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The Circular Economy Potential of Spent Hens' Co-Products and By-Products in Italy by Material Flow Analysis

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Abstract: Eggs represent one of the most consumed animal products worldwide. In Europe, over 366 million laying hens and 6.1 Mt of derived eggs have been estimated in 2020, and Italy represents the fourth largest producer (41 million hens and 0.79 Mt of eggs). Egg production has been identified as relatively environmental-friendly, but several environmental concerns have been recently raised considering the inefficient spent hens' management. Spent hens are generally euthanized and composted or incinerated, producing greenhouse gases while at the same time significant nutrients are lost. First, the research reviews the egg supply chain characteristics and the alternative spent hens' valorization pathways. Then, using the material flow analysis, the research quantifies and qualifies the consistencies of laying hens and protein content included in spent hens across Italy, providing a comprehensive assessment of the national scenario under an environmental and circular perspective. Furthermore, the research develops an inventory of the spent hens' co-products and by-products in Italy, focusing on the flows of proteins for further environmental studies. The research has highlighted that over 13,948 t of proteins could be extracted, distinguishing between those embedded within offal, feathers and blood. In addition, spent hens can be used for human consumption, as well as for material or energy recovery through anaerobic digestion or microbial fermentation. Results are addressed to farmers, who are required to boost their environmental performances, and public authorities, who must implement sustainable strategies to collect spent hens.

Keywords: circular economy; egg supply chain; environmental sustainability; material flow analysis; poultry industry; spent hens

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1. Introduction

Eggs represent encapsulated sources of macro and micronutrients, which meet human food requirements [1,2], and are among the most consumed animal products worldwide [3]. Eggs provide essential lipids, proteins, vitamins, mineral and trace elements, and offer roughly 140 kcal/100 g [4]. In the European Union, over 366 million laying hens and 6.1 Mt of eggs have been estimated in 2020, and Italy represents the fourth largest producer soon after France (0.97 kt), Germany (0.89 Mt) and Spain (0.86 Mt). The Italian egg industry produces over 12.6 billion eggs, for an amount of 0.80 Mt of fresh product and approximately 1.4 billion euro each year. Such amounts are produced by 41 million laying hens [5]. In light of the Directive 1999/74/EC [6], since 2012 it is not possible anymore to produce eggs by keeping hens in battery cages. Several alternative housing systems have been introduced in hens' husbandry, distinguishing between cage systems and non-cage systems. In Italy, it has been estimated that 49% of farms adopt floor-management systems, 42% rely on enriched-cages, 5% adopt an organic free range and 4% a conventional open-run [5], with potential significant implications on the sustainability of the egg production [7].

Under the environmental perspective, egg production has been identified as relatively environmental-friendly compared with other animal commodities [8,9]. The resource consumption and the environmental burdens vary according to the adopted housing system. The average CO_2eq emissions associated with conventional egg production have been estimated at 2300 kg CO_2eq per t fresh product in Canada, of which approx. 90% are due to feed, manure management and pullets [7,10]. Such an amount is increased to more than 2900 kg CO_2eq per t of fresh product in the case of free-range breeding, whereas the most sustainable breeding is represented by the organic one, whose emissions have been estimated at less than 1500 kg CO_2eq per t [7]. In Spain, similar results have been reported by Albin et al. [11], who have estimated the carbon footprint of intensive eggs production at 3500 kg CO_2eq per t of fresh product. In terms of water consumption, the green water footprint of eggs ranged from 1.91 to 2.11 m^3 per kg, whereas the blue water footprint from 0.58 to 0.64 m^3 per kg and the grey from 0.48 to 0.58 m^3 per kg [12]. However, along with the impacts associated with eggs production, they must also be added the environmental impacts associated with the management and the disposal of spent hens.

The environmental sustainability of the entire egg supply chain is affected, on the one side, by eggs production, and on the other side by spent hens' management, which are disposed at the end of their egg-laying cycle (approx. 1 year). On average, spent hens can be sold as whole birds, cut-up parts and ground meat in the poultry market, but such pathways destined to human food uses have been decreasing in recent years due to economic, cultural or taste reasons [13–15]. Spent hens' meat is a good protein source and is rich of omega-3 fatty acids and low cholesterol [16], but it remains tough and fibrous due to the high collagen content and to the several cross linkages, and such characteristics prevent their meat from being preferred by consumers compared to other poultry meat [17]. Moreover, considering that animals cannot be fed with ingredients obtained from by-products of the same species [18,19], the use of spent hens to obtain feedstuffs has declined [20]. Hence, in light of the market viability principle and assuming that no profitable pathways have yet been identified in the academic literature [21], spent hens are generally euthanized and landfilled or incinerated [15,22], producing greenhouse gases while significant proteins and other nutrients are lost.

Firstly, the present research reviews the egg supply chain characteristics on the global scale and the alternative spent hens' valorization pathways according to a systematic literature review [23]. Secondly, using the material flow analysis [24], the research quantifies and qualifies the consistencies of laying hens and the protein content included in spent hens in Italy, providing a snapshot of the national egg supply chain. In light of the Regulation (EC) 1069/2009 [18]—which highlights the need to boost (food) waste valorization from breeding to by-products transformation, and which considers (food) waste disposal as a "nonrealistic option" due to its related unsustainable environmental costs and risks—the research discusses spent hens' valorization pathways, with specific reference to non-food purposes. Recent studies have highlighted the need to advance research towards the sustainable valorization of livestock waste to recover biopolymers [19] and acquire both economic and environmental savings [25]. However, although several studies have investigated conventional methods for animal waste treatment such as compositing, vermicomposting, biogas production and value-added products [26], few researchers have identified opportunities of innovative and eco-friendly biomaterials production through protein extraction.

Moreover, it is essential to boost measurement tools to estimate the quantities of co-products and by-products towards sustainable valorization pathways. Specifically, the National Recovery and Resilience Plan (NRRP) lists among its targets the need to promote circular economy, ecological transition and sustainable waste management, whereas the Common Agricultural Policy (CAP) asks to mitigate and adapt climate change, including the reduction of greenhouse gases emission, the improvement of carbon sequestration and the promotion of sustainable energy. These targets, as outlined by the most recent technical standards, technical reports and the drafts of international standards, such as the "Measurement of Circularity—Methods and Indicators for Measuring Circular Processes in Organizations" [25], depend on the quantitative and qualitative measurement of waste, co-products and by-products, which at present represents an essential step for conducting research in the circular economy field.

In light of these premises, the research quantifies and qualifies the consistencies of laying hens and protein content included in spent hens across Italy, providing a comprehensive assessment of the national scenario under an environmental and circular perspective. Moreover, it develops an inventory of the spent hens' co-products and by-products in Italy, focusing on the flows of proteins for further environmental studies. The research is addressed to farmers and companies involved in egg production and spent hens' management, which in Italy account for over 2600 farms, of which 1444 are large companies and breed more than 1000 heads per farm. Such companies, which are distributed across Italy from Veneto (25%) to Sicily (7%), need to develop more sustainable practices to treat spent hens. Moreover, the research is addressed to public authorities, which are asked to implement sustainable strategies to collect spent hens and enhance the environmental sustainability towards circular economy and industrial symbiosis.

2. Literature Review

2.1. Search Strategy

In line with Snyder [23], which distinguishes among three different typologies of literature reviews, namely systematic, semi-systematic and integrative, the present section provides systematic results related to the egg supply chain and to the trends of valorization pathways for spent hens worldwide. The purpose of the systematic review is to synthesize and compare evidence, answer to specific research questions and adopt a comprehensive and consistent search strategy [23].

In light of the main purpose of the research, the systematic literature review tries to provide and answer the subsequent research questions: (RQ1) Which are the main characteristics of the egg supply chain under the environmental perspective? and (RQ2) Which are the most diffused valorization pathways for spent hens?

To reply to the above-mentioned research questions, the authors have investigated several keywords' combinations on Scopus database, which is considered as a collector of standardized, reputable and high-quality research, according to a TITLE-ABS-KEY search [27,28]. On the one hand, to investigate the egg supply chain characteristics through suitable (and standardized) environmental accounting methods, the authors have selected the subsequent keywords: "egg supply chain" AND "sustainability" OR "circular economy" OR "life cycle assessment" OR "material flow analysis" OR "footprint". On the other hand, to explore the spent hens' valorization pathways in depth, the authors have selected: "spent hens" AND "sustainability" OR "circular economy" OR "prevention" OR "reuse" OR "recycling" OR "recovery" OR "disposal" OR "incineration". The end-of-life pathways related to spent hens have been selected according to the Waste Framework Directive. Regarding the inclusion criteria, the authors have selected articles published in the timeframe 2012–2022, in peer-reviewed journals and in English.

Peer-reviewed articles emerging from the TITLE-ABS-KEY search have been further catalogued and selected for in-depth review according to the PRISMA guidelines [29], which distinguishes among identification, screening, eligibility, inclusion and interpretation.

2.2. Bibliometric Analysis

At first glance, it appears that no articles correspond to the use of the keyword "circular economy", whereas several have been associated with the word "sustainability" in the egg supply chain (25 contributions). Furthermore, the combination "egg supply chain" and "life cycle assessment", which represents a standardized accounting method for the assessment of the environmental impacts associated with products or processes, has resulted in 15 peer-reviewed articles. In the field of spent hens' research, a total of 16 articles has emerged, highlighting the scarce interest in its research. The highest number of articles has resulted from the combination "spent hens" AND "disposal" (six contributions).

During the identification stage, 67 articles have been collected and catalogued in Microsoft Excel according to authors' names, articles' titles, year of publication, publishing journal, and digital object identifier (DOI). Before screening, 15 contributions have been deleted as duplicates. During the screening stage, articles have been read in depth and an additional 22 contributions have been deleted because they neither deal with the environmental sustainability assessment of the egg supply chain nor explore the different disposal and/or valorization pathways of spent hens. Last, 30 articles have been declared eligible for in-depth review and have been included in the systematic literature review, of which 22 dealt with the egg supply chain characteristics (Section 2.3.1) and eight were related to the spent hens' valorization pathways (Section 2.3.2).

As indicated, most of the contributions have been published in the *Journal of Cleaner Production* (six articles), followed by *Sustainability and Journal of Food Science* (two contribution each), for a total of 22 different publishing journals. In such journals have been published articles dealing with the egg supply chain characteristics, whereas those investigating the spent hens' valorization pathways have been published in *Food Chemistry*, *Journal of Food Science*, or *Journal of the Science of Food and Agriculture*, for instance. In regard to the research timeline, the vast majority or articles have been published in 2022 (five contributions), followed by 2018, 2019 and 2020 (four contributions each). Significant results have been reported regarding the region of the first authors' affiliation, which reveals the main geographical areas interested in the phenomenon under investigation. It emerges that 14 studies out of 30 (46%) have been conducted by Canadian authors and two studies by American researchers, for a total of 16 different geographical areas. In the European Union, Germany, Italy, the Netherlands, Poland and Sweden, research on the egg supply chain has been conducted, but none of them with specific reference to spent hens' valorization pathways.

2.3. Textual Analysis

2.3.1. Egg Supply Chain Characteristics under the Environmental Perspective (RQ1)

Figure 1 illustrates the egg supply chain, as presented by Bux and Amicarelli [30], Pelletier et al. [31,32] and Mitrovic et al. [33]. The egg supply chain starts with breeder flock facilities, which provide eggs to hatcheries, which are then placed into incubators for a total of 21 days. Male chicks are disposed of, whereas female chicks are sent to pullet facilities until the age of 18–19 weeks. Once female pullets are mature, they are transferred to layer facilities, where they lay eggs for approximately 50 weeks. During this time, pullets and laying hens are fed with a diet locally produced and generate an average of 300 eggs per hen [34]. After 70–72 weeks, layer eggs are cycled out of production and are disposed in different manners (Section 2.3.2). Eggs obtained from layer hens are transferred to grading facilities, where they are graded for size and typology, washed, packaged and sent to retail or to other industries for further transformation [10].

As outlined by Pelletier [10] and Ershadi et al. [34], raw materials required to produce feed input are canola oil, corn, DL-methionine, L-Lysine, L-Threonine, limestone, monocalcium phosphate, premix, sodium bicarbonate, salt, soya meal and wheat. In addition to conventional feed, a variety of feed derived from rendered livestock by-products could be used to feed pullets and hens, such as fat and bone meal products from cattle and swine [10,18,19]. In the pullet facilities, inputs required are feed, water and energy, whereas manure represents the largest output. The same inputs are required in the layer facilities, but it should be highlighted that the environmental impacts recorded in such a stage depend on the housing system adopted. In regard to shell egg processing and packaging production, energy and water are required as inputs, as well as additional energy for transportation of finished products (i.e., shell eggs) to retail and distribution.

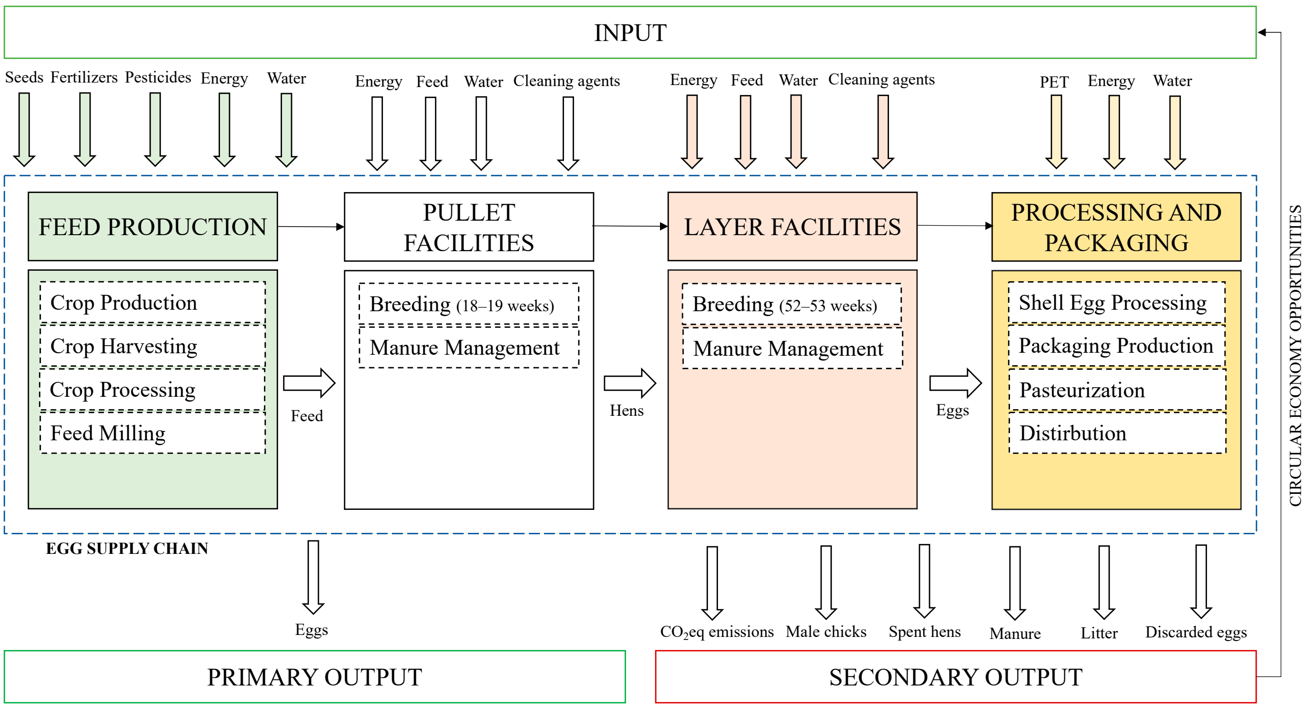

Figure 1. Egg Supply Chain Flow-chart. Source: Personal elaboration by the authors.

In terms of environmental impacts associated with the egg supply chain, it emerges that feed production and supply are the major contributors to climate change, irrespective of the different housing system [35]. Furthermore, manure management represents another environmental hotspot, but several valorization pathways can be applied, such as the energy valorization as feedstock for anaerobic digestion or as fuel for biomass-burning power stations [35].

Among various waste, a key waste is the poultry litter, which can be described as a by-product of the egg production cycle and consists of bedding material, manure, dead skin, feed leftovers, water, feathers and resulting microbiota [36]. In addition, other waste streams can be identified, such as discarded eggs, namely eggs unfit for human consumption, eggshells, male chicks and spent hens. In general, landfilling represents the easiest (and cheapest) option, but other opportunities regard composting, rendering and incineration. In the field of male chicks, it is estimated that each year more than 7 billion male chicks are discarded worldwide [37], whereas approx. 96.4 kg of spent hens per t of eggs have been estimated by Pelletier et al. [38]. Hence, spent hens must be appropriately treated to enhance the sustainability of the entire egg industry.

2.3.2. Spent Hens' Valorization Pathways (RQ2)

Spent hens, defined as "a poultry by-product", have little economic value for processing and mostly end up in landfills [39]. In general, laying hens produce eggs for several years, but for economic reasons the egg industry keeps them for a maximum of 18 months, since after one year the hens' eggs production declines to about 65%, as well as the eggs' quality [15]. Table 1 summarizes the eight studies, which have investigated the different spent hens' disposal and valorization pathways from 2012 to 2022. Furthermore, three additional contributions suggested by experts in the field or found by serendipity have been added as follows: Freeman et al. [40,41], Kersey et al. [13] and Kersey and Waldroup [42].

Table 1. Spent Hens' Valorization Pathways in the Literature.

Authors	Research Item	Valorization Pathway
Kersey et al. [13]	Spent hens	Spent hens processed at commercial renderers using proprietary procedures to obtain meals.
Fan and Wu [15]	Spent hens	Conventional uses of spent hens, such as food, animal feed, pet food and compost, and emerging uses such as biomaterials and functional food ingredients.
Zubair et al. [39]	Proteins	Proteins plasticized and processed into films by compression molding.
Freeman et al. [40,41]	Proteins	Spent hens grinding or mechanically deboning with/without mechanical picking to produce proteinaceous by-product meals.
Kersey and Waldroup [42]	Spent hens	Spent hen proteins as a nutrient source in diets for broiler chickens on the basis of digestible amino acid content
Fan et al. [43]	Proteins	Muscle proteins hydrolysate prepared by food-grade thermoase to investigate antihypertensive effects in rats.
Safder et al. [44,45]	Fats	Fats extracted using supercritical carbon dioxide and converted into epoxides for the development of a bio-plasticizer.
Yu et al. [46]	Proteins	Muscle proteins digested into peptides using commercially available enzymes for anti-inflammatory applications.
Wang et al. [47]	Fats	Omega-3 polyunsatured fatty acids to produce functional foods (chicken surimi).
Jin et al. [48]	Spent hens	Proteins hydrolysates from mehanically deboned chicken meat to produce sausages.
Wang et al. [49]	Proteins	Proteins modified by sodium dodecyl sulfate or urea to develop wood adhesive for dry or wet applications.

Source: Personal elaboration by the authors.

Out of the eight selected contributions, the research conducted by Fan and Wu [15] represents a review article, whereas the other are research articles. In general, and as outlined by Fan and Wu [15], it is possible to distinguish conventional and emerging valorization pathways for spent hens. On the conventional side, Freeman et al. [40,41] and Kersey et al. [13] have investigated the production of proteinaceous by-product meals or rendered meals, respectively. In terms of emerging uses, several authors have explored the opportunities to develop functional food, such as Wang et al. [47], Fan et al. [50] and Yu et al. [46]. Fan et al. [50], for instance, have discussed the opportunities to develop antihypertensive foods, whereas Yu et al. [46] have evaluated possible anti-inflammatory applications. In terms of biomaterials production, Zubair et al. [39] have experimented with the production of films through plasticized proteins, and Safder et al. [44,45] have tested the development of epoxides to bio-plasticizer through fats.

3. Materials and Methods

The first purpose of the research is to identify the number of spent hens in Italy, distinguishing per region. Secondly, an effort will be made to quantify the different components of spent hens' co-products and by-products, which could be obtained from the spent hens' optimization. Furthermore, in light of the protein content of co-products and by-products, the research records their flows in Italy by the material flow analysis and identifies possible valorization pathways according to the current scientific trends. Figure 2 illustrates the stepwise approach and the research strategy, distinguishing among four steps, namely: (i) systematic literature review (Section 2); (ii) material flow analysis (Section 3.1); (iii) quantification of spent hens in Italy, measurement of co-products and by-products and evaluation of protein extraction (Sections 3.2 and 3.3); and (iv) inventory development and interpretation of results (Section 4).

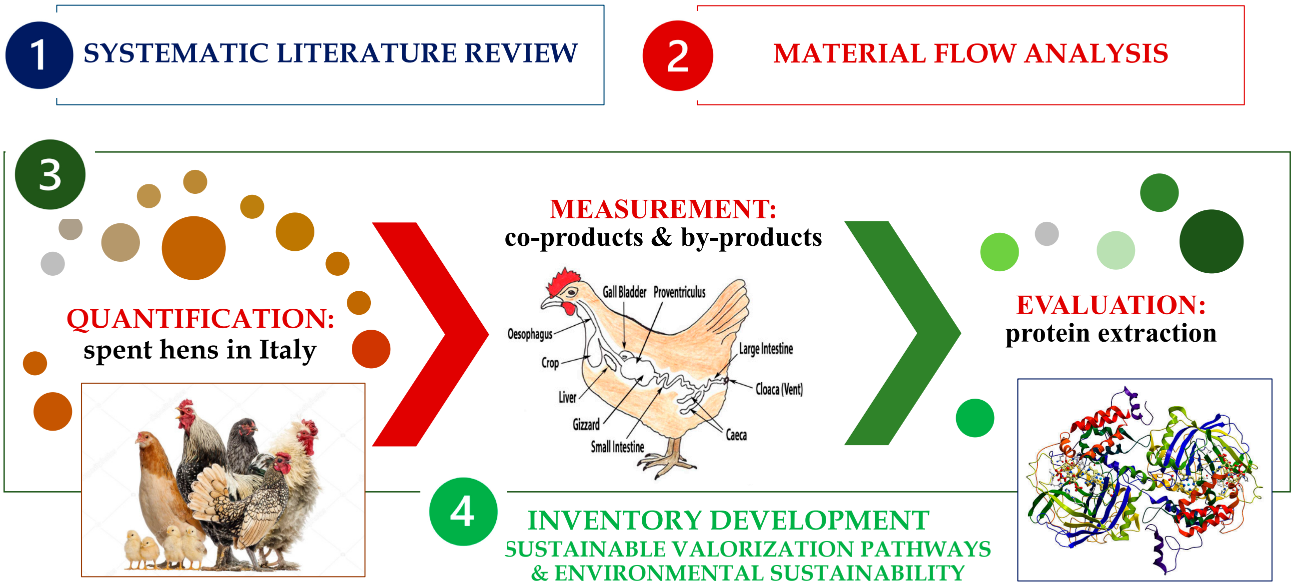

Figure 2. Research Strategy. Source: Personal elaboration by the authors.

3.1. Material Flow Analysis

The number of spent hens in Italy, as well as the number of co-products and by-products and proteins embedded within their flows, is assessed through the material flow analysis, which is defined as a "systematic assessment of the state and change of materials flow and stock in space and time" [24]. It is an effective tool for assessing sustainability and circularity within at the macro, meso and micro level. In the present research, the material flow analysis was conducted using the software STAN 2.7 (substance flow ANalysis) on secondary data collected on national official statistics and reports [5] and international articles and contributions [15,20,40,41,44,45]. The software, developed by the Institute for Water Quality, Resources and Waste Management at Vienna University of Technology, balances material flows within a specific system and helps to compare the scale of resource flows illustrating networks and related interconnections. STAN 2.7. assumes that uncertain quantities are normally distributed on the basis of their mean values and standard distributions (standard uncertainties). As 95% of all data are included within the interval mean value ± two times the standard deviation, a 95% confidence interval has been applied [51,52]. In STAN 2.7., the authors have estimated an uncertainty value in the assessment of the flows of proteins, which depends on: (i) the variable weight of co-products and by-products, namely feathers, blood and offal; and (ii) the variable amount of the protein content in each co-product and by-product, as outlined in Section 3.2. Last, an additional ±5% uncertainty has been applied in the field of the protein content per region, in terms of weight.

3.2. Spent Hens' Characteristics

Under the physiological perspective, the laying hen's body grows rapidly after birth until sexual maturity (16–24 weeks), and the average body weight ranges from 1400 g at 20 weeks of age to 1500–1800 g at 70 weeks of age [15]. Table 2 presents the average spent hen composition in weight. Results show that, on average, a spent hen's body is composed of approx. 65.16% of moisture, 20.77% of proteins, 11.24% of fats and 2.83% of ash.

Table 2. Spent Hens' Composition in terms of Weight (Average Weight: 1650 g).

Source	Moisture (g)	Proteins (g)	Fats (g)	Ash (g)
Fan and Wu [15]	997.43	305.25	259.88	87.45
Freeman et al. [40,41]	965.25	295.35	315.15	74.25
Zubair [53]	1100.55	282.15	232.65	34.65
Safder et al. [44,45]	991.65	353.10	254.90	36.30
Okarini et al. [54]	1188.00	377.85	57.75	26.40
Semwogerere et al. [20]	1207.80	358.05	62.70	21.45
Average	1075.11	328.63	185.46	46.75

Notes: Fan and Wu [15] consider a hen carcass without feather, head, feet and viscera, whereas Safder et al. [44,45] do not indicate the hen body components.

In light of Karuppannan et al. [53] and Lasekan et al. [55], it is possible to distinguish among spent hens' co-products and by-products, namely feathers, blood and offal (including head, feet, viscera), which represent 5–7%, 2–7% and 30–32% of the hen's boneless body, respectively. It means that bones represent approximately 40–45% of the hen's living body. In terms of proteins, results show that (i) the feathers' content is about 85–99% in weight (wt.); (ii) the blood content is 60–80% wt.; (iii) the bones' content is 23–24% wt.; (iv) the skin content is 17–20% wt.; and (v) the offal content is 11–15% wt. [53].

3.3. Study Area and System Boundaries

Italy represents the fourth egg producer in Europe, accounting for 0.78 Mt of eggs destined to human consumption in 2021, for an amount of 12.6 billion eggs and an economic value of EUR 1.4 billion. The Italian egg industry bred over 40 million laying hens in approximately 2600 farms and is 100% self-sufficient [5]. Hence, the entire number of live animals considered in the research are reared in Italy and the trade balance (import and export) is quite null [19]. Figure 3 illustrates the consistency of the laying hens in Italy in 2020, distinguishing per region. The highest amount of laying hens is bred in Veneto (25%), followed by Lombardy (24%) and Emilia-Romagna (18%). Overall, the Northern regions account for over 75% of the Italian laying hens.

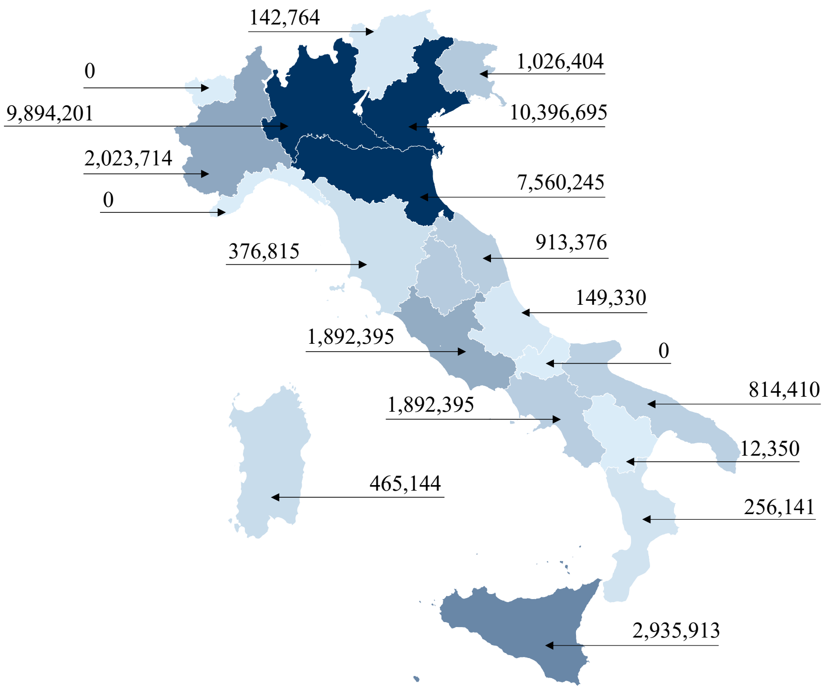

Figure 3. Study Area and Laying Hens' Consistency in Italy per Region in 2020 (heads). Source: Personal elaboration by the authors on Ismea Mercati [5].

4. Results and Discussion

4.1. Material Flow Analysis

Table 3 identifies the number of spent hens (t) in Italy per region, distinguishing between moisture, proteins, fats and ash on the basis of the average spent hens' composition (Table 2). It emerges that approximately 67,155 t of spent hens are produced in Italy, that account for a total of 43,758 t of moisture, 13,948 t of proteins, 7549 t of fats and 1900 t of ash.

Table 3. Material Flow Analysis of Spent Hens' Composition in terms of Weight.

Region	Spent Hens (t)	Moisture (t)	Protein (t)	Fat (t)	Ash (t)
Veneto	17,155	11,178	3563	1928	486
Lombardy	16,325	10,637	3390	1834	462
Emilia-Romagna	12,474	8128	2590	1402	353
Sicily	4844	3156	1006	544	137
Piedmont	3339	2175	693	375	94
Lazio	3112	2027	646	349	88
Friuli-Venezia-Giulia	1694	1103	351	190	47
Umbria	1569	1022	326	176	44
Marche	1507	981	313	169	42
Campania	1478	963	306	166	41
Apulia	1344	875	279	151	38
Sardinia	767	500	159	86	21
Tuscany	622	405	129	69	17
Calabria	423	275	87	47	11
Abruzzo	246	160	51	27	7
Trentino-Alto-Adige	236	153	49	26	7
Basilicata	20	13	4	2	1
Valle d'Aosta	-	-	-	-	-
Liguria	-	-	-	-	-
Molise	-	-	-	-	-
Total (Italy)	67,155	43,758	13,948	7549	1900

Source: Personal elaboration by the authors. The weight of spent hens per region (t) is calculated by multiplying the heads of laying hens reared in each region (Figure 2) per the average weight of each spent hen (1650 g), whereas the weight of moisture, proteins, fats and ashes is calculated by multiplying the weight of the spent hens per the average coefficient identified in Table 2 (i.e., 65.16% of moisture, 20.77% of proteins, 11.24% of fats and 2.83% of ash).

Specifically, Figure 4 illustrates the material flows of proteins contained within spent hens' co-products and by-products, distinguishing among proteins contained in bones, feathers, blood and offal. The quantity of proteins contained in the spent hens' co-product and by-products have been obtained by multiplying their consistencies (in terms of weight) for their protein content. Uncertainties consider the proteins' variable content as outlined in Section 3.2.

The highest number of spent hens' by-products is represented by bones (38,614 t), followed by offal (8847 t), feathers (1712 t) and blood (1427 t). In terms of spent hens' proteins, it emerges that over 13,949 t of proteins could be obtained from spent hens' valorization in Italy, of which (a) 9074 t could be extracted from bones; (b) 2300 t from offal; (c) 1575 t from feathers; and (d) 998 t from blood. Out of boundaries is the fresh meat, which could be obtained from spent hens, which amounts to approx. 16,553 t, as well as other components (e.g., fats), which amounts to over 36,650 t.

The largest quantity of proteins from spent hens is available in Veneto (3562 t), followed by Lombardia (3391 t) and Emilia Romagna (2590 t). Considering the spent hens' valorization pathways (Section 2.3.2), it is possible to theoretically evaluate the opportunities from protein extraction from spent hens in Italy. Specifically, some opportunities to produce biomaterials from spent hens' protein extraction in the food and non-food sector are discussed: (a) proteins processing into food packaging films by compression molding for 10 min at 120 °C and 3500 psi pressure using a carver press [39] and (b) proteins to develop wood adhesive for dry or wet applications [49].

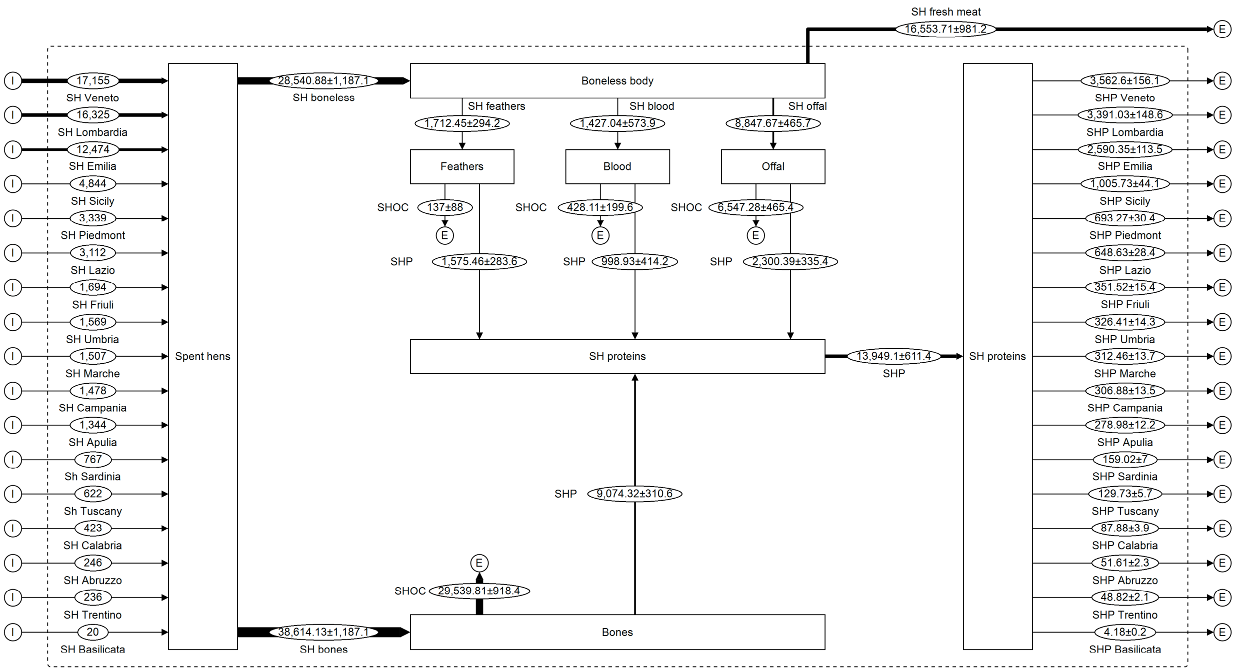

Figure 4. Spent Hens' Proteins Material Flow Analysis in Italy in 2020 (t). Notes: SH = spent hens; SHOC = spent hens' other components; SHP = spent hens' proteins. Source: Personal elaboration by the authors using STAN 2.7. In the assessment of the flows of proteins, the uncertainty value considers: (i) the variable weight of co-products and by-products, namely feathers, blood and offal; and (ii) the variable amount of the protein content in each co-product and by-product, as outlined in Section 3.2. Last, an additional ±5% uncertainty has been applied in the field of the protein content per region, in terms of weight.

4.2. Recovery of Proteins

First, it seems essential to point out that the recovery of proteins depends on the efficiency of the extraction method. Figure 5 describes the main protein extraction methods, according to Fan and Wu [15], which are based on proteins' solubility at different pHs. Results show that myofibrillar proteins and collagen are the dominant proteins in spent hens [49], as well as sarcoplasmic proteins and stromal proteins, such as elastin and keratin [47].

Zubair et al. [39] applied the alkali-aided method, highlighting that its efficiency depends on the solubility of protein at a high pH, the sediments' size after centrifugation and the solubility at the isoelectric point, and reach a 74% protein yield through a solubilization at a pH value of 12 as well as a 96% at a pH value of 5.75. Such yields, which could be theoretically obtained from spent hens' proteins recovery, are higher than those reported from turkey (66%) [57], bovine and porcine (51–56%) [58] meat. However, Zubair et al. [39] have discussed the need to add plasticizers such as glycerol to spent hens' proteins to achieve the required thermoplastic behavior of the proteins derived films. Bionanocomposite films obtained from spent hens' proteins, blended with 25% glycerol and 3% chitosan, could reach the highest elongation at break (1590%). On the other hand, if the strength of films is preferred to the elongation, an additional 5% of nanoclay must be added to the blend, whereas glycerol should be decreased to 20%. Such blend generates bionanocomposite films with 11.37 MPa of tensile strength. Also, considering that films should be addressed to produce food packaging, their water vapor permeability have been estimated, which ranges from 2.18 to 2.71 g mm/m^2 d kPa. This means that films obtained from spent hens' proteins are less permeable compared to those obtained from turkey or fish proteins [58], and nanoclay plays a fundamental role since it acts as a physical barrier to the movement of water molecules. To sum up, it appears that spent hens' proteins are suitable to develop protein/clay hybrid bionanocomposite films, which could be used to produce suitable food packaging due to their good properties. Among others, spent hens' films can preserve food from moisture due to their good water vapor permeability. Considering the alkali-aided method adopted by Zubair et al. [39], it could be possible to extract approximately 9899-12 842 t of proteins and produce a suitable sustainable food packaging.

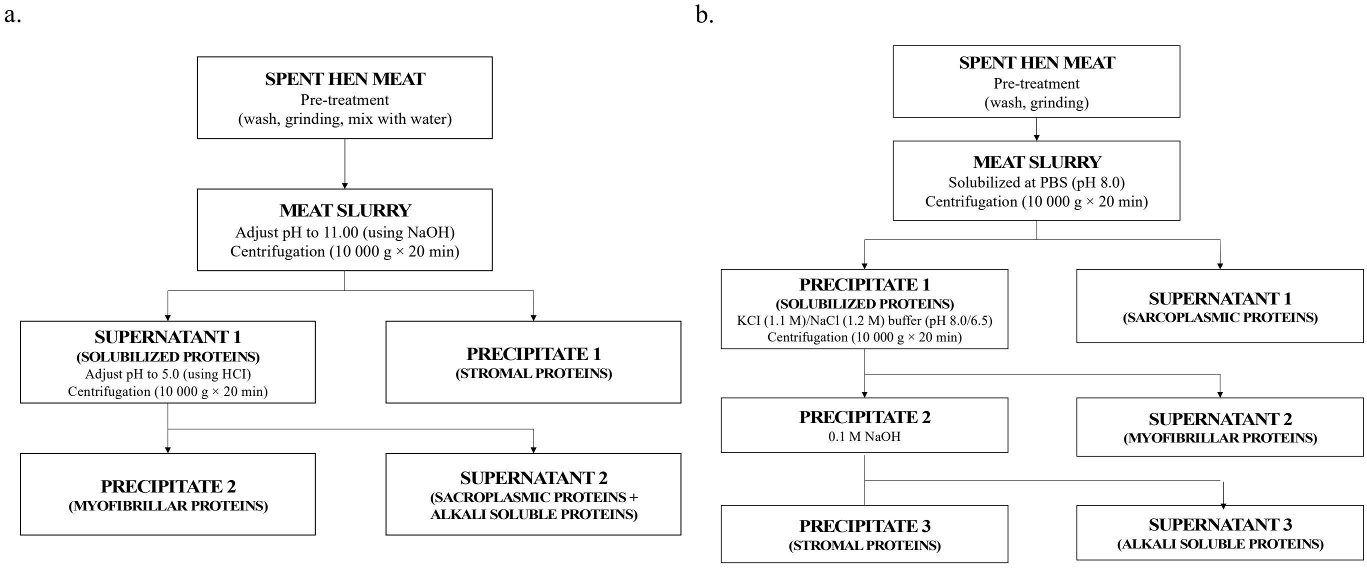

Figure 5. Protein Extraction Methods. Source: Personal elaboration by the authors on Fan and Wu [15]. Notes: Protein extraction (**a**) is retrieved from Fan et al. [50], whereas protein extraction (**b**) is retrieved from Zubair [56].

Wang and Wu [57] have experimented with the production of wood adhesive for dry or wet applications from spent hens' proteins, extracting them at an alkaline pH and recovering them at an acidic pH according to the pH-shifting method at 4 °C. On the other side, fats and heavy connective tissues have been removed prior to blender grinding, and the obtained ground spent hen meat has been mixed. After filtrating and centrifugating the slurry, three layers have been obtained, namely, fats, myofibrillar and collagen. Once the myofibrillar layer has been obtained, the pH of the slurry has been adjusted and proteins rich supernatant has been collected. Then, proteins have been mixed with sodium dodecyl sulfate, urea and alkaline solution, and such protein solutions have been considered as "protein adhesives". It has been estimated that the dry strength of the protein adhesive increases (from 6.57 $\pm$ 0.34 to 8.55 $\pm$ 0.56 MPa) as the urea concentration increases (from 1 to 8 M), but the highest water resistance (3.35 $\pm$ 0.10 MPa) is reached at around 3 M urea.

4.3. Co-Products and By-Products Valorization Pathways

The research focuses on the recovery of proteins, but several other valorization pathways could be considered for spent hens. In light of the waste management hierarchy [58], which identifies five different pathways in a priority order, it is possible to distinguish between prevention, re-use, recycling, recovery (e.g., energy recovery) and disposal. Specifically, in the field of food waste valorization in the meat supply chain [18,30], the disposal of co-products and by-products should be considered as a "nonrealistic option" (extrema ratio), both for its unsustainable environmental costs and for the associated economic losses.

The most sustainable solution in terms of waste management concerns prevention, which encompasses "measures taken before a substance, material of product has become waste", such as the re-use of the products or the extension of their lifespan [58]. One first option to prevent spent hens from becoming waste involves their use as food for human consumption. Some countries other than Italy, such as China, Korea, India, Thailand or Brazil [15], are used to sell spent hens as whole birds, or as cut-up parts and ground meat in the poultry market. The consumers' acceptance of spent hens is relatively high in China, where spent hens represent a regular component of table foods, as well as in Korea or India, where consumers process spent hens into chicken soups, snacks and processed meat [14,15,59]. In Italy, these prevention pathways have declined due to cultural or taste reasons, since spent hens' meat is tough and fibrous due to the high collagen content and several cross linkages. However, if it were possible to reinsert spent hens in the poultry market, in Italy it would be possible to sell over 67,705 t of meat per year, with considerable savings in environmental (i.e., no new animals bred) and economic (i.e., sale of the product as is and reduction in treatment and disposal costs) terms.

According to the definition of re-use, which means "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived" [58], it appears rather complex to apply the concept to spent hens' co-products and by-products, whereas it seems more suitable to deal with recycling. Such a concept has been defined as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes" [58]. It includes the reprocessing of organic material (i.e., material recovery), but it does not include energy recovery for obtaining biofuels, for instance.

In the field of material recovery, it should be remarked that spent hens' co-products and by-products have been considered for a long time as low-valuable materials [60]. However, there are several processes which regard their recovery, namely the anaerobic digestion to produce digestate and biofertilizers, the microbial fermentation to obtain bio alcohols, or the carbonization and activation to boating bio-sorbents [30,61]. Such processes must be considered as alternatives to the proteins' extraction (e.g., enzymatic hydrolysis), which are addressed to obtaining biopolymers, biochemicals and bioplastics and represent, currently, one of the best opportunities to recycle spent hens into products with high added value (Section 4.2).

One last option before disposal regards the energy recovery of spent hens' co-products and by-products, through anaerobic digestion, into biogas. Considering the average theoretical methane potential of food waste (0.52–0.53 m^3/kg) [62] and considering the number of co-products and by-products generated in Italy each year, it would be possible to estimate a theoretical biomethane production of 35–37 million m^3. Nevertheless, this amount depends on the collection capacity of the organic material, as well as on the technologies available on the national territory for anaerobic digestion. This requires, albeit at an advanced level of technological maturity, considerable economic investments in the various municipalities [60,63,64].

4.4. Theoretical Implications and Future Research Directions

The measurement of material flows is essential to developing inventories and promoting circular economy strategies in the agri-food sector. One latest technical specification, namely the UNI/TS 11820:2022 [65] on the "Measurement of Circularity—Methods and Indicators for Measuring Circular Processes in Organizations", has defined the material flow analysis as a complementary method to acquire data and has suggested its use, among other existing methods, to collect quantitative and qualitative data to boost circular economy [25].

In light of the current research, no article quantifies the recovery rate of spent hens in Italy, raising doubts on the efficiency of the egg industry and on the knowledge of the farmers with regard to the different spent hens' valorization pathways. The research has highlighted the need to measure the laying hens' consistency and the proteins and nutrients content hidden within their flows across Italy. Hence, the enhancement of industrial symbiosis practices and circular economy strategies to boost the environmental sustainability of the entire egg industry is required.

Considering that the vast majority of laying hens is located in Veneto, Lombardia and Emilia Romagna, namely in the Northern regions of Italy (approx. 71%), it appears interesting to discuss the opportunity of development of industrial symbiosis networks towards the collection of spent hens and the extraction of proteins contained in their co-products and by-products. The industrial symbiosis paradigms are essential to tackling linear economy and enhancing the circular economy and could at the same time boost economic and environmental sustainability in the meat sector [19,66]. However, the implementation of the industrial symbiosis requires, among other variables, the development of trust and education among farmers and entrepreneurs, as well as a huge investment towards mapping material flows at the local level and financial incentives to industries and research institutes [67]. Industrial symbiosis must be interpreted as an approach to realize the circular economy, intended as a regenerative system in which waste from one system can be recovered into secondary raw materials for another system [68]. Specifically, proteins from spent hens could be used to produce biomaