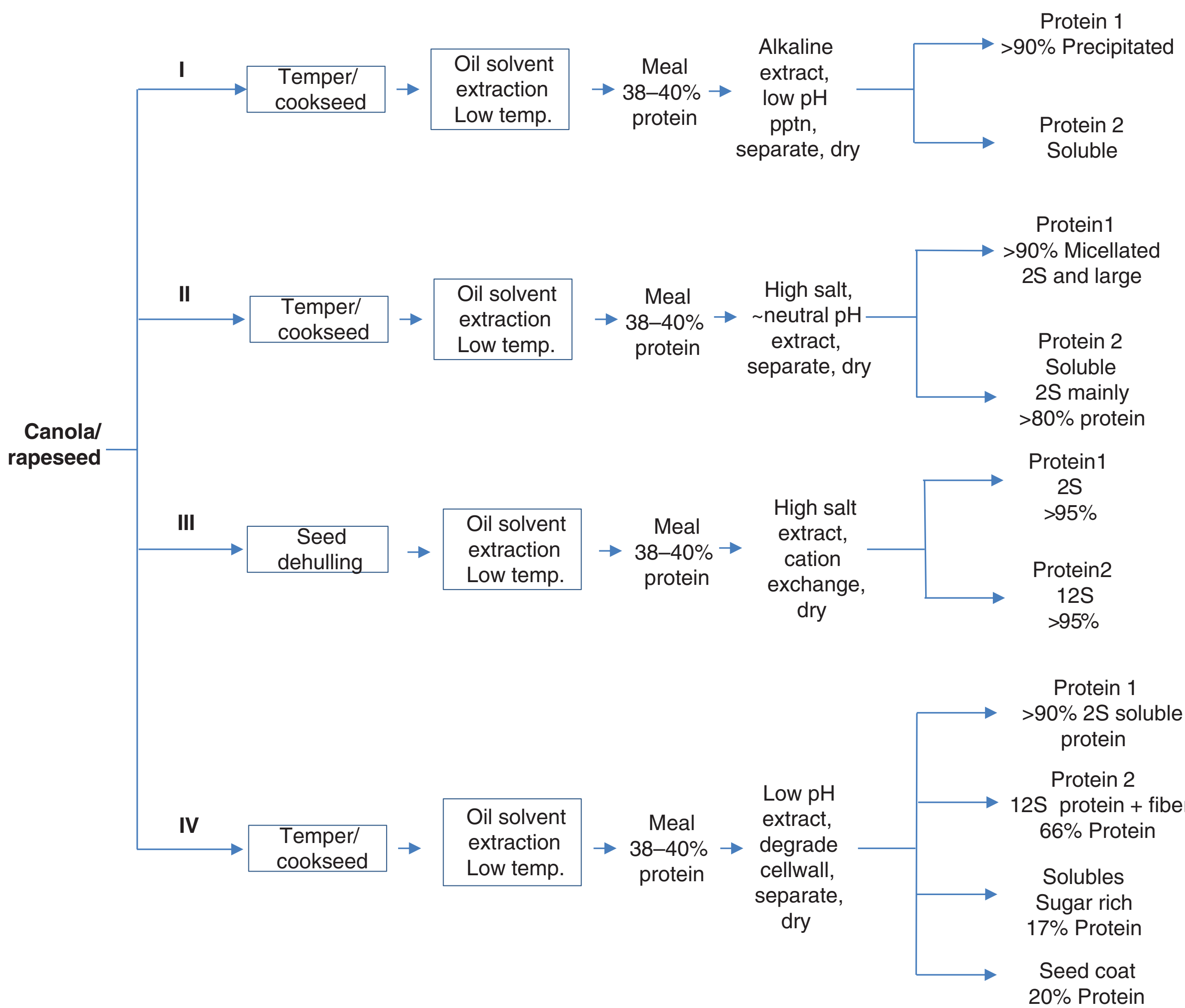

Fig. 1 RSC protein processing technologies available in the literature. (1) Alkali extraction of protein and recovery at low pH (Diosady, Xu, & Chen, 2005; Maenz, Newkirk, Classen, & Tyler, 2004; Newkirk, Maenz, & Classen, 2009; Shi, Smolders, Willemsen, Vermunt, & Hylkema, 2017; Tang, 2009), (2) protein micelle formation method (Schweizer, Green, Segall, & Willardsen, 2013), (3) chromatographic separation (Bérot, Compoint, Larré, Malabat, & Guéguen, 2005), and (4) meal component fractionation method (Wanasundara & McIntosh, 2013)

plants (located in western Canada) process RSC, while the remaining three (located in eastern Canada) process soybeans and RSC (COPA, 2017a). In 2016, these companies processed 8.85 million tonnes of RSC seed, generating 3.86 million tonnes (4.1 billion L) of RSC oil and 4.99 million tonnes of RSC meal (COPA, 2017b). Their operations are based on large-scale capital-intensive solvent extraction technology that achieves more than 99% extraction efficiency when compared with the mechanical presses (less than 90% oil removal) typically used in small-scale processes (Kemper, 2005). The last step in the solvent extraction process involves desolventizer-toasting that uses high-temperature steam to remove hexane from the meal, prior to storage. This step generates the desolventizer-toasted (DT) meal and is considered to be the most detrimental step for meal proteins because the excessive heat not only degrades essential amino acids but also results in adverse changes to the protein structure and functionality (Becker, 1983; Pudel, 2011). In addition, the process imparts glucosinolate breakdown products and seed coat-associated phenolic compounds to the meal; hence, DT meal is unsuitable as a starting material for extracting the remaining components (protein and fiber) (Newkirk, Classen, & Edney, 2003; Wanasundara, 2011; Wanasundara et al., 2016). The other type of RSC meal available is produced by full-pressing, which refers to mechanical

Table 1 Selected list of RSC protein patented technologies[a]

Inventors	Title	Patent number	Assignee	Issued
Murray, F. D.	Oilseed protein extraction	US 6,005,076	Burcon[b]	1999
Murray, D., Myers, C. D., and Barker, L. D.	Protein isolate product	4,285,862	General Foods	1981
Murray, E. D., Maurice, T. J., Barker, L. D., and Myers, C. D.	Process for isolation of proteins using food-grade salt solutions at specified pH and ionic strength	4,208,323	General Foods	1980
Barker, L. D., Martens, R. W., and Murray, E. D.	Production of oil seed protein isolate	8,741,356	Burcon	2002
Schweizer, M., Green, B. E., Segall, K. I., and Logie, J.	Method of producing a CPI	8,580,330	Burcon	2013
Schweizer, M., Green, B. E., Segall, K. I., and Logie, J.	Soluble CPI production ("nutratein")	8,697,144	Burcon	2014
Schweizer, M., Green, B. E., Segall, K. I., and Willardsen, R.	Compositions containing novel CPI	9,011,959	Burcon	2015
Segall, K. I., Green, B. E., and Schweizer, M.	Production of CPI without heat treatment	8,999,426	Burcon	2015
Segall, K. I., Williardsen, R., and Schweizer, M.	Preparation of CPI involving isoelectric precipitation	8,877,281	Burcon	2014
Schweizer, M., Green, B. E., Segall, K. I., and Willardsen, R.	CPI	8,609,153	Burcon	2013
Schweizer, M., Green, B. E., and Willardsen, R.	Preparation of CPI and use in aquaculture	8,557,322	Burcon	2013
Schweizer, M., Green, B. E., Segall, K. I., and Logie, J.	Process for the preparation of a CPI	8,580,330	Burcon	2013
Green, B. E., Xu, L., Milanova, R., and Segall, K. I.	Color reduction in CPI	8,475,853	Burcon	2013
Schweizer, M., Green, B. E., Segall, K. I., and Willardsen, R.	Process for the preparation of a CPI	8,460,741	Burcon	2013
Segall, K. I., Green, B. E., and Schweizer, M.	Preparation of CPI without heat treatment	8,343,566	Burcon	2013
Segall, K. I. and Schweizer, M.	Production of 2S canola protein involving ion exchange	7,750,119	Burcon	2010
Schweizer, M. and Segall, K. I.	Protein isolation procedures for reducing phytic acid	7,687,088	Burcon	2010
Tang, Q. N.	Oilseed protein concentrates and isolates, and processes for the production thereof	8,623,445	BioExx	2009
Tang, Q. N.	Oilseed protein concentrates and isolates, and processes for the production thereof	8,529,981	BioExx	2009
Tang, Q. N.	Protein concentrates and isolates, and processes for the production thereof from toasted oilseed meal	8,535,907	BioExx	2013
Shi, J., Smolders, G. J. F., Willemsen, J. H. M., Vermunt, J. H. A. J., and Hylkema, N. N., 2017	Rapeseed protein isolate, food comprising the isolate and use as foaming or emulsifying agent	WO2017102535 A1	DSM Ip Assets B.V.	2016
Maenz, D. D., Newkirk, R. W., Classen, H. L., and Tyler, R. T., 2004	Fractionation and processing of oilseeds	US 6,800,308 B2	University of Saskatchewan/ MCN	2011
Newkirk, R. W., Maenz, D. D., and Classen, H. L.	Filtration of vegetable slurries	7,989,011	MCN Bioproducts	2011
Newkirk, R. W., Maenz, D. D., and Classen, H. L.	Oilseed processing	US 7,629,014	MCN Bioproducts	2009

