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Sustainability in the Canadian Egg Industry—Learning from the Past, Navigating the Present, Planning for the Future

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Abstract: Like other livestock sectors, the Canadian egg industry has evolved substantially over time and will likely experience similarly significant change looking forward, with many of these changes determining the sustainability implications of and for the industry. Influencing factors include: technological and management changes at farm level and along the value chain resulting in greater production efficiencies and improved life cycle resource efficiency and environmental performance; a changing policy/regulatory environment; and shifts in societal expectations and associated market dynamics, including increased attention to animal welfare outcomes—especially in regard to changes in housing systems for laying hens. In the face of this change, effective decision-making is needed to ensure the sustainability of the Canadian egg industry. Attention both to lessons from the past and to the emerging challenges that will shape its future is required and multi- and interdisciplinary perspectives are needed to understand synergies and potential trade-offs between alternative courses of action across multiple aspects of sustainability. Here, we consider the past, present and potential futures for this industry through the lenses of environmental, institutional (i.e., regulatory), and socio-economic sustainability, with an emphasis on animal welfare as an important emergent social consideration. Our analysis identifies preferred pathways, potential pitfalls, and outstanding cross-disciplinary research questions.

Keywords: Canada; eggs; sustainability; animal welfare; economics; supply management

1. Introduction

Food systems are at the center of human well-being. In addition to satisfying a basic human need (i.e., regular access to food in sufficient quantity and of sufficient quality), food is also often a central contributor to our economies and cultures, and often even to our individual identities. However, activities in the agri-food system are also at the center of many of our most pressing sustainability challenges. The production of food—in particular, in the livestock sector—contributes a large fraction of current anthropogenic resource demands and environmental pressures [1–3]. For this reason, livestock industries are naturally the focus of a growing body of sustainability research and management initiatives [4].

Taken together with projected increases in food production globally and a trend towards diets higher in livestock products, this has spurred considerable interest in the concept and practice of "sustainable intensification" in the livestock sector [4]. According to Pretty et al. [5], sustainable intensification is defined as "producing more output from the same area of land while reducing negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services." Clearly, however, sustainable intensification efforts may also have potential benefits and trade-offs across socio-economic, institutional, and other aspects of sustainability that must be carefully considered.

Life cycle thinking (LCT) has emerged as a core concept in sustainability science [6]. LCT refers to adopting a systems-level perspective on industrial activities. This perspective enables us to understand how different kinds of potential sustainability benefits and impacts are distributed along agri-food supply chains, as well as trade-offs that may occur with respect to different valued outcomes when particular changes are implemented. Environmental life cycle assessment (e-LCA) is a commonly used tool, based on LCT, for studying and managing the resource/environmental dimensions of food supply chains [4]. In recent years, a rich body of research has applied this tool to evaluate a variety of livestock production systems and technologies in different contexts, and as a basis for understanding the respective merits of potential sustainable intensification technologies (for a review of 173 recent papers, see McClelland et al. [7]).

While such research is clearly of considerable value, it is by itself insufficient to support sustainability decision-making for the livestock sector since it considers only a subset of important sustainability criteria that inform our decisions [8]. In reality, the varied forces that influence how we produce and consume livestock products along with the associated benefits and impacts are complex, often interacting, and variable over time. They include changes in technology and management practices, evolving societal expectations and consumer preferences, and the regulatory context in which specific industries operate. Efforts to understand current sustainability challenges in the livestock sector and to identify preferred paths forward can benefit from interdisciplinary approaches that evaluate these forces with respect to historical trends, current conditions, and possible futures.

Egg Farmers of Canada, the industry body governing the production and marketing of eggs within the supply-managed Canadian egg industry, provides research monies to support four Research Chairs at Canadian universities. These Research Chairs respectively undertake independent research in the fields of economics (Doyon), public policy (Muirhead), animal welfare (Widowski), and sustainability (Pelletier) of broad or direct relevance to the egg industry. The current analysis brings together the expertise, research, and perspectives of each of these Chairs to present an integrated study of the past, present and possible futures for this industry. Specifically, the purpose of the analysis is to identify: (1) the key factors that have shaped the modern Canadian egg industry; (2) the issues and opportunities it currently faces; and (3) potential synergies and trade-offs across the multiple dimensions of sustainability that should be considered on an interdisciplinary basis in choosing among viable paths looking forward.

2. Methods

The analysis is presented in three sections. The first section provides a historical perspective, describing the emergence and evolution of the Canadian egg industry over the past century until the present. It is organized into subsections respectively addressing: key technological and management changes, including their influence on the efficiency and environmental sustainability impacts of egg production; the development and implications of the supply management system that governs the industry; the factors that have influenced the economics of egg production, including changing consumer preferences and social expectations; and, as an important aspect of the latter, the emergence of animal welfare as both a societal concern and field of study/application for the egg industry.

The second section, also organized into four subsections, describes challenges that the industry currently faces in each of these domains that may undermine its sustainability, as well as potential solutions. Possible trade-offs across sustainability domains that such solutions may imply are identified. On this basis, the final section summarizes some of the key areas for interdisciplinary research and collaboration that are necessary to support choosing among alternative courses of action to enable a sustainable egg industry in Canada into the future.

3. Discussion

3.1. Canadian Egg Industry Retrospective (Circa 1920 to Present)

3.1.1. Technology, Management, and Resource Efficiency

Although a small number of specialized, commercial egg farms in Canada existed in the early part of the 20th century, egg production was generally one among a series of activities undertaken on the mixed-farming operations that were characteristic of Canadian agriculture at that time. Beginning in the 1920s, however, the egg industry entered a period of significant and sustained industrialization. Two major developments that were particularly important to the specialization and intensification of egg production were the adoption of cage systems for housing laying hens and improved genetic selection for egg production and feed conversion efficiency.

From 1923–1924, D.C. Kennard performed the first experiments keeping laying hens in confinement at the Ohio Agricultural Research Station, using livability and production as the main measures of success [9]. However, cage systems were not immediately adopted for commercial use. This was because indoor confinement for longer periods of time was only possible once the complete ration, which was developed in 1924, was made available on the wider market in 1929 and the Rural Electrification Act of 1936 in the US enabled barns to be lit artificially. The ability to keep laying hens indoors revolutionized the egg industry [10,11]. Whereas eggs were previously a seasonal (spring) food in temperate climates, they could now be produced continuously year-round [12].

According to Lee, 1938 marked the year when farmers had "satisfactorily solved the many problems of management which were responsible for the failure of earlier battery plants (so called because of the methodical (militaristic) nature of organizing the cages in stacked groups or batteries)" [10]. The need for steel during World War II, however, meant that the production of cages was halted (except for a small number of chick batteries) until after the war when the battery cage boom started on the Pacific coast of the US and in the UK [10].

Individual cages were initially used because they eliminated issues with cannibalism and allowed for the practice of "positive culling," or removing birds from the flock that are "laying at a slow unprofitable rate or [have] quit laying altogether" [13]. However, due to the cost advantages of housing multiple birds in the same cage, the battery cage was adapted to house small groups of hens [14]. Beginning in the 1960s egg production in Canada transitioned from "free-run" (i.e., indoor non-cage) to cage-based production.

Genetic selection of laying hens for egg production and feed use efficiency in cage systems also began in earnest following World War II. Canadian Donald Shaver built a global breeding organization for layer and broiler strains [15]. The availability of electricity-powered incubators and the relatively short incubation cycle for eggs facilitated rapid progress in selection for production efficiency [16]. At the same time, development of improved management practices for disease prevention such as biosecurity protocols, along with the advent of poultry vaccines, served to improve bird health and reduce losses due to mortality [17,18]. Over time, advancements in housing technology including artificial ventilation systems and climate control, automated feeding, egg collection and manure removal were implemented, thereby reducing labor and allowing for thousands or tens of thousands of birds to be housed in a single barn.

In combination, these technology and management changes have enabled considerable improvements in resource efficiency and the reduction of environmental impacts associated with producing eggs in Canada. For example, annual rate of lay among Canadian laying hens has increased from less than 100 eggs per year in the early 20th century to over 300 at present [19]. Between 1962 and 2012, an interval of 50 years, rate of lay increased by more than 50%. This same 50-year interval was also marked by declining mortality rates (falling from roughly 13% in the early 1960s to 3.2% at present for pullets and laying hens combined), and by much improved feed conversion efficiencies. With respect to the latter, producing 1 kg of eggs in 1962 required over 3 kg of feed compared to the current average of 2 kg on contemporary egg farms [20].

Efficiency changes have been equally pronounced along the supply chains that ultimately support Canadian egg production. Among these, the most influential in terms of life cycle resource use/emissions-related sustainability impacts have been: (a) a 50% reduction in the energy intensity of ammonia production for nitrogen fertilizers (one of the most energy and emissions intensive aspects of modern agriculture); (b) improved yield-to-fertilizer and energy input ratios for the production of agricultural feed inputs (for example, corn yields in the province of Ontario increased 96% over this interval while nitrogen inputs per ton of crop declined 44%); and (c) improved efficiencies in freight transport, which connect activities all along the Canadian egg supply chain [20].

As a result, of these changes, the overall environmental footprint (i.e., including all supply chain activities) of producing eggs in Canada has, on average, declined 61%, 68%, and 72% for acidifying, eutrophying, and greenhouse gas (GHG) emissions while energy, land and water use decreased by 41%, 81% and 69% respectively per unit production. Moreover, despite that egg production volumes roughly doubled in Canada since the early 1960s, the absolute resource and environmental impacts for the industry as a whole were estimated to be 41%, 51% and 57% lower for acidifying, eutrophying, and greenhouse gas emissions, respectively. Supply chain energy, land and water use are 10%, 71% and 53% lower in aggregate [20]. These changes reflect a combination of farm-level efficiency gains (15–40%, depending on impact category) associated with improved management practices, superior bird genetics, and vaccine developments; changes in feed composition (29–60%); and changing efficiencies in activities along the supply chains that ultimately support egg production (0–56%) [20].

Life cycle assessment research has hence enabled a nuanced understanding of both the magnitude and distribution of a variety of environmental sustainability impacts along the contemporary Canadian egg supply chain, the relative importance of specific inputs to and activities associated with egg production as sources of these impacts, and the comparative impacts of egg production in alternative housing systems [21]. A relatively small number of variables explain the characteristic sources and distribution of life cycle resource use and emissions for eggs and egg product supply chains in Canada. Among these, feed composition and feed conversion efficiency in pullet and (in particular) layer facilities emerge as the strongest explanatory variables. Manure management is the second critical determinant of life cycle resource efficiency and emissions. Manure-related emissions are influenced by several factors, including feed composition (i.e., N and P content of feed inputs), feed conversion efficiencies, and manure handling strategies. Although more strongly influenced by supply chain feed inputs, direct water and energy use in facilities also make non-trivial contributions to the overall water and energy resource requirements for egg production. The contributions of egg processing and packaging, as well as egg breaking and further processing to overall supply chain resource use and emissions for eggs and egg products are relatively small [21]. These insights are largely consistent with similar research of intensive egg production in other countries (for example, [18,22–27]).

Pelletier [21] reported resource efficiencies and life cycle environmental performance by housing system type for the Canadian egg industry in 2012. Among the five housing technologies considered (i.e., conventional cages, enriched colony cages (which provide all of the equipment found in conventional cages with the addition of equipment that is intended to allow hens to express some of their behavioral priorities), free-run, free-range, and organic), both the life cycle inventory and impact assessment results suggested fairly similar levels of performance between systems for most variables. Feed conversion efficiencies were slightly higher in cage-based production, and mortality rates were substantially lower compared to non-cage systems. Of note was the higher variability in performance levels observed between reporting facilities for non-cage production systems, likely reflecting the substantial research and development investments and management experience gained for cage-based production over time relative to the emerging cage-free sector. Only for organic production were life cycle resource use and emissions significantly different from the other housing systems [21]. Here, the lower observed resource use and emissions intensity of organic eggs was attributable to the lower impacts of feed production rather than differences in farm-level efficiencies, where mortality rates were highest among the housing systems considered. At present, over 80% of laying hens in Canada are kept in conventional cages, and the remainder in either enriched cages, free-run barns, or free-range systems.

3.1.2. Shifting Regulatory Conditions for the Production and Marketing of Eggs

The intensification of the egg industry from the 1920s onward meant that increasing numbers of eggs were finding their way onto the market. While the consumption of eggs rose steadily over time, the growth in egg production often outstripped demand, leading to overproduction and hardship for egg farmers [28,29]. Critically, farmers only received prices that allowed a fair return for short periods of time after low prices had pushed out the most vulnerable producers. While a shortage of product briefly forced prices up, the cycle would start over as farmers re-entered the business or ramped up production and again prices would plummet due to an oversupply of eggs. This was a perennial problem and the Canadian Minister of Agriculture in 1959, Douglas Harkness, noted that "The only long-term solution to the current problem is a decrease in egg production to the point where there is a more realistic balance between supply and domestic requirements" [30].

An additional complication was cheap egg imports from the United States. This meant Canadian farmers often had to accept egg prices that not only reflected tough domestic competition, but also a cheaper international price. The US, with its more robust economies of scale, undercut Canadian prices. Furthermore, provinces with surplus production would seek markets outside their borders, often undercutting prices and causing local producers' incomes to drop [31].

The new realities of the price-cost squeeze borne by agricultural producers and trends towards more specialized, capitalized, and vertically integrated operations caused significant concern among family farmers who saw producer prices drop and their earnings decrease despite ever more costly farm investments. While some industry experts believed that the movement towards vertical integration was inevitable and that only a few of the largest Canadian egg producers would survive, others argued that egg producers needed to create a system that would permit them to succeed without the corporatization of the family farm [32,33].

The continued instability of egg prices galvanized discussions about the need for farmers to organize and institute measures that would secure fair returns. Foremost among these discussions were proposals to create provincial marketing boards to regulate the production and sale of eggs on a quota system basis. Critics of the idea of marketing boards cited infringements on their freedom to act independently. Some egg farmers also recognized that provincial production quotas would only work if a national production plan were instituted that addressed the issue of egg imports from the US [34].

In July 1971, provincial representatives reached an agreement in principle whereby production would be controlled by marketing boards in each province and the national market would be shared based on average production figures calculated from 1968 to 1970. This led to the passage of the Farm Products Marketing Agencies Act in January 1972, which allowed for the creation of the Canadian Egg Marketing Agency (CEMA) later that year. The system of "supply management" had come to the Canadian egg industry [35].

Despite some initial growing pains, by 1976 CEMA had turned the corner, becoming solvent and revising and consolidating the comprehensive egg marketing plan, which meant uniform pricing, quota planning, and overproduction penalties introduced in all provinces. The processes were coming into place that allowed for the successful operation of a national supply management system that promoted its social and economic sustainability. The system of supply management helped end market chaos and enabled farmers to earn a living wage and offer consumers a fair price, while demonstrating a commitment to improved egg farming practices. At present, CEMA, renamed Egg Farmers of Canada in 2008, oversees the quota-based production and marketing of eggs from over 1000 farms distributed across all ten Canadian provinces and one territory.

3.1.3. Shifting Social Preferences and Socio-Economic Conditions

Supply Management

Over the years, the economics of the egg industry has been driven by improvements in technology, genetics, feeds, and management; resulting in productivity gains in rate of lay, in feed conversion and in lower mortality rates. Supply management, which shaped the marketing of eggs in Canada since 1971, has been similarly important for the economics of egg production, largely through the prevention of egg surpluses—a primary rationale for its implementation. Production controls were intended to prevent the boom/bust cycle of commodities production. Whereas the huge swings so characteristic of commodity sales played havoc with planning and investment [36], supply management provided income stability for farmers and, for consumers, predictability in meal costing and planning [37].

Price fluctuations were also perceived to favor processors and supermarkets, who drove down the prices paid to farmers. Indeed, many farmers believed that they were being exploited by several ruthless buyers who were only interested in making money [38]. In July 1971, for example, a dozen eggs cost 17 cents retail in Toronto, while the cost of production was about 31 cents. Prices were, in the words of a Canadian Egg Producers Council document provided to the minister of agriculture, "disastrously low . . . extending from 1970, through 1971 and the first half of 1972" [39].

As the document went on to note, "Not only this but the public interest is badly served by the economic waste and inefficiency that is an inevitable consequence of severe cyclical instability, and by the instability of consumer prices—sometimes extremely (and to the producer disastrously) low, but at others unnecessarily high as production inevitably falls to inadequate levels under the pressure of persistent losses." With the passage of Bill C-176, the *Farm Products Marketing Agencies Act* on 31 December 1971, the way was clear to establish a national system of egg production, based on provincial organization, that soon stabilized production, farmer incomes, and consumer prices. Significant improvement in farm income for egg farmers subsequently allowed them to invest in technology, as well as to respond to changes in consumer demand, such as for specialty eggs [40].

Although egg farmers' financial situation has been improved by supply management, eggs in Canada remain a cheap source of good quality protein. Figure 1 shows that evolution of the index price for eggs is similar to that of beef, relative to general inflation (CPI). One should note, however, that the real price (versus the index) of eggs is much cheaper than the price of beef, on a gram of protein basis.

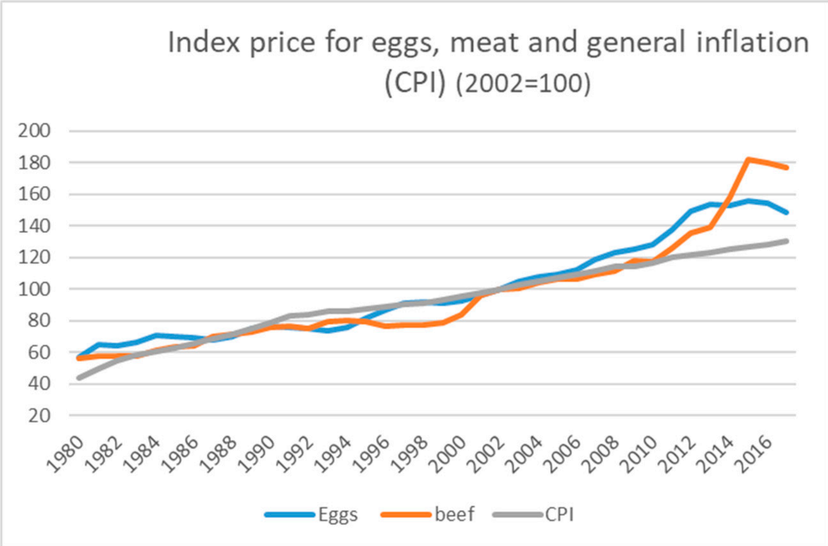

Figure 1. Consumer price index (CPI) for eggs, meat and general inflation in Canada from 1980-2016 (source: Agriculture and Agri-Food Canada [41]).

Shifting Consumer Preferences

The third major variable impacting the economics of egg production has been shifting consumer preferences. For instance, in 1980, Canadians were consuming roughly 22 dozen eggs a year. However, due to cholesterol concerns in the 80s and 90s, per capita consumption reached a low of 14.5 dozen in 1995, as illustrated in Figure 2. New research and a better comprehension of the various types of fats has rehabilitated egg consumption, which has been steadily increasing to the current annual rate of more than 20 dozen eggs per capita. Thus, Canadian egg farmers have seen steady market growth for over ten years, after a decade of significant cuts in production quota in the 80s.

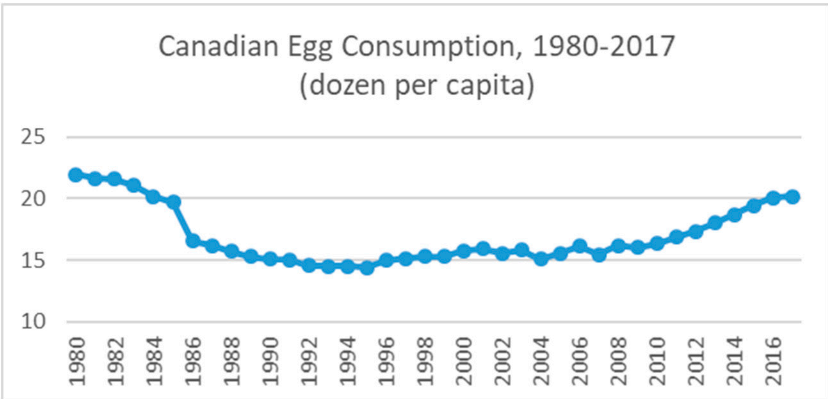

Figure 2. Canadian egg consumption (dozen per capita), 1980-2017 (source: Agriculture and Agri-Food Canada [42]).

Another important change in consumer demand in the 2000's is seen in the larger share of the specialty eggs market, which was roughly 12% in Canada in 2017. Specialty eggs are a value-added product, with differentiation based on either egg composition (omega-3, vitamin D eggs), the perceived quality (brown eggs), or the conditions under which eggs are produced (organic, free-run, and free-range eggs), as illustrated in Figure 3.

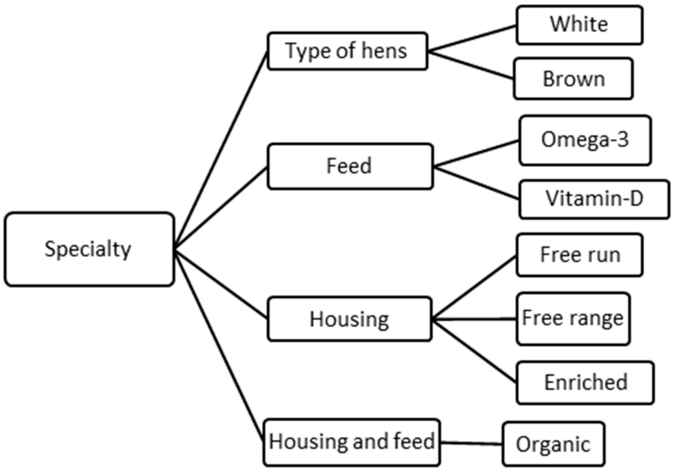

Figure 3. Specialty eggs in the Canadian market, by attribute.

The emergence of the specialty eggs market reflects the fact that buying food has evolved from a purely survival focus to include more nuanced nutritional as well as social preferences and environmental considerations. Animal welfare is an important issue that has been partially addressed through the offering of specialty eggs with specific animal welfare attributes (Figure 3 under housing). Those eggs command a higher retail price to reflect higher cost of production [43]. However, a disconnect between consumer willingness-to-pay and the desire for animal welfare [44] is likely to result when internalization of animal welfare costs is imposed on producers [45].

3.1.4. Animal Welfare

Public Concern for the Welfare of Laying Hens

Concurrent with the adoption of battery cages came growing public debate regarding the welfare of laying hens. Newspaper articles as early as 1953 advanced the same arguments that are still articulated today to either criticize or justify the use of cages. Key criticisms include lack of space, the inability of hens to perform natural behaviors, and that "the system makes the hen 'a mere egg laying machine'" [46]. In defense of cages, arguments are that they decrease disease and facilitate the provision of clean food and water.

Terms such as laying hen "plants" [10], "factories" or "egg machines" [47] were initially used to describe production efficiencies and were lauded because of the amount of control given to egg farmers. In the post-war period, however, such terms were given a negative connotation, and emotive terminology, for example "concentration camp," was increasingly used [48]. The book "Animal Machines" [48], and a subsequent UK government report addressing the welfare of farm animals [14], criticized animal production systems that severely restrict animal movement and behavior. The Brambell Report also clarified that a high production rate cannot alone be used as an indicator of good animal welfare. Nonetheless, by 1970, most hens in Canada (and elsewhere in the developed world) were kept in battery cages [49].

Beginning in 1976, regulations for animal housing systems in Europe were gradually established, beginning with the Council of Europe Convention on the Protection of Animals Kept for Farming Purposes [49]. Over the next few decades, a few individual European countries enacted minimum space allowances (or outright bans) for hens in cages, and a 1986 EU Directive set a minimum size for cages. This culminated in the EU Council Directive 99/74 for laying hens, which prohibited the use of non-enriched cage systems in all EU countries as of January 2012 [50]. According to the Directive, hens in cages must have a minimum of 750 cm^2 per hen and hens in non-cage systems must be stocked no greater than nine hens per m^2. All hens, regardless of housing system, must have a nest, perches, and litter to allow pecking and scratching [50]. In 2016, 55.6% of hens in the EU were housed in enriched cages with the remainder in free-run, free-range, and organic non-cage systems.

In Canada, the process for setting animal welfare standards for farm animals, coordinated by the Canadian Federation for Humane Societies (CFHS), was initiated in 1980 [51]. This process aimed to develop voluntary codes of practices for all livestock species. The first Code of Practice for Care and Handling of Chickens was published in 1983, followed by the Code of Practice for the Care and Handling of Pullets and Laying hens in 2003. These codes laid out recommendations for space allowances and other aspects of animal care, primarily for hens housed in battery cages [51]. In 2005, the National Farm Animal Care Council was established and developed a new and more rigorous process for developing science-informed codes. Code committees currently include multi-stakeholder representation from farmers, government agencies, scientists, CFHS, and national food retailer, restaurant, and food service associations. The process for code development includes establishment of a scientific committee that drafts a scientific report and review of the literature on key welfare issues, as well as regular re-evaluation of each code in response to developments in scientific and production knowledge [51].

In 2012, Egg Farmers of Canada (EFC) initiated a review of the 2003 Code under the guidance of the National Farm Animal Care Council. The new Code of Practice for laying hens was released in early 2017. The code requires all hens to be provided nests, perches, scratch mats or foraging material by 2036, similar to the EU Directive. While allowing for continued adoption of enriched cages, the code also sets more detailed standards for non-cage systems than are in place in the EU. Although the codes are not legislated, "when included as part of an assessment program, those who fail to implement requirements may be compelled by industry associations to undertake corrective measures or risk a loss of market options. Requirements also may be enforceable under federal and provincial regulation" [52].

Food Retailers as Drivers of Change

In Canada (and North America more broadly), changes to hen housing based on animal welfare concerns are coming much later compared to Europe and have been primarily market or producer driven (in response to pressure from customers and animal protection groups) rather than regulatory. In 2000, the United Egg Producers (a US trade organization) developed animal husbandry guidelines and an auditing program that set a minimum space allowance for laying hens in conventional battery cages [53]. That same year, McDonald's set a higher minimum space requirement for hens in their egg supply chain in the USA and Canada [54], followed soon after by Burger King and Wendy's. Over the next decade, several US states passed laws that essentially banned conventional cages [53]. However, a federal bill (The Egg Products Inspection Act Amendment "The Egg Bill)" introduced to US Congress in 2012 and 2013 that aimed to eliminate conventional battery cages but still allow for the adoption of enriched cages subsequently failed [55]. Corporate campaigns soon followed to obtain pledges from major food retailers, food service industries, and food manufacturers to purchase eggs solely from hens kept in cage-free systems.

In 2015, the first few North American restaurants, grocers and manufacturers made pledges to purchase eggs only from non-cage systems. In February 2016, EFC announced that no new conventional cage systems were to be installed after July 2016, but that both enriched cages and non-cage systems would be allowed. Shortly thereafter, the Retail Council of Canada, which comprises most large grocery chains in Canada, committed to sourcing only cage-free eggs by the end of 2025 [53]. By the end of 2016, an unprecedented number of North American corporations made commitments to cage-free housing which will require new or retrofitted barns for over 200 million hens in the United States and Canada by 2026 [55].

3.2. Canadian Egg Industry Prospective

3.2.1. Current Challenges and Opportunities for Improved Technology, Management, and Resource Efficiency

Leveraging continued efficiency gains and emissions reductions in the egg industry is important from the perspective of resource and environmental sustainability and may be supported by four separate but complementary foci. However, any recommended management or technology initiatives need necessarily be considered taking into account potential trade-offs with respect to other aspects of sustainability—for example, costs, animal welfare impacts, and acceptability to consumers.

Sustainability Management Best Practices

The first necessary focal area involves identification and dissemination of environmental sustainability best management practices in the context of current production norms, specific to housing system type. The 2012 benchmark LCA of the Canadian egg industry [21] demonstrated considerable variability in efficiencies among egg farms, with highest variability among producers using non-cage systems. For example, non-trivial differences in feed conversion efficiencies, rate of lay, and mortality rates are observed between industry leaders and laggers. Scenarios to assess the life cycle resource use and emissions mitigation potential of achieving best reported performance for feed conversion efficiency and rate of lay, as well as sourcing low-impact feeds suggest that further reducing the resource and emissions intensity of Canadian egg products by over 50% may be possible [21]. Concerted efforts to identify the factors that enable some farms to outperform others—whether related to management practices, in-place technologies, or other variables (for example, breed of hen), and programs to mainstream these factors industry-wide may enable substantial improvements in industry-average performance. Promotion and achievement of best practices would likely improve the profitability of egg production for individual farmers—in particular, through reducing use of costly feed and energy inputs. It is unclear, however, what positive or negative animal welfare impacts may arise, hence any recommended strategies must be carefully assessed on this basis.

Sustainable Feed Sourcing and Formulation

The second priority focal area is feed composition. The largest share of supply chain resource use and emissions associated with contemporary egg production is attributable to the feeds supplied to pullets and layers [18,21]. Data collected for the 2012 national benchmark LCA study indicated considerable diversity in the range and geographical origin of feed inputs from agricultural, livestock, fisheries, and other production systems [21]. Each feed input that may potentially be sourced for use in poultry feeds is also characterized by a distinctive life cycle resource use and emissions profile, with considerable variability between specific feed materials. Each material is similarly distinct in terms of its nutritional value for poultry, as well as its cost. Feed formulation is currently informed primarily by nutrition and cost considerations. However, “least environmental cost” feed input sourcing is the most critical lever for supply chain environmental sustainability management for egg production. Development of a regionally resolved feed formulation decision support tool that will integrate nutritional, cost, and environmental impact data for major feed input supply chains for the Canadian poultry industry is therefore desirable. Integration of nutritional and cost criteria with environmental impact data is essential, since feed input sourcing recommendations based on environmental criteria alone may result in feeds that are uneconomical or that result in poor feed conversion efficiency (hence negating any gains associated with lower environmental cost feed inputs).

Nitrogen Use Efficiency

Nitrogen use efficiency (included, but not limited to, manure management) is the third priority focal area for environmental sustainability management in this industry [21,56,57]. Nitrogen use efficiency and loss is important in terms of the net energy, nitrogen, and carbon footprint balance of egg production, and has important implications for air quality, human and animal health [58]. For farms producing their own feeds and cycling manure nitrogen on-farm, minimizing N loss is also economically important. Several variables are influential in nitrogen use efficiency and cycling, such as feed composition, feed conversion efficiency, moisture content of hen excreta, and manure management strategies [57]. The latter includes collection and handling technologies, residency time in storage, storage cover, and land application and incorporation methods. Manure belt systems and manure drying have been proposed as one strategy to reduce losses of nitrogen as ammonia from layer hen manure, as well as to improve air quality [59]. Implementation of any such technology should be carefully assessed with respect to the estimated potential systems-level (i.e., life cycle) benefits and trade-offs, including costs. However, interventions that improve air quality will generally also improve hen welfare as well as worker health.

Sustainable Intensification Technologies

The fourth priority focal area for improving the environmental performance of egg production is the identification and implementation of sustainable intensification technologies at farm level. Some promising sustainable intensification technologies for the egg industry include, for example, those related to waste valorization, lighting, use of renewable energy sources, and energy-efficient housing. Each of these will have cost implications, hence consideration of payback time is important. Therefore, too, is attention to potential hen welfare impacts.

From a "life cycle" perspective, waste valorization represents a significant opportunity for improving both resource/environmental efficiencies and profitability in the egg industry. While prior research has underscored the potential limitations and benefits of a subset of relevant waste valorization opportunities (for example, biogas production from poultry manure) [60–64], current knowledge regarding the distribution and fate of key waste streams along Canadian egg supply chains, as well as the comparative efficacy of existing waste valorization technologies is underdeveloped. Moreover, further research and technology development for novel waste valorization strategies is needed in support of increased diversion of under-used waste streams including egg shells, mortalities, and end-of-lay hens. With respect to the latter, the depopulation strategies for hens at end of lay, as well as potential hen transport requirements if a larger fraction of spent hens are to be processed for human consumption, will be particularly important from an animal welfare perspective.

Direct energy inputs to layer facilities for lighting, heating, ventilation, and other processes make a non-trivial contribution to life cycle resource use and emissions for egg production and are also an important cost of production consideration [18,21]. Similar energy inputs are also required upstream along egg supply chains for breeder facilities, hatcheries, and pullet facilities. Integration of renewable energy systems both for layer facilities and along egg supply chains may therefore provide significant opportunities for improving the life cycle environmental sustainability performance of the Canadian egg industry. A variety of renewable energy technologies are currently being employed at a subset of egg production facilities across the country. To date, however, there has been no systematic accounting of the distribution, scale, feasibility, mitigation potential and scalability of these technologies for egg production supply chains. With respect to the latter considerations, any such accounting must necessarily consider geographical and climatic factors including the spatial and temporal distribution of solar and wind resources to advance regionally appropriate, renewable energy technology deployment recommendations. Economic costs and payback time need also be considered.

Another area for green technology development and deployment in the egg industry is with respect to hen housing and other building infrastructure. As much as 30% of greenhouse gas (GHG) emissions are attributable to the building sector, largely due to energy use over the lifespan of buildings (UNEP 2009). Net zero energy building technologies aim to create buildings that produce at least as much renewable energy on site as they consume on an annual basis. Such technologies hence have the potential to substantially mitigate anthropogenic GHG emissions [65]. Little work has been advanced to date to evaluate the feasibility and mitigation potential of net zero energy building technologies in the intensive animal agriculture sector (also a key GHG emitter), where housing is typically employed for confined poultry, as well as for pork and dairy production. Such production facilities require energy inputs for lighting, climate control, ventilation, feed delivery, egg collection, manure management, and sanitation activities. Direct, farm-level energy use for egg production may account for as much as 25% of cradle-to-farm gate life cycle energy use and GHG emissions [18,21]—depending on farm location, on-farm efficiencies, and energy sources. Changes to ventilation systems may, however, have negative impacts on air quality, in turn impacting both worker and hen welfare, and short-term technology costs must be weighed against long-term returns resulting from energy savings.

Lighting systems for livestock production, in particular for poultry, are influential for animal health and productivity [66,67]. Diverse lighting systems have been used in the poultry industry. Most recently, light emitting diode (LED) lighting systems have been developed for poultry housing. These systems are primarily marketed based on their energy efficiency compared to competing lighting systems, which can effect significant cost savings for producers. However, several researchers have reported differences in egg weight, shell strength, rate of lay, bird behavior and feed conversion efficiency under different single and combined monochromatic LED light regimes [68–70]. Carefully selected LED lighting regimes may therefore have important implications for environmental sustainability performance which go far beyond direct, farm-level energy savings. This is particularly true with respect to changes in feed use efficiency, since feed inputs are the largest contributor to both costs and to supply chain resource use and emissions for egg production [18,21], as well as rate of lay and mortality rates—both of which influence feed use efficiency. Optimizing LED lighting systems for sustainability objectives therefore presents an important research area that must necessarily bridge resource/environmental, economic, and animal welfare considerations.

The current environmental performance profile of the industry largely reflects the production of eggs by hens in conventional cages. As previously described, slightly superior efficiencies are currently achieved in cage and enriched cage facilities, reflecting optimization of both management strategies and genetics for cage-based production in the industry over time. Efficiencies are slightly lower, and more variable between farms for non-cage systems (for example, with respect to mortality rates) [20]. As the industry transitions away from conventional cage-based production, both farm management and genetics optimization efforts will be required to close the currently modest efficiency gap between production in conventional cages and alternative housing systems. This will be similarly important to maintaining the profitability of egg production. It should be noted, however, that selective breeding for increased rate of lay looking forward may result in unacceptable welfare trade-offs as a result of further compromising the skeletal integrity of hens.

3.2.2. Current Challenges and Opportunities with Respect to Regulatory Conditions

Stakeholders Support for Supply Management

If Canadian egg farmers were not to show strong support for supply management, it would likely be dismantled in a relatively short period of time—in particular, given persistent pressure from international trading partners such as the United States. The former Canadian Wheat Board is a good example of the potential consequences of non-unanimous support among farmers—the institution lost its ability to be the sole purveyor of Western Canadian wheat and barley. Although egg farmers have and continue to demonstrate strong support for the system, how growth in consumption is allocated between Canadian regions has caused tensions. For instance, some regions have argued in the past that they should get greater quota allocation based on their lower cost of production. However, others argue that since those regions already produce more than they consume, their cost advantage is cancelled by the cost of transporting eggs long distance. Those tensions have been solved through negotiations and are currently low.

While challenges exist, supply management continues to find support among Canadians because they recognize that the system allows farmers to receive adequate compensation for their products, while also providing consumers with a fair price, and encourages a strong and stable domestic supply. In addition, unlike the United States and the European Union, which subsidize their producers heavily and have not been able to control periods of intense overproduction (especially in the dairy sector, which has led to needless producer suffering and wasted production as well as harmful effects for the environment) Canada only produces what is required to meet demand [71–73]. Similar to the dairy industry, the egg industry also suffers when farmers cannot cover their cost of production. In 2013, for example, French farmers destroyed hundreds of thousands of eggs to protest overproduction and the subsequent drop in prices [74]. Canada's system of supply management is not only more responsible, it is also a more sustainable model because it does not lead to resource wastage and pollution associated with overproduction. It also fairly compensates workers, who are then able to support their rural economies and create more vibrant and sustainable rural communities [75]. Doyon and Bergeron [76] found that investments on farms under supply management in Canada are more important (excluding quota investments) than those on non-supply-managed farms, because of the confidence and stability of revenue associated with supply management. Those on-farm investments also generated more jobs for farms under supply management and the economic impact was mostly directed towards rural areas.

Supply Management and Animal Welfare

A supply-managed industry is also better equipped to facilitate an orderly transition to non-conventional cage-based production and may actually support greater innovation given that producers get predictable and fair returns. This, in turn, encourages experimentation without the same degree of risk experienced elsewhere [40]. Beyond product innovation and consumer choice, Canada's supply-managed egg sector may allow for a smoother transition to alternative housing options in egg farming because it will, as it becomes mainstream, compensate farmers for the additional costs of production associated with these more expensive housing alternatives to conventional cages. The turmoil that was caused when the European Union demanded new housing standards without fair farmer compensation should serve as a warning against unsupported and uncompensated mandatory changes in farming practices [74].

3.2.3. Current Challenges and Opportunities with Respect to Social Preferences and Socio-Economic Conditions

Specialty Eggs and Collective Pricing

The first important economic issue currently facing the Canadian egg industry relates to pricing along the value chain. The current cost of production formula that is used by EFC to determine producer egg prices reflects egg production in battery cages. Farmers receive a premium from egg graders to produce specialty eggs and premiums are negotiated on an individual basis, sometimes with written contract or sometimes with a verbal agreement. Moreover, retail prices are sometimes at odds with the cost of production. For example, vitamin D eggs have a premium at retail of roughly 30% while the cost of production is barely affected. On the other hand, graders take important market risks while supplying organic eggs, given that they must guarantee a premium to egg farmers to motivate the capital cost involved, while having little to no guarantees on volume from retailers. Thus, organic eggs might end up in the regular supply chain, at the sole expense of the grader. As the percentage of specialty eggs on the market increases, the private nature of premiums might conflict with the collective principles of supply management. It might also cause problems in gathering sufficient information for determining the cost of production. How price will be transmitted along the value chain should also be a concern. Different options are being explored to address this issue. One possible option is to put at the disposal of farmers contract types for specialty eggs with price information. This would insure more fairness and reduce the asymmetry of information between graders and egg farmers. Another option would be, assuming that the growth of specialty eggs will continue, to have add-on to the cost of production for various types of specialty eggs. For example, organic dairy producers receive the cost of production plus 22 $ per hectoliter in Québec. This add-on can be revised on a regular basis using cost items.

Consumer Confidence

The second issue relates to the confidence of consumers in specialty eggs. This has not been an issue so far in Canada. However, as the variety of specialty eggs increase, how can the consumer be assured that, for example, the vitamin D and Omega-3 free-range brown eggs purchased are really what was paid for? Certification is likely to become important in this regard. As an example, Australia recently experienced a confidence crisis for consumers regarding what free-range implies in the absence of certification. The situation has also created uncertainty for egg farmers leading to a significant underproduction of free-range eggs. The increasing prevalence of sustainable sourcing initiatives in the food sector may also place new burdens on producers with respect to measuring and communicating around sustainability performance, goals, and progress.

The emergence of specialty eggs implies that attached to the private value of an egg is a social attribute that can be associated with a public good dynamic. However, even though specific social attributes are becoming more important for some buyers, preferences are currently heterogeneous among consumers. This raises interesting issues regarding achieving an appropriate balance between private and public choice, and whether and to what extent this is best influenced by market forces and/or regulations. For example, which type of production is best with respect to animal welfare, the environment, or for workers [22]? At what cost? Interdisciplinary research is required to identify the appropriate balance between competing attributes, the extent to which stakeholder incentives are aligned and, in turn, the preferred regulatory or market-based strategy.

Citizens Versus Consumers

The third issue relates to the potential disconnect between the pressure to transition to cage-free production (largely resulting from lobbying of retailers and fast-food chains in Canada by animal welfare organizations) and consumer willingness-to-pay for cage-free eggs. As previously mentioned, cage-free production may actually engender trade-offs with respect to animal welfare, the environment, workers' welfare, and economic efficiency. This nuance may be lost on most consumers, who tend to react adversely to the very idea of cage-based production.

For instance, Doyon et al. [44] found that when presenting consumers with fictive names for housing systems, the three out of twelves names containing the word cage were by far the ones considered as the least likely to promote hen welfare. On the other hand, the researchers also found that when consumers were provided with additional information on the enriched cage system, they showed increased preference for these eggs relative to regular eggs.

Given that cage-free eggs are readily available but represent less than 10% of the table eggs sold in Canada, one must naturally wonder about the impact on consumers and on demand for moving completely to cage-free egg production by 2025. Norwood and Lusk [77] found that consumers were willing to pay, on average, between 53% and 100% more for cage-free eggs over battery cage eggs. These results come with important standard deviation, meaning that some participants are not willing to pay more for cage-free eggs, and in some instances, some would pay less.

California is an interesting example. Cage-free eggs represented less than 10% of consumption in 2008 when a referendum (Proposition 2) to ban battery cages was voted on by 64% of eligible voters. Malone and Lusk [45] estimate that California's law banning battery cage increased the retail cost differential between California and the national egg price average by 51%, while that differential was historically around 15%. The cost for consumer surplus is estimated by the authors to be between $400 and $850 million.

3.2.4. Current Challenges and Opportunities for Improving Hen Welfare

As previously described, the Canadian egg industry is in the early stages of transitioning away from housing laying hens in conventional cages. However, to inform the selection of alternative housing systems, it is critical to understand the animal welfare trade-offs associated with different housing systems, as well as how these might impact on resource/environmental and socio-economic sustainability considerations. Rational decision-making must ultimately reflect consideration and accommodation across these domains.

Ethical Concerns and Scientific Measures

Concerns about animal welfare can be divided into three areas, which form the bases for measures used in science-based evaluations [78]. These comprise measures of biological function that include health, mortality, physical condition and production performance and measures of emotional or affective states of animals that include pain, fear, discomfort, reward, and pleasure. Naturalness, a third concept of what constitutes a good life for animals, is less amenable to scientific evaluation. However, it is often defined as the ability to perform natural or species-typical behavior. By quantifying and comparing the innate drive of animals to perform specific behavior patterns we can determine what animals want (find rewarding), lending objective measures of affective states to the concept of naturalness. All three categories of criteria are articulated in most formal definitions of animal welfare, but it is important to recognize that different stakeholders vary in the degree of importance they place on the different measures. Farmers and veterinarians tend to value measures of biological function, animal welfare scientists tend to value measures of subjective states and members of the broader community value naturalness [78]. In the case of housing systems for laying hens, these criteria are often conflicting. Public acceptance can drive farming practices, but public perceptions do not always align with scientific evidence [79].

While most formal definitions of animal welfare include the ability to express "normal" or innate behavior, the scientific consensus is that it is neither practical nor necessary for hens to be able to perform all types of behavior [80]. Empirical research has focused on identifying the candidate behaviors that are most important for hens. Specifically, nesting, perching, foraging, and dustbathing are considered to be behavioral needs or behavioral priorities [80]. Thus, provision of enough space and resources to support these behavior patterns are included in most science-based standards.

Welfare Trade-Offs Related to Different Laying Hen Housing Systems

Several literature reviews and scientific reports have summarized findings from studies comparing the welfare of hens in different housing systems [81–84], including reports comparing various welfare indicators collected on large-scale commercial farms [85–89]. Generally, all these reports indicate significant trade-offs for different aspects of welfare for hens in different housing systems. Some observed differences likely reflect the lesser degree of experience among farmers housing hens in alternative systems, underscoring the desirability of identifying and disseminating best management practices with respect to improved welfare outcomes in these systems.

Conventional cages generally result in good health, hygiene, and low mortality, but the lack of nests, scratch areas and perches coupled with lack of space impose a high degree of behavioral restriction for hens. Even basic activities such as locomotion, stretching and wing-flapping are significantly constrained in conventional cages [84]. It is also well established that the lack of load bearing exercise reduces bone strength of hens.

Hens housed in cage-free systems with nests, perches, and litter (or free-range with access to the outdoors) have substantial opportunities to perform a greater range of behaviors, but also incur a significantly greater risk of mortality, injury, and poor health [83,84]. Feather pecking and cannibalism are major causes of feather loss, poor welfare, and higher mortality, which are mitigated by the highly controversial practice of beak trimming in many management systems. A recent analysis of data from 3500 commercial flocks in the EU indicated that mortality rates were significantly higher and considerably more variable in non-cage and especially in free-range systems compared to cage systems [89]. In that study, genetic strain of the hen was a significant factor and risks were considerably greater when hens were not beak trimmed. Smothering, another cause of mortality for hens housed in large group sizes, occurs when birds mass together and pile on top of one another [90]. Piling can occur when birds become frightened and panic or when they crowd together at different times of day to access different resources, for example in communal nests [91] or to dust bathe on litter [92].

Enriched (furnished) cages generally result in production, health, and mortality rates that are comparable to or better than conventional cages [21,85,86,88]. With more space and added furnishings, hens in enriched cages have greater opportunities to express motivated behavior than in conventional cages. Nests in cages are generally well-used and result in hens showing more "settled" (satisfied) nesting behavior [93]. Perching behavior and/or the increased space and locomotion in enriched cages results in stronger bones than in conventional cages [94,95]. However, the scratch mats provided in enriched cages do not fully support foraging or dust bathing behavior [85], and this poses one of the biggest challenges for full welfare benefits of enriched cages.

Trade-Offs among Welfare, Economics, Environmental Impact and Human Health

Providing hens with greater space allowances increases both building capital costs and operating costs per dozen eggs produced [96]. Labor costs can be substantially higher, particularly in non-cage systems. Housing hens in alternative systems can also result in reduced efficiencies from lost product (damaged eggs in enriched systems and eggs laid outside of the nest in non-cage systems), higher mortality and reduced feed efficiencies due to energy expenditure related to increased exercise. Poor feather condition from feather pecking increases bird heat loss which must be compensated by higher feed intake or supplemental heating of barns [97]. All these factors can increase cost of production and will also undermine resource efficiency/environmental objectives.

Air quality is also significantly affected by provision of foraging substrate. Higher levels of aerial dust and microbes compromise hen health and worker health and safety [98,99]. Emissions of ammonia and particulate matter from barns may also increase risks to public health [100]. Developing means for mitigating air quality issues inherent in non-cage systems is an important area for future research.

Genetic selection for increased egg production has also come at the expense of hen health and welfare. The demand for calcium to support shell formation of the large numbers of eggs that modern layers produce results in poor skeletal health manifested as osteoporosis, fragile bones, and subsequent risks for bone breakage [101]. Despite advances in nutrition to support the calcium and phosphorus requirements of hens, a major portion of the calcium required for egg formation comes from the hen's skeleton which progressively weakens over her lifetime. Osteoporosis is exacerbated by restricted housing and the lack of load bearing exercise. However, although opportunities for exercise in enriched and non-cage housing do result in stronger bones, the skeleton of the modern laying is still relatively weak and increased freedom of movement also increases risks for bone fractures from collisions with furnishings. The keel bone (sternum) is particularly susceptible to fractures and prevalence rates have been reported to range from 10 to 30% in conventional cages, 20 to 60% in enriched cages and greater than 85% in non-cage systems [102]. Genetic selection for improved bone strength may provide a solution, although there appears to be an inverse relationship between production traits (egg number and shell quality) and bone strength.

Huge gains can be made for not only improving hen welfare and but also reducing loss in resource efficiencies by refining system design (technology) and optimizing nutrition, genetics, and management of alternative housing systems. The large degree of variability found in the literature (e.g., [89]) highlights the potential for non-cage systems to perform well. Research aimed at improving system design, with regards to hens being able to navigate the system without injury, and to readily use nests is essential. Performance testing combined with genome-wide DNA marker analyses are proving valuable tools for genetic selection that balances production and feed efficiency, skeletal integrity and the behavioral traits (i.e., use of nests and reductions in feather pecking) necessary for improving efficiencies and hen welfare in non-cage systems [103].

4. Synthesis and Conclusions

Based on our analysis of historical trends and current regulatory and socio-economic conditions, we identify several major challenges for or threats to the sustainability of the egg industry, along with a variety of alternative strategies to resolve them. We further posit that resolution of these challenges must be supported not only by interdisciplinary research but also by knowledge transfer to enable reconciliation of potential trade-offs between alternative courses of action.

These identified challenges largely relate to shifting consumer and other stakeholder preferences and expectations, which create pressures on egg producers to adapt their practices to produce eggs in particular ways and with particular attributes [104]. It should be underscored that such preferences may not be sufficiently knowledge-based, nor sufficiently informed of potential trade-offs. Foremost among these is the current pressure to transition from cage to non-cage housing systems, based on animal welfare considerations. In a recent survey, US consumers were asked to indicate whether moving from conventional to cage-free housing would have none, positive or negative impact on hen health, hen behavior, natural resource use efficiency, worker health and safety, food safety and egg quality [79]. Well over 50% and upwards of 70% of respondents indicated positive impacts for all the various attributes, respectively, although scientific evidence indicates either no or negative impacts for all of them.

There are distinctive trade-offs with respect to welfare outcomes, with different housing systems variously providing for superior or poorer outcomes, depending on the specific measure considered. At the same time, alternative housing systems imply different resource efficiency/environmental sustainability outcomes. Performance in non-cage systems is currently more variable and somewhat poorer than conventional and enriched colony cage-based production, hence research and development of technology and management strategies to optimize production in alternative housing systems is highly recommended. Perhaps more important is the transfer of research and practical knowledge to farmers transitioning to these new housing and management systems. It is well established that the knowledge, skills, attitudes, and beliefs of the stock people caring for livestock and poultry have profound effects on welfare and production performance of the animals in their care. Training can be used to increase knowledge, change attitudes, and improve performance. While many farmers move from managing simpler to more complex housing systems, a steep learning curve can be expected, with performance and efficiencies continuously improving as they did for conventional cages. Since many farmers may view the transition as being forced upon them, their attitudes about the systems may be negative and may also need to evolve with experience [105,106].

One strategy that has been tested in the UK is the development of comprehensive animal welfare assessments and benchmarking tools combined with feedback and educational materials for farmers. This top-down approach can be delivered within quality assurance schemes or as industry-wide initiatives and involve scientists, veterinarians, government extension specialists and various industry stakeholders. One example is Assurewel [107], a 6-year collaboration among the University of Bristol, RSPCA, and the Soil Association of the UK. As part of this, the FeatherWel project [108] specifically aimed to reduce injurious pecking on UK farms by providing an assessment tool that farmers could use to measure and track feather condition in their flocks together with advice on practical strategies to prevent the problem. Mullan et al. [109] reported that 59% of the 662 UK farmers involved in the project made management changes to improve welfare during the first year of the program, and there was a significant reduction in feather loss from year 1 to year 2. Another approach tested more broadly in the EU as part of the Horizon 2020 EU Research and Innovation program was the Hennovation project [110]. Hennovation also targeted solutions to feather pecking but by developing and disseminating technical innovations using "practice-driven innovation networks" comprising farmers, scientists, veterinarians and farm advisors. Management practices were developed and tested on farms by farmers and the results shared through on-line training, web-based tools and facilitated sessions [111].

In Canada, improvements in both animal welfare and resource use efficiency could be realized by combining efforts for development, knowledge transfer and implementation of best practices for both aspects of sustainability together. The infrastructure and resources of the supply management system could support the framework for such an approach. Currently, a feather scoring system for Canadian egg producers has been distributed through the provincial boards as part of an epidemiological study and benchmarking exercise [112].

The transition to alternative housing systems also presents challenges for Canadian producers from an economic stand-point, which can be partially remedied through the development of cost of production formulas that ensure a fair return to producers within the supply-managed industry. Such a development will serve to reduce risk for both producers and graders, and provide more predictable prices for consumers.

The continued rise of sustainable sourcing as a management consideration for agri-food supply chains, along with generally increasing expectations for accountability and transparency with respect to sustainability management, reporting, and demonstration of improvement, will also likely challenge the egg industry to respond accordingly. From a logistical perspective, it is imperative that farmers be enabled to participate in related initiatives in a non-burdensome manner. This will require development of rigorous sustainability measurement and reporting tools that are both transparent and easy to use. It must be anticipated that multi-criteria sustainability reporting tools that incorporate a combination of environmental, animal welfare, economic, and other indicators will likely highlight the inevitability of trade-offs associated with different management or technology alternatives for the industry. With respect to improvement opportunities, a variety of technology and management options are available that may improve environmental sustainability outcomes, but each must be simultaneously evaluated with respect to potential negative impacts on animal welfare and cost of production.

Another persistent threat to industry sustainability is pressure to dismantle the supply management system that currently governs egg production in Canada. This would likely precipitate consolidation and vertical integration in the industry, with many/most of the currently 1000+ farms disappearing. The opening up of the Canadian market to US egg imports would also likely considerably reduce domestic production.

Loss of supply management would also potentially undermine the ability to orchestrate a smooth transition to alternative housing systems in the Canadian egg industry. There is need for further research to understand potential welfare and sustainability trade-offs of production in supply-managed versus non-supply-managed contexts. Although conventional economic logic would predict higher efficiencies under free market conditions, data suggest similar feed conversion efficiency between US and Canadian flocks but higher mortality rates for US layers (6.7% mortality rate reported for the US for 2010 for conventional cage production, compared to 3.2% for Canada in 2012). However, the concentration of egg production in the US in grain-producing areas creates higher transport-related efficiencies compared to the nationally distributed production (which often necessitates more transportation of feed inputs) characteristic of the Canadian supply-managed industry. At the same time, distributed production reduces the need for more higher impact, refrigerated transport and, potentially, food waste.

There are also a variety of existential threats to the industry that merit consideration. Managing for the future is clearly fraught with uncertainties. Nonetheless, a subset of additional challenges that the egg industry will almost certainly grapple with can be identified with some measure of confidence. First, the growing awareness of the centrality of the agri-food system (in particular, the livestock sector) to many of our most pressing sustainability concerns points towards increased competition for legitimacy in the food space looking forward. Indeed, this is underscored by the rapid emergence and proliferation of sustainable sourcing schemes for agri-food products, largely driven by food processors, retailers, and fast-food chains. Grace of the nutritional value of eggs (currently the reference product for nutritional quality in broadly accepted measures such as Protein Digestibility Corrected Amino Acid Scores (PDCAAS) and Dietary Indispensable Amino Acid Scores (DIAAS)), as well as the relative efficiency of producing poultry compared to swine and ruminants, the egg industry is relatively advantaged at the outset. Nonetheless, it would be both prudent and strategic for the industry to be proactive with respect to positioning in this regard—in particular with respect to actively communicating around the coupled nutritional and sustainability benefits of eggs. This may also prove important considering growing markets for alternatives to animal products, including egg replacement products.

Second, projected growth in food production globally will only serve to exacerbate competition for land, energy, water, and other resources, as well as further disrupt global biogeochemical cycles and systems including the nitrogen and phosphorus cycles and the global climate system. The egg industry will likely be impacted by these changes at multiple levels. This includes emerging regulatory responses which may require operational and technological changes within the industry, potential cost increases for inputs such as feed and energy, greater uncertainty associated with yields along feed input supply chains and increased extreme weather events (and associated heating and ventilation challenges). These phenomena will create sustainability risks and opportunities. It is incumbent on the industry, at the leadership level, to remain attentive and to respond nimbly and effectively to such risks and opportunities as they emerge.

A third wild card for the egg industry is the extent to which disruptive technologies may alter both perceptions and norms regarding the production and consumption of food. For example, emerging technologies such as 3D printing of food will enable precision nutrient delivery, tailored to individual dietary needs and preferences, as well as incorporation on non-traditional protein alternatives such as insect protein. Against this backdrop, positioning of traditional foods such as eggs in the food space based on nutritional attributes may enjoy diminishing returns.

More directly relevant to the egg industry will be growth of the in-vitro biomass and animal product replacements sectors. Since the widely publicized creation of the first lab-grown beef burger in 2013, research, investment, and commercial development in this emerging disruptor sector has burgeoned. Cultured animal products may redefine how we think about, produce, and consume animal protein in the future. While clearly directly competitive with beef, pork, and chicken in the near to medium term, comparable advances in producing cultured egg and dairy substitutes are also likely over time. More directly relevant to the egg industry are vegan and vegetarian egg replacement products, which may have lower resource and environmental impacts as well as eliminate animal welfare-related concerns.

In short, the egg industry faces multiple risks and opportunities from a sustainability perspective in the coming years. Some are immediate and tangible, others less certain with respect to probability, magnitude, and consequence. Supporting the egg industry in successfully navigating this future will require effective research on multiple fronts and, in many cases, interdisciplinary research and knowledge mobilization that draws on the perspectives, tools, and competencies of multiple research areas to recognize and navigate inevitable trade-offs.

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