Table 1 Continued

Inventors	Title	Patent number	Assignee	Issued
Diosady, L. L., Xu, L., and Chen, B.-K.	Production of high-quality protein isolates from defatted meals of *Brassica* seeds	6,905,713	n.a.	2005
Cameron, J. J. and Myerts, C.	Rapeseed protein isolate	4,418,013	General Foods (Don Mills, CA)	1983
Diosady, L. L., Rubin, L. J., and Tzeng, Y.-M.	Production of rapeseed protein materials	4,889,921	The University of Toronto	1989
Cameron, J. J. and Myerts, C.	Novel protein isolation procedure	4,366,097	General Foods (Don Mills, CA)	1982
Wanasundara, J. P. D. and McIntosh, T.	Process of aqueous protein extraction from *Brassicaceae* oilseeds	8,557,963	AAFC	2013

[a] Although some patents have identical titles or descriptions, they protect different scopes of an invention.

[b] Burcon Nutrascience (MB) Corp.

extraction typically used in small-scale operations involving capacities of 10–500 tonnes of RSC seeds per day, approximately 1/10th of the capacity of a solvent extraction facility (Gunstone, 2004). Full-pressing produces lower-oil yield and higher-processing cost per tonne of seed relative to solvent extraction. However, its capital investment costs are lower, and the quality of oil is higher when compared with that from solvent extraction (Matthäus, 2016; Niewiadomski, 1990). Residual oil content in the full-press meal is 5–8% (Gunstone, 2004; Matthäus, 2016). Cold-pressing, which is similar to screw-pressing, typically uses nonpretreated seeds (heat inactivation of enzymes) and operates at a slower rate ensuring low temperature of the oil not to exceed 60 °C (Matthäus, 2016), resulting in a meal with 10–15% oil (Matthäus, 2016). Since mechanical pressing does not subject the meal to excessive heat as in DT systems, damage to proteins within the meal is comparatively less. However, high residual oil content of the meal from full-pressing and cold-pressing affects the extraction efficiency of protein and fiber (Matthäus, 2016), necessitating an additional step to remove the oil (Wanasundara, 2011; Wanasundara et al., 2016).

RSC Protein-Processing Technologies

Nature of Available Technologies

Technologies for extracting RSC proteins involve aqueous extraction followed by adsorption or membrane separation methods. The four most widely cited methods (Fig. 1) are (1) alkali extraction of protein and recovery at low pH (Diosady et al., 2005; Maenz et al., 2004; Newkirk et al., 2009; Shi et al., 2017; Tang, 2009); (2) protein micelle formation method (Schweizer et al., 2013); (3) chromatographic separation (Bérot et al., 2005); and (4) meal component fractionation method (Wanasundara & McIntosh, 2013). Alkaline extraction is the most widely studied method for RSC protein production, with primary advantages of high protein yield and minimal interactions between phytic acid and protein (Ghodsvali, Khodaparast, Vosoughi, & Diosady, 2005).

A detailed technical description of differences between these technological pathways is beyond the scope of this paper. Nevertheless, the technologies depicted in Fig. 1 involve various protocols for protein extraction and recovery, thereby generating protein products of varying yield and composition, which would also influence product chemical composition and functional properties. Target markets are thus created and can be differentiated on the basis of two broad protein purity categories: protein concentrates (70% protein) and protein isolates (minimum 90% protein) (Soyatech LLC, 2014). From a marketing vantage point, the adoption of soy protein as a standard explains part of its dominance in the market (in addition to its production history that dates back to the 1980s). Because of the high level of phenolic-rich seed coat in the RSC meal fraction (relative to soybean, which has a dehulling step), commercial concentrates and isolates from RSC involve more extensive processing compared to soybean to produce protein products that meet the industry standards (Wanasundara, 2011). As shown in Fig. 1, the commercial extraction of concentrates is generally performed in neutral or acid medium while protein isolates are extracted in alkaline medium and further processed to obtain higher protein levels (Aluko & McIntosh, 2001, 2005; Tan et al., 2011; Wanasundara et al., 2016).

Industrialization/Commercialization of RSC Protein Processing Technologies

The technologies summarized in Fig. 1 are complemented by significant patenting in this area (Table 1), which demonstrates the scope of intellectual property rights and freedom to operate in advancing RSC plant proteins for human food applications. Table 1 partly elucidates how patents can be a source of competitive advantage. The broader the scope of subject matter claimed by the inventor, the greater the number of competing technologies that will infringe the invention. Technologies depicted in Fig. 1 and supplemented by the partial list of patents in Table 1 provide insights into some pioneering endeavors to commercialize canola proteins beyond the discovery phase. This is evident from the breadth of patents from BioExx and Burcon, which illustrate both the important role of patents in stimulating R&D and innovation, as well as enabling inventors to assume risks associated with their intensive R&D investments. For instance, the commercial exploitation of Burcon's technology is based on three protein products generated by its processes: Supertein®, Puratein®, and Nutratein®. These end-products are fundamentally enabled by US Patent 7,687,087 B2 and a suite of subsequent intellectual property as indicated in Table 1. According to Schweizer, Segall, Medina, Willardsen, and Tergesen (2007), these Burcon products have low allergenicity and superior organoleptic and functional properties compared with RSC proteins produced by methods similar to traditional soy protein products that involve harsh chemicals (strong acids and bases). Supertein® (a 2S napin fraction) is particularly high in sulfur-containing amino acids, an important nutritional attribute of a food protein. Supertein®'s high solubility (>90%) and ability to generate clear solutions even under acidic pH conditions (compared to soy, egg white, and whey) have value-added applications in fortified beverages. Schweizer et al. (2007) also reported that Supertein®'s heat stability permits pasteurization while its foaming properties are comparable with those of egg white proteins. Puratein® (an 11S cruciferin fraction) has good emulsification, thickening, and heat-induced gelation properties, with better performance as a gelling agent compared to soy protein isolate. Its applications include replacing egg yolk in products such as cakes, other baked goods, dressings, meat substitutes (vegetable burgers), and as an ingredient binder. Nutratein® contains both albumin and globulin protein fractions that are completely soluble in water at low pH. It has applications in protein fortification for human nutrition, pet foods, and aquaculture. Nutratein® and Supertein® received Generally Recognized as Safe (GRAS) status by the US FDA for food applications (US FDA, 2010).

Other commercial domain of *Brassica* proteins relates to those produced by another plant protein pioneer, BioExx Specialty Proteins Ltd. (discussed below in greater detail), which developed two canola protein products: Isolexx® (a protein isolate) and Vitalexx® (a fully hydrolyzed protein). The process produces a protein isolate with amino acid composition and functional properties (e.g., full water solubility over a wide range of pH, foaming, emulsification, and gelling) that enable potential applications in products such as sports nutrition drinks, energy foods, dressings and toppings, and baked goods. Isolexx® received approval as a safe, novel food by the European Food Safety Authority (EFSA Panel, 2013) while the US FDA GRAS notification provides approval for their use in a variety of foods and beverages (US FDA, 2016).

More recently, DSM Nutritional Products (the Netherlands) launched a gluten-free RSC protein isolate marketed as CanolaPro™ based on its patented process (Table 1). The process starts with cold-pressing of RSC seeds to preserve the native state of the proteins in subsequent extractions. The aqueous extraction involves mixing the RSC meal (press cake) with an aqueous salt solution (meal:water ratio of 1:5–1:20) comprising 1–5% NaCl (w/w) at 40–75 °C for 30–60 min, followed by separation of the protein-rich solution from the insoluble material. The pH of the extract is adjusted over a range of 2–12, followed by clarification using citric acid and/or ascorbic acid as buffers to remove nonprotein substances. A solid/liquid separation step (using a membrane filter press or centrifugation) removes the residual fat and precipitates, followed by ultrafiltration/diafiltration to concentrate and wash the extract and remove antinutritional factors (e.g., polyphenols, residual phytate, and glucosinolates). The protein isolate is optionally whitened using sodium sulfite, with the final protein isolate containing <10 ppm of sulfite (US FDA, 2016). The RSC protein isolate contains two major protein fractions: napin and cruciferin. A GRAS notice has been recently filed for this RSC protein isolate for use as a nutritional and functional ingredient in commercial food products, including prepared foods, meat analogues, beverages, baked goods, protein-enriched bakery products, sports nutrition, weight management, dairy products, medical nutrition, and elderly nutrition (US FDA, 2016). CanolaPRO™ is a non-genetically modified organism (GMO), gluten-free, nondairy protein. The commercial utility of a gluten-free RSC protein isolate is backed by patent claims that cover processes for the preparation of a gluten-free native RSC protein isolate, including all functional uses (foaming, gelling, and emulsifying), recognizing the commercial application for individuals with coeliac disease.

MCN Bioproducts Inc. (Saskatchewan), founded in 2000 by University of Saskatchewan researchers, represents yet another example of early canola protein commercialization, specifically its two protein concentrate products: Can Pro soluble protein (SP; 60% protein) and Can Pro insoluble protein (IP; 68% protein) based on cold-pressed meal as the feedstock. The technology, which fundamentally involves alkaline extraction of protein and recovery at low pH and heat, is enabled by US patents and by University of Saskatchewan inventors (Table 1) who subsequently spun-off MCN as a start-up company. Section "RSC Innovation Value Chain Including Protein" provides additional details related to the company's commercial operations.

There are also other more recent processes that have generated proteins with attributes that are competitive in this market. For instance, the process developed by Agriculture and Agri-Food Canada (AAFC) inventors (Fig. 2) (Wanasundara & McIntosh, 2013) extracts two major storage canola proteins (2S napins and 12S cruciferins) based on an aqueous extraction process that is different from the preceding processes (Table 1). A significant aspect of the AAFC process is that it separates more potent allergenic protein of *Brassica* seeds, napin, from cruciferin and other proteins by exploiting their divergent solubilities under different pH conditions, using unit operations commonly used in the food ingredient industry. The separation of major allergens enables regulatory approval, a significant factor in the commercialization of RSC proteins.

Overall, there are chemical and technical differences between protein products generated from these technologies. This includes some cross-contamination between protein types (11S with 2S), or a predominance of one form of protein (e.g., 11S or 7S; 7S in canola is a partially dissociated 11S protein) in precipitated protein and the other (e.g., 2S) in the supernatant or soluble fraction. As noted previously, Puratein® is predominantly 7S and Supertein® is predominantly 2S. Both proteins are recovered in the BioExx process as well, with Vitalexx™ being produced from the initial water extract and Isolexx™ being recovered from hydrolysis of the unextracted material.

Technological Pathways to Protein: RSC vs. Soybean

Differences in technological pathways to protein isolates between RSC and soybean (the industry leader) can be considered as one of the key factors in the economics of protein industry. One of the defining differences relates to value-chain integration of the processes for generating end-

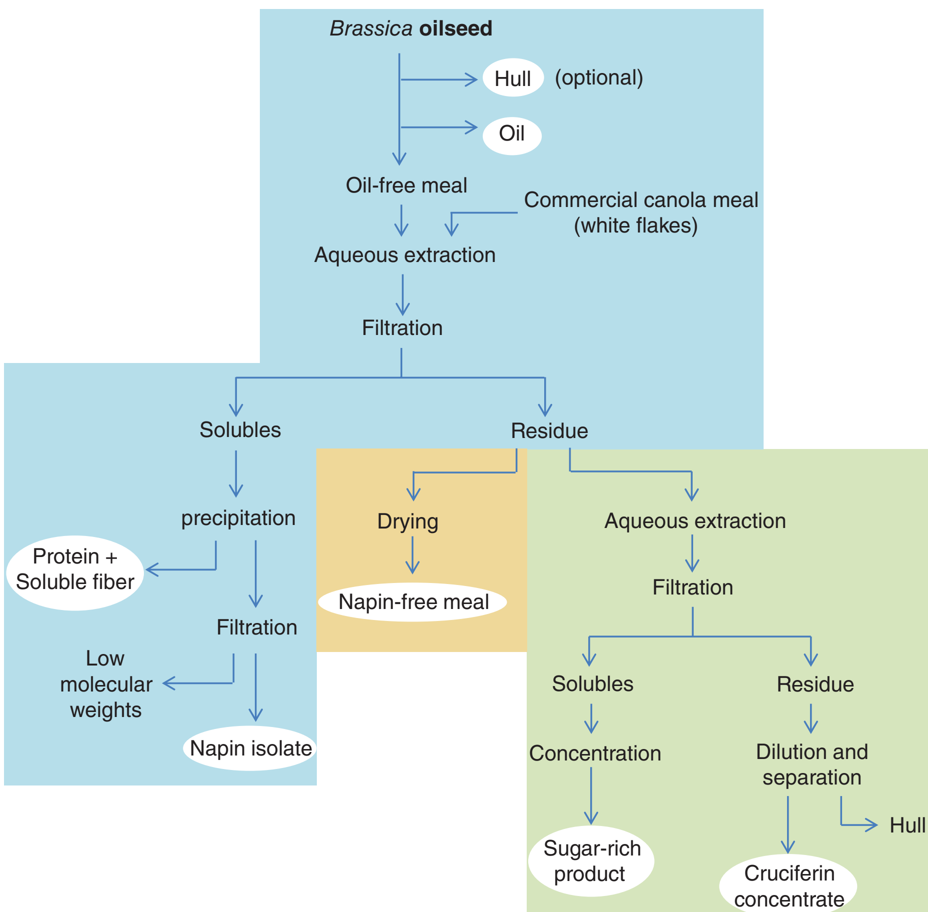

Fig. 2 AAFC technology for *Brassicaceae* oilseed (including RSC) protein extraction (Wanasundara & McIntosh, 2013) (process steps in either yellow or green shaded area can be combined with process steps in the blue shaded area to obtain multiple products from *Brassica* oilseeds according to this modular process)

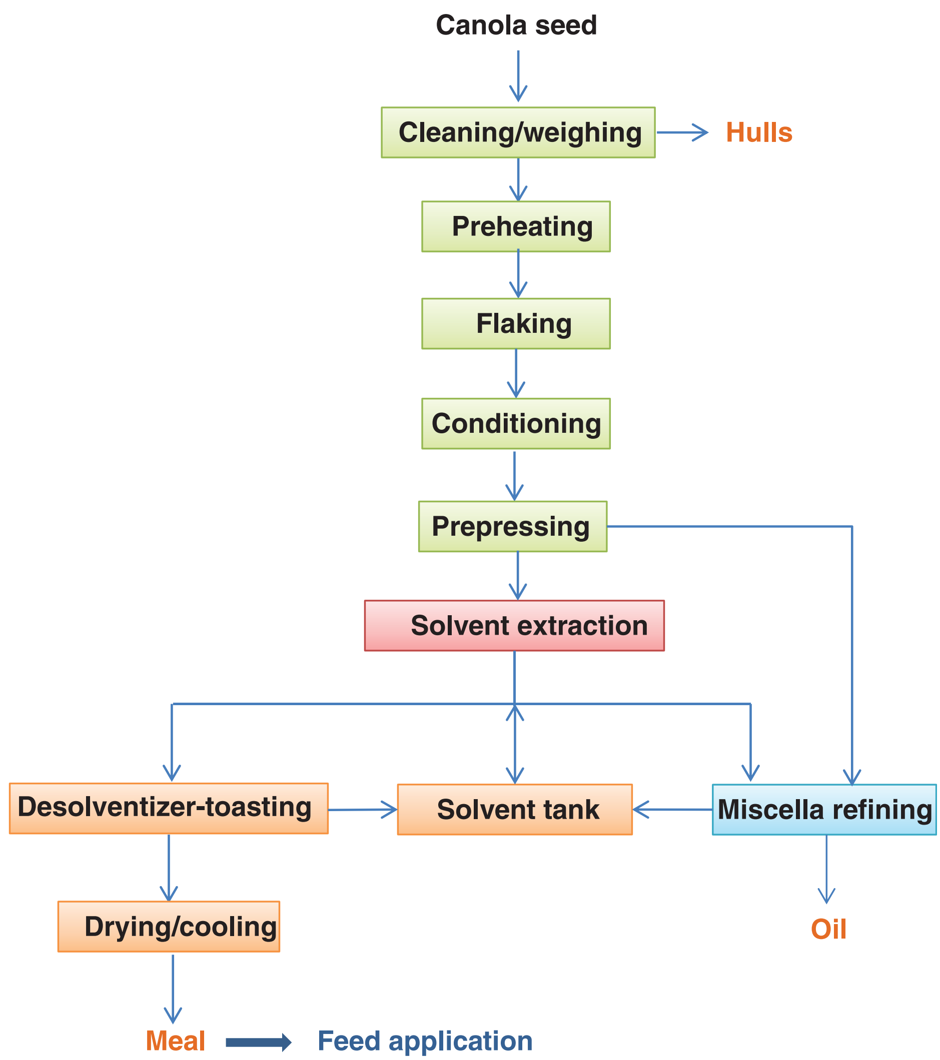

Fig. 3 Flow diagram of typical manufacturing process for RSC meal and oil (Canola Council of Canada, 2017b)

protein products (Figs. 3 and 4). In processes that involve soybean (Fig. 4) (FAO, 2017b), the large-scale soybean crushing industry is integrated with value-added processing chain; the enormous volume of soybean meal generated from the crushing industry can account for the quantity required as a starting feedstock for further fractionation and extraction of soy protein and coproducts. In the case of soybean crushing, flakes from the extractor also contain 35–40% solvent. However, the method used to remove the solvent depends on the targeted market for the flakes, namely animal feed or human food applications (Witte, 1995). In other words, there are integrated add-on unit operations involving flow splitting of soybean meal into two streams destined for animal feed application and protein extraction for human foods. Soybean flakes targeted for animal feed (95% of flakes from soybean crushers) can be processed in a desolventizer-toaster (DT). The remaining flakes (5% of annual soybean crush) targeted for human consumption are processed using a specialty or flash desolventizer, which involves exposure to noncontact steam or superheated hexane in vacuum followed by cooling. During this process, the solvent is removed rapidly to ensure integrity of the proteins. The flash desolventized flakes are ordinarily called white flakes, which provide an ideal feedstock for the production of protein concentrates, protein isolates, and soy flour for human food applications (Nazareth, Deak, & Johnson, 2009; Witte, 1995). The recognition of the adverse impact of DT in soybean dates back to the early 1960s (Becker, 1983; Becker & Tiernan, 1976), with seminal work of researchers at the Northern Regional Research Laboratory of United States Department of Agriculture (USDA) (Peoria, IL), while the Centre for Crops Utilization Research, Iowa State University, and others later observed that DT degraded protein and caused moisture bailing, scorching, denaturation, loss of bulkiness, and poor moisture absorption, which are not desirable in high-quality

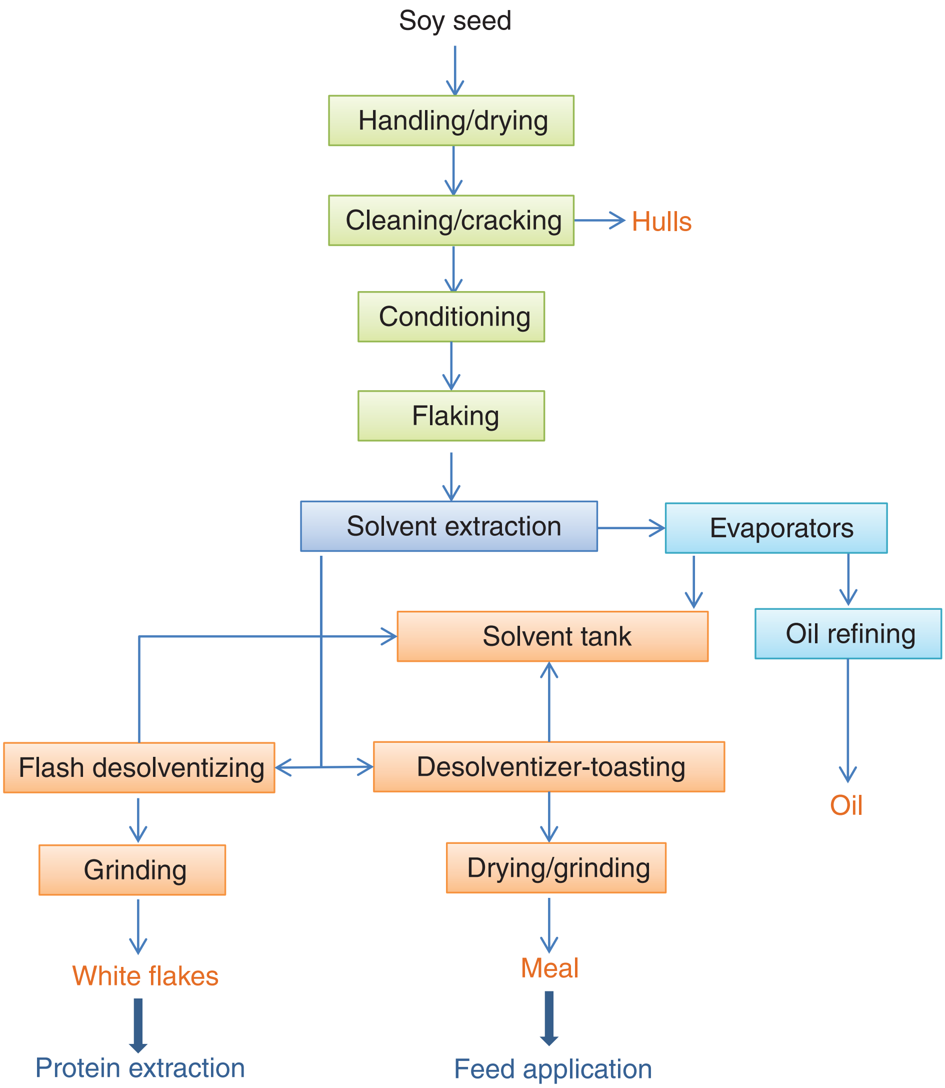

Fig. 4 Flow diagram of manufacturing process for soybean meal and oil including add-on flash desolventizing step (FAO, 2017b)

food products (Mustakas, Kirk, & Griffin, 1962; Mustakas & Sohns, 1979; Wu, Murphy, Johnson, Fratzke, & Reuber, 1999; Wu, Murphy, Johnson, Reuber, & Fratzke, 2000). Subsequently, pilot-plant demonstrations that flash desolventizing of soybean flakes improved the quality of the protein extract and provided foundations for the incorporation of technological processes in large soybean-crushing plants. As will be discussed later, this difference in innovation and configuration between the two oilseed sectors has implications for technoeconomic cost of protein production.

By contrast, the RSC crushing industry (depicted in Fig. 3 for RSC process) generates 100% DT meal under the current industry paradigm (Canola Council of Canada, 2017b). Under this paradigm, oil is the more highly valued coproduct because it generates high margins for the crushing plant. Furthermore, although the low-valued DT RSC meal is unsuitable as a starting feedstock for RSC protein extraction, it has a readily available feed market. Currently, there are constraints in tapping into an existing RSC prepress solvent extraction facility by adding a flash desolventizer to process some of the marc (solvent-saturated RSC) for protein extraction. In particular, this would require not only expensive retrofitting of RSC processing plants but also a clear commercial incentive for such a high capital investment. A detailed technoeconomic assessment of the cost of retrofitting current processing infrastructure would also be required to inform investment decisions. Overall, there is a value-chain disconnect that does not integrate RSC crushing and downstream RSC protein recovery. These two paradigms directly affect cost and represent a barrier to entry in the market for start-up companies.

As a specialty or flash desolventizer is not available in RSC-crushing processes, protein manufacturers must

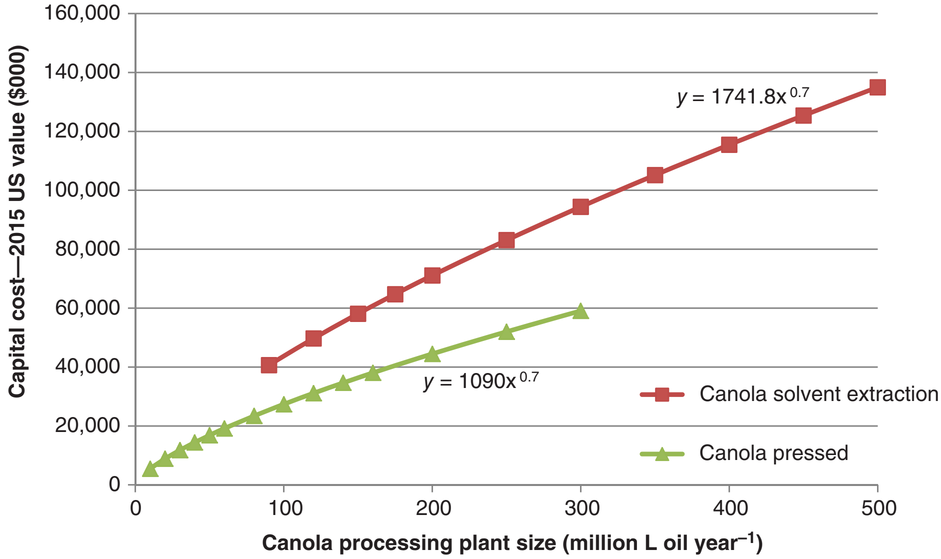

Fig. 5 Capital costs for RSC extraction: prepress solvent extraction vs. mechanical pressing (Miller, Sultana, & Kumar, 2012)

generate their own starting meal (Fig. 1). A complete modeling of the processes is beyond the scope of this paper. Nevertheless, Fig. 5 compares capital costs of solvent extraction and mechanical pressing to provide further insights into the magnitude of costs associated with generating a feedstock from scratch for protein extraction. Fig. 5 is derived from empirical data by Miller et al. (2012). Soybean plants thus have an added incentive for greater meal diversification because soybean oil accounts for approximately 40% of total revenue; hence, the greater emphasis on meal and hulls (Cheng & Rosentrater, 2017). This is in contrast to RSC oilseed crushing, where oil is the most valuable product, accounting for 70–80% of the total revenue and backed by readily available feed market to absorb the low-value meal coproduct. Hence, value-added diversification of soy meal to provide expanded markets for the protein meal has typically been a key strategy in the generation of higher profit margins to soybean crushing, which has led to soybean's highly diversified utilization and dominance in food and nonfood applications.

RSC Innovation Value Chain Including Protein

The scale-up and demonstration stages are among the most critical in a new technology because they are associated with a significant increase in demand for funding, technical and business skills, support, and infrastructure to expedite full scale-up. The overall process involved in full-scale commercialization of RSC can be viewed in terms of the economics of finance and the concept of technology innovation chain, or what is called the stage-gate model developed by Cooper (2006). Indeed, economists in seminal work dating back to the early 1960s, for instance, Arrow (1962), have elucidated the complex innovation chain involved in converting a research invention into a successful commercial innovation. In this case, the innovation chain refers to stages of technology development and includes components ranging from basic research to full-scale commercial adoption. Fig. 6 presents stage gates (top frame) and an amalgamation of various concepts to illustrate the complex interaction of the various intervening steps. The top part shows the typical innovation chain divided into five salient phases: Stage 1: discovery research involving basic science, concept design, invention disclosure, and characterization of intellectual property (patent, trade secret, etc.); Stage 2: feasibility—: applied research involving proof-of-concept and reduction to practice; Stage 3: technology development and demonstration; Stage 4: product development and commercialization; and Stage 5: industry adoption. The stages are not mutually exclusive; the arrows indicate feedback between various phases. The middle depicts the investment climate and the associated R&D investment intensity curve. The shape of the curve shows how R&D funding is typically more readily available from the public sector for basic research (the "hill") compared to the intermediate (pilot demonstration) stages (the "valley").

At the core of the innovation chain is the "Valley of Death" (Auerswald & Branscomb, 2003) that describes the resource gap between R&D and the technology commercialization phases. The "Valley of Death" represents challenges of transitioning from public sector to private sector R&D funding. In this situation, the innovating firm is confronted with high demands for cash compounded by a low ability to raise the cash from the private sector market, specifically from angel investors (who invest at the early

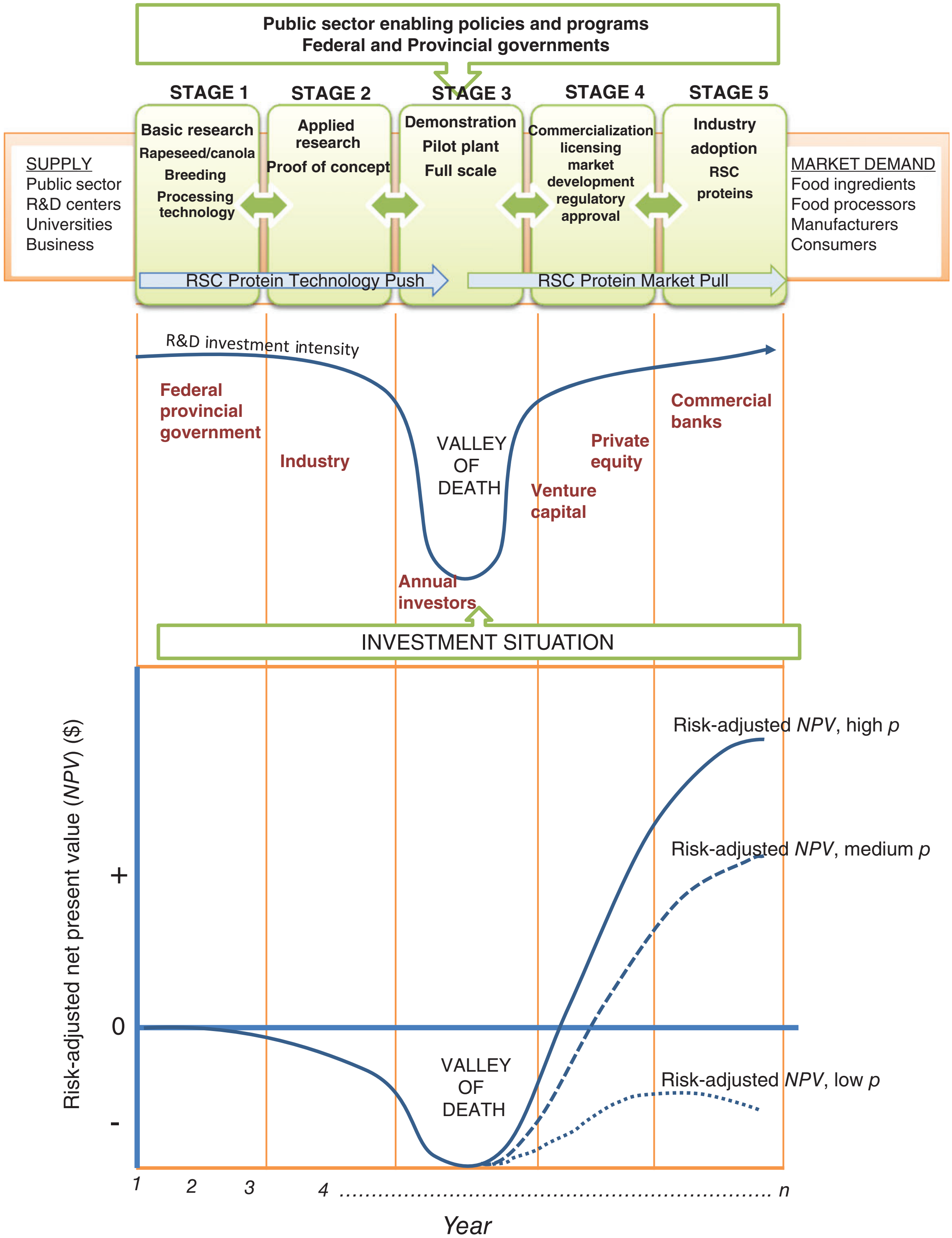

Fig. 6 *Brassica* protein innovation chain model and NPV associated with price (*p*) (figure adapted based on Cooper's stage-gate model [Cooper, 2006], Auerswald and Branscomb's innovation chain model [2003], and textbook theories of finance [Dixit & Pindyck, 1994])

commercialization stage) and venture capitalists (who consider financing upon demonstration of concrete initial sales) (Auerswald & Branscomb, 2003). Fig. 6 also presents three hypothetical risk-adjusted net present values (NPV), which are a function of a desired rate of return by investors and their risk preference (Dixit & Pindyck, 1994). Venture capitalists typically invest in high-return companies that have high potential for rapid and steady sales growth, as well as a strong proprietary new technology or dominant position in an emerging market. In this case, they seek very high rates of return (typically 30–50%). Fig. 6 also depicts the interface between science/technology push and business/market pull within the *Brassica* protein innovation chain. Science/technology push is often predicated on the notion that advances in scientific knowledge determine the rate and direction of innovation. Business/market pull refers to the notion that an innovation developed through R&D is in response to an identified business/market need, and that changes in business/market conditions are the driver for the private sector to invest in order to satisfy unmet needs. The transition between science/technology push and business/market pull is not necessarily linear, and involves feedback mechanisms; hence, the two phases are complementary. Although a range of activities are involved in the commercialization of RSC protein discoveries, they can be grouped under two general categories: (1) proof-of-concept demonstrating the commercial applicability of RSC protein technologies/products and (2) scalability of the RSC protein technology into a business value proposition that is commercially attractive to investors, which includes the development of a concrete business case, identifying ingredient manufacturers or key food manufacturers for the technology, inter alia. BioExx, Burcon, and MCN Bioproducts provide empirical examples of the transition along the RSC protein innovation chain.

BioExx *Empirical Business Case*

A detailed case study of RSC protein isolate commercial pioneer BioExx was carried out to illustrate the commercialization pathway in the context of the innovation value chain depicted in Fig. 6. The information used here was extensively researched from public domain sources available for publicly traded companies, including BioExx's publicly issued statements, annual reports, media statements, and filings with the Toronto Stock Exchange (TSX) and the Ontario Securities Commission.

BioExx (Bio-Extraction) was founded in 2003. The company went public on March 16, 2006, via an initial public offering (IPO) on the TSX. Its 40,000 tonnes annum^{-1} canola-crushing plant (located in Saskatoon, Saskatchewan) had a projected output of more than 17.5 million L of crude degummed canola oil, 13 million kg of meal, and 11 million kg of protein concentrate (65% purity level) per year at full capacity. The capital cost was estimated by GEA Process Engineering Inc. at US$65 million. An 80,000-tonne canola protein plant was also planned for Minot, North Dakota (USA), at a capital cost of US$130 million. Both estimates are for the core protein-processing area and exclude auxiliary costs for land, buildings, screw presses, and utilities infrastructure. BioExx was enabled by a family of RSC protein patents (Table 1), which competitively positioned the new company in the RSC protein market with two notable products: Isolexx® (90% protein isolate) and Vitalexx® (90% fully hydrolyzed protein isolate). BioExx also reported two protein concentrates: Advantexx™ 70 (70–75% protein) and Advantexx™ 80 (75–85%).

BioExx also signed a number of commercial memoranda of understanding and long-term purchase and sale agreements with numerous entities ranging from small niche producers to large multinationals involved in the use and marketing of specialty proteins. BioExx estimated the value of its distribution agreements at $300 million over 10 years. In terms of financing, BioExx received project funding from several organizations to support further R&D of its RSC protein products. Public sector funding included grants totaling $3.59 million from sources such as AAFC (Advancing Canadian Agriculture and Agri-Food Saskatchewan Program, and Agri-Opportunities Program). Private sector sources included securities offering purchases of shares by investment banks and sale of common shares to the public on the TSX. These included 35.55 million shares with gross proceeds of $60 million.

Other operational aspects of BioExx involved implementation of programs for regulatory compliance with FDA (USA), Canadian Food Inspection Agency (Canada), and Good Manufacturing Practices Plus (Europe) standards for good manufacturing practices in food production and food safety. These operations culminated in the production of the world's first commercial rapeseed protein isolate (Isolexx®) by BioExx with >95% purity as announced by the company in August 2010. BioExx reported production

Table 2 Summary of BioExx annual financials: 2009–2012

Year	Total revenue	Total expenses	Net income	Earnings per share ($)	Stock price (end of year)
2012	648,255	63,928,110	−63,279,855	−0.29	0.08
2011	5,348,230	35,459,890	−30,111,660	−0.15	0.15
2010	3,268,235	14,873,619	−11,605,384	−0.09	2.36
2009	4,170,507	9,830,162	−5,659,655	−0.06	2.06

Source: BioExx annual reports.

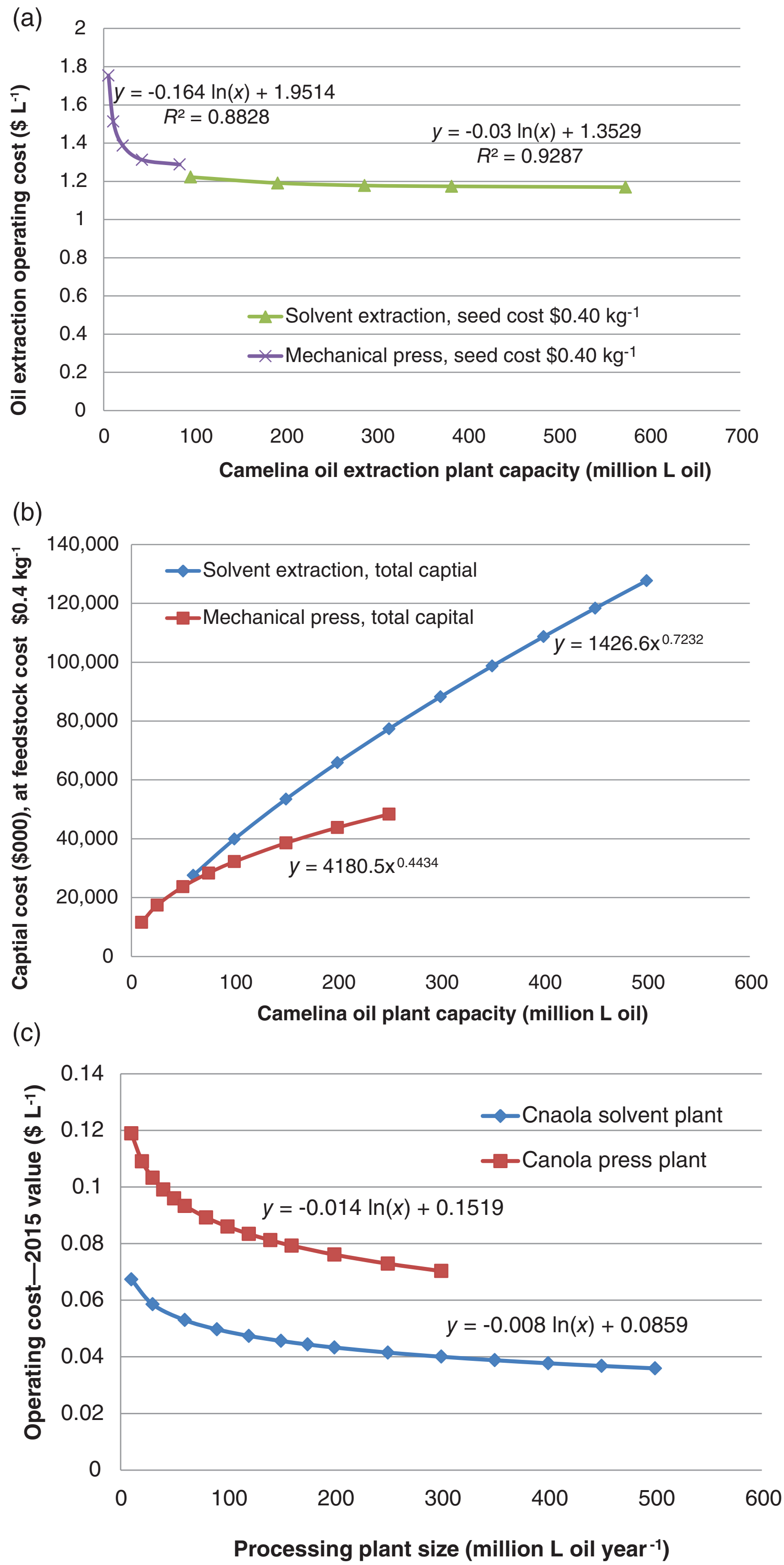

Fig. 7 (a) Comparative operating costs for *Brassica* (camelina) oilseed processing: mechanical presses vs. prepress solvent extraction (Mupondwa, Li, Falk, et al., 2016; Mupondwa, Li, Tabil, et al., 2016). (b) Comparative capital costs for camelina oil extraction: mechanical press vs. solvent extraction (Mupondwa, Li, Falk, et al., 2016; Mupondwa, Li, Tabil, et al., 2016). (c) Comparative operating costs for canola oil extraction: mechanical press vs. solvent extraction (Miller et al., 2012)

of 60 kg of canola protein isolate (CPI) and 120 kg of canola protein concentrate (CPC) per tonne of canola seed processed (2.4 million kg CPI and 4.8 million kg CPC $year^{-1}$). At this scale, this translates into combined sales of \$14–29 million $annum^{-1}$. This is based on a market value of \$6000–8000 $tonnes^{-1}$ for CPI and \$4000–6000 $tonnes^{-1}$ for CPC.

BioExx's commercial protein operations commenced in June 2011. Its initial short-term target focused on the production and sale of RSC protein with purity levels >80%, for which it reported the existence of an established, significant, and strong market. BioExx also noted that given similarities between customers and applications for proteins with purity levels of 80% and 90%, pricing was the only differentiating factor. For the most part, these two levels of purity are applied interchangeably in many food and beverage products (e.g., protein shakes, bars, baked goods, confectionaries, meat analogues, and meal replacers). In this regard, BioExx sold its Advantexx80™ (>80% purity protein canola isolate), while it conducted additional R&D to achieve 90% purity, which was the company's target for offering a 90% protein isolate to the market. This purity would enable BioExx to extract additional premium since the market generally prices 80% purity proteins at approximately 15–20% discount relative to 90% purity proteins. For instance, whey protein isolates with 90% purity are priced at \$13.00 kg^{-1}, while whey protein concentrates with 80% purity are prices at \$11.00 kg^{-1}. However, BioExx priced its 80% CPI at \$6.00 kg^{-1}, given market conditions and pricing of competitive and established protein products of similar quality (soy and whey proteins). The company had a higher premium pricing guidance for its Isolexx™ 90% protein purity.

Table 2 summarizes the company's reported financial results. There was no reported revenue prior to 2009 as the company was in the development phase at this juncture. Table 2 shows negative income and earnings per share for the entire duration of the company's operation (2009–2012), with a return on equity (ROE) of −171.64%. Base on the innovation chain model (Fig. 6), this corresponds to a very-low-risk-adjusted NPV. The company also found the operation of a small scale 40,000 tonnes crush-only plant economically challenging vis-à-vis competing against the economies of scale of the sector. The greatest constraint reported is related to inadequate financial resources to construct and scale-up the Saskatoon plant to its fully operational scale of 11,000 tonnes CPI $annum^{-1}$.

Studies by Mupondwa, Li, Falk, Gugel, and Tabil (2016) and Mupondwa, Li, Tabil, Falk, and Gugel (2016) on another *Brassica* oilseed, camelina, demonstrated that a small-scale mechanical press has higher operating costs per tonne of seed than a large-scale prepress solvent extraction plant facing similar feedstock costs (Fig. 7a) (within their respective ranges of operating scales). This is notwithstanding the fact that a large-scale solvent extraction plant faces higher capital costs (Fig. 7b). This is illustrated for canola oil processing based on empirical data by Miller et al. (2012) (Fig. 7c). Hence, without a fully operational RSC protein production scale, BioExx's production platform would be challenged. Furthermore, the company reported inability to find partners, who instead preferred lower-risk vegetable proteins that were already commercially available.

On October 1, 2013, BioExx closed its Saskatoon plant with creditor protection provided by the Ontario Superior Court of Justice. The company's stock dropped by 20%. Table 2 shows the performance of BioExx shares on the TSX (2009–2012). The stock was consequently delisted from the TSX effective November 6, 2013, for failure to meet listing requirements. Subsequently, European investment company Siebte PMI Verwaltungs GmbH (Germany) purchased all of BioExx's intellectual property (patents and trademarks, including Isolexx®, Vitalexx®, Advantexx™, and Advantexx™) (EU, 2014). Siebte has interest in placing RSC protein on the market as a novel food ingredient (Ontario Court of Justice, 2014). A new company, Teutexx, has since emerged with a commercial focus on commercializing Isolexx® and Vitalexx® (TeuTexx, 2015). There are no available operational details currently.

In the context of Fig. 6, the concept of going public (via an IPO) represented a significant stage-gate milestone (end of Stage 3) in the large-scale commercialization of RSC proteins. In itself, this is often considered a measure of success given the large payout associated with an IPO. Going public accorded BioExx significant advantages. These include (1) enabling the company to consolidate its capital base (to fund R&D, capital investment in the scale-up of canola protein extraction, and paying off current debt) and (2) providing public visibility in the market for its novel RSC protein products. Obviously, going public also places significant performance pressure on start-ups, such as (1) focus on short-term growth due to constant need to increase current earnings at the expense of strategic investments and (2) cost of regulatory reporting (disclosure for investors) and compliance with the Securities Exchange Act. The public disclosure of operational details could expose a new IPO to competitors, while the cost of regulatory financial compliance and reporting are disproportionately borne by smaller companies. Nevertheless, the whole process of going public is based on due diligence in which BioExx had to satisfy key prerequisites, including demonstrating (1) a highly innovative product, (2) ability to compete in the plant protein market segment, (3) good prospects for high growth from RSC protein sales typically over a 5-year span, and (4) ability to satisfy requirements for financial audit.

Based on the market prospects for RSC proteins as described in this paper, as well as BioExx patent portfolio of its core technology, there is no doubt that these requirements were met, although the company still had to work very diligently to qualify for an IPO.

Overall, BioExx had a good start-up, founded on significant R&D, solid intellectual property base, and regulatory approval of its RSC proteins. The company encountered financial constraints that affected the commercial scale-up of its RSC protein extraction, while economies of scale and related market factors affected its ability to compete against large players (incumbents mostly focused on alternative plant proteins, such as soy and pea). In the case of RSC protein isolates, there are a number of factors to consider at this "Valley of Death" stage to attract investment to take RSC protein beyond this phase. First, the fractionation processes and the derived protein products must have the ability to compete with established or mature technologies on the market, notably, soybean processes and the plethora of soy protein products. The reference to economies of scale in RSC protein production suggests that the high cost of production represents a perceived risk of committing to an investment decision that is costly to reverse or entail high abandonment costs relative to established technologies. The plethora of new technologies described in Fig. 1 is based on operations that generate their own feedstock from small-scale mechanical presses. This capital investment is necessitated by the nonavailability of mainstream meal from canola-crushing plants as a viable feedstock for protein fractionation and extraction.

Brief Overview of Other RSC Start-Up Companies

In view of the preceding discussion, it is worthwhile to provide a brief overview of other RSC protein start-up companies that managed to stay afloat. Burcon (previously mentioned in "Industrialization/Commercialization of RSC Protein Processing Technologies") is another recognized pioneer of RSC proteins, in particular its Nutratein® and Supertein® RSC proteins (US FDA, 2010). Burcon's entry into the plant protein market was highlighted by a significant milestone involving a 2003 partnership in which ADM would manufacture and commercialize Puratein® and Supertein® RSC protein isolates using Burcon's extraction technology (Food Navigator, 2006; Nutra Ingredients, 2003). ADM is a leading multinational and major processor of soybean, wheat, corn, and cocoa. In 2012, Burcon announced termination of this RSC protein development agreement with ADM, citing subsequent lack of interest by ADM (Food Navigator, 2012). Instead, ADM signed a 20-year licensing agreement with Burcon focusing on commercialization of Burcon's soy (Clarisoy™) protein technology for which there are already existing markets (Food Navigator, 2012). On December 6, 2017, Burcon announced receipt of notification from the NASDAQ Stock Market (under which its stock is traded) stating that the company did not meet NASDAQ's listing rules requiring a minimum market value of its listed securities to be US $50 million. While this is only a notification, it points to challenges that key RSC start-ups have experienced in this domain, including challenges in meeting a minimum share price, number of shareholders, and the level of shareholders' equity. Table 3 presents Burcon's financial summary based on public domain filings with the Securities Exchange Commission. Table 3 shows negative income and earnings per share from 2013 to 2017, with ROE of −157.88% for 2017. The company's share price dropped from a high of $3.70 in 2013 to $1.56 in 2017. Nevertheless, Burcon pursued a different strategy by partnering with ADM to commercialize Clarisoy™ protein technologies.

The other company (also noted in "Industrialization/Commercialization of RSC Protein Processing Technologies") is MCN Bioproducts, founded in 2000 to commercialize Can Pro SP (60%), CanPro IP (68%), CanPro fiber protein, and CanSugar (Daun, Eskin, & Hickling, 2011). The company was profiled as a manufacturer of plant-based canola protein products for feed, food, and cosmetics markets in Canada and internationally (Bloomberg, 2017). In 2007, MCN licensed its technology to CanPro Ingredients Ltd. (Saskatchewan), a company headed by one of the cofounders of MCN (CanPro Ingredients Ltd, 2017). CanPro Ingredients is an integrated biorefinery producing specialty canola oil, CPC, and high-protein alfalfa for aquaculture and animal feed market (CanPro Ingredients Ltd, 2017). In 2012, MCN Bioproducts was bought by US multinational agri-food firm Bunge through the acquisition

Table 3 Summary of selected financials for Burcon: 2013–2017

Year	Total revenue	Total expenses	Net income	Earnings per share ($)	Stock price (end of year)
2017	70,000	4,400,000	−4,330,000	−0.12	1.56
2016	80,000	5,150,000	−5,070,000	−0.14	2.56
2015	80,000	5,280,000	−5,200,000	−0.16	2.39
2014	90,000	5,490,000	−5,400,000	−0.17	3.70
2013	30,000	5,480,000	−5,450,000	−0.18	2.85

Source: Burcon annual financial reports.

Table 4 Structure of protein market by competitor, product type, value of sales, and research and development (R&D) expense (2016 values unless specified)

Company	Country	Type of protein	Revenue ($ million)	R&D ($ million)
Michael Foods, Inc.	USA	Egg protein	1728	16.3
Cal-Maine Foods, Inc.	USA	Egg protein	1910	na
Moark, LLC	USA	Egg protein	627	na
Rose Acre Farms, Inc.	USA	Egg protein	585	na
Luberski, Inc.	USA	Egg protein	350	na
Sonstegard Foods Company	USA	Egg protein	125	na
Henningsen Foods, Inc.	USA	Egg protein	59	na
The Ballas Egg Products Corporation	USA	Egg protein	15	na
Gelita North America Inc.	USA	Gelatin	225	na
Rousselot Dubuque Inc.	USA	Gelatin	140	na
PB Leiner USA Corp.	USA	Gelatin	19	na
Nitta Gelatin Na, Inc.	USA	Gelatin	2	na
The Kraft Heinz	USA	Gelatin	26,490	120
Glanbia Public Limited Company	Ireland	Whey protein, milk protein concentrate, casein and caseinates	3000	9.8 (€8.8)
Leprino Foods Company	USA	Whey protein	2700	na
Davisco Foods International, Inc.	USA	Whey protein and milk protein concentrate	104	na
Hilmar Cheese Company, Inc.	USA	Whey protein	247	na
Protient, Inc. (merged with PGP International Inc.)	USA	Whey protein	70	na
Bongards' Creameries	USA	Whey protein	133	na
Fonterra Cooperative Group Ltd.	New Zealand	Whey protein, milk protein concentrate, casein, and caseinates	12,380	11.5
Kerry Group	Ireland	Milk protein concentrate, casein and caseinates	6460	220
Erie Foods	USA	Milk protein concentrate	0.14	na
FrieslandCampina DMV	Netherlands	Casein and caseinates	13,790	82 (€74)
Arla Foods Limited	England	Casein and caseinates	2890	na
Dupont (Solae LLC)	USA	Soy protein	503	na
ADM Company	USA	Soy protein and wheat gluten	62,350	123
Cargill, Incorporated	USA	Soy protein and wheat gluten	120,400	40[a]
Manildra Group USA (Honan holdings U.S.A., Inc.)	USA	Wheat gluten	23,450	na
MGP Ingredients, Inc.	USA	Wheat gluten	318,260	916
Tereos Sucres (Syral)	France	Wheat gluten	974	na
Roquette America Inc.	USA	Wheat gluten	213,990	na
White Energy Holding Company, LLC	USA	Wheat gluten	44,650	na
Roquette Frères	France	Pea protein	2140	na
Burcon Nutrascience Corporation	Canada	Pea protein, rice, and canola protein	0.08	2.7
Nutri-Pea Limited	Canada	Pea protein	1.14	na
Axiom Foods, Inc.	USA	Pea protein, rice, and canola protein	8.16	na
Farbest-Tallman Foods Corp.	USA	Pea protein	14	na
Parrish & Heimbecker, Limited	Canada	Pea protein	236	na
BioExx	Canada	Rice and canola protein	na[b]	na
TerraVia Holdings, Inc. (Solazyme)	USA	Algae proteins	18	31
Aurora Algae, Inc.	USA	Algae proteins	14	1.9[c]

Source: D&B Hoovers database, Frost & Sullivan market report, and annual report of companies.

[a] 2017 value.

[b] BioExx was analyzed based on an annual sales of $6.7 million. The company filed for bankruptcy in 2013.

[c] R&D expense in 2015 and 2014 was $1.9 and $12.2 million, respectively.

of MCN's patents and related assets for the production of RSC protein concentrates for use in pet, livestock, and aquaculture diets (Market Wired, 2012). There is little available information on MCN's commercial operations. Recently, DSM, a Dutch multinational, entered the RSC protein market based on its "Proteins of the Future" project led by scientists at the DSM Biotechnology Centre in Delft (the Netherlands) (DSM, 2017; Shi et al., 2017). Although there is little market data on the current performance of the company's RSC protein isolate CanolaPro™, DSM is still listed as RSC protein supplier. Isolexx® and Vitalexx® (formerly owned by BioExx) are now being commercialized under a new company, TeuTexx Protein (TeuTexx, 2015). There is no market information to determine whether the strategy is different this time.

Competitive Market Force in RSC Protein Commercialization

The commercialization of RSC proteins in this context can be further elucidated by applying Porter's Five Forces Model (Porter, 1985) that determines competitive intensity, and therefore, attractiveness of a market, namely rivalry, threat of substitutes, bargaining power of suppliers, bargaining power of buyers, and barriers to entry. The combined strength of these five forces determines a given industry's potential via its influence on prices, costs, and the required level of investment. A critical aspect for the protein sector is that the stronger the forces, the greater the barriers that must be overcome within that business environment. Globally, large companies (typically with annual revenues of more than $1 billion) account for a significant portion of this industry and include top players: For instance, Cargill and ADM generate annual revenues exceeding $50 billion in the soy protein and wheat gluten market (Table 4) (Fuglie et al., 2011). A structure in which a few large companies have a very high market share is referred to as an oligopoly. This structure is similar to a monopoly in which one firm dominates the market. The only difference is that in an oligopoly, two or more firms dominate the market. This structure necessitates economies of scale and scope in terms of food processing, integrated storage, distribution, and marketing. The structure is also characterized by high sunk costs (i.e., irreversible costs already incurred) that cannot be recovered. Such costs are a barrier to market entry by new players. The above structure characterizes the global protein food processing industry. Table 4 presents the structure of the protein market and key competitors in which ADM, Cargill, and DuPont (Solae) dominate the soy protein market, while start-ups Burcon and BioExx are early entry players commercializing RSC proteins. Soy protein and wheat gluten together accounted for 99% of the plant protein market in North America in 2015, while RSC proteins are still confined to niche markets in North America, with primary concentration in Canada where both their commercialization is being driven by the three companies (Frost & Sullivan, 2016).

In the context of Porters Five Forces threat of entry, the above illustrates challenges that new entrants to an industry face to gain market share by bringing new capacity and rivalry. The threat of entry is influenced by the extent of barriers that include capital requirements to scale up protein production to large-scale commercial production, economies of scale and supply-side advantages enjoyed by incumbents, and preferential access to channels of distribution. Incumbents who are first-movers enjoy first-mover advantages, including setting standards (soy protein isolate), tying up suppliers and distributors, and creating significant brand loyalty. The interplay of these five forces can influence the ability of new entrants to access the supply chain, including the distribution and vertical transmission of risk, and magnitude of transaction costs. A new protein product challenging the market space occupied by established rivals (e.g., soy protein) has several barriers that it needs to overcome, starting with the market segmentation strategies of the incumbent. For instance, the soy protein market is broadly segmented by (1) protein type (soy protein concentrate, protein isolate, soy protein flours, and soy milk), (2) protein function (liquid, powder, bar, and tablets), (3) protein use (meat additives, sports nutrition, nutraceutical functional foods, confectionery, and pharmaceuticals/health), and (4) supply/marketing channel and region (supermarkets, hypermarket, and web-based convenience store) (Singh et al., 2008). Substitute products or imitations must find their share in this crowded space further constrained by branded diversified product space and innovative marketing. Large firms have considerable brand image and loyalty backed by massive advertising expenditure to counteract the threat of substitute products and build growth for their products, and global supply chain. All these are supported by their continued technological development and innovation through their well-funded R&D (Table 4) in new processes and product applications (Hoover's Inc., 2017). For example, extensive research that led to soy protein health claims represents yet another competitive edge against new substitute products lacking such official regulatory endorsement (Health Canada, 2015; Krul, Mauro, & Mukherjea, 2014; US FDA, 1999).

Summary: Commercialization Opportunities for RSC Proteins

The analysis provided in this paper presents a context that must be taken into account in efforts to support significant commercialization of RSC protein in food applications.

This context is useful because of the many opportunities that RSC proteins can exploit in the market for plant proteins, backed by significant science and novel processing technologies capable of producing food-grade RSC protein isolates free of antinutritive compounds and insoluble fiber. From a technology integration vantage point, there is a need for quantitative technoeconomic determination of how the current processing infrastructure facilitates greater economies of scale for RSC feedstocks used to extract RSC proteins. This could include scope for design of entirely new integrated capital infrastructure in which the diversion of part of the rapeseed meal to specialty protein fractionation and extraction is an integral component. RSC is a successful oilseed crop with numerous textbook examples of crop innovations related to breeding, production technologies, biological knowledge, integration of crop biotechnology, human and animal nutrition, and oil-processing technologies. Science has substantiated protein production technologies that have been generated since the inception of the commercial crop almost 50 years ago. The alternative protein ingredient market is going through rapid change involving changing consumer attitudes and food preferences, further providing impetus for new food product innovations by the food industry that are aligned with new consumer preferences. There are opportunities for RSC to enter the emerging and growing gluten-free ingredient segment within the overall alternative plant protein market. RSC technologies also provide a foundation for evolving sustainable fractionation technologies founded on the emerging biorefinery concept for total (coproduct) utilization. Indeed, existing processes can be adopted to satisfy emerging clean technology paradigms, including labeling requirements from a food regulatory vantage point to address issues of food allergens. Overall, in the context of a *Brassica* innovation chain, there is a greater role for the *Brassica* processing sector to stimulate the evolution of an integrated RSC protein value chain. This would ensure that innovation occurs along the entire value chain (from production to high-value applications), instead of being characterized as a fragmented assortment of feedstocks and technologies responding to market opportunities.

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Conflict of Interest The authors declare that they have no conflicts of interest.

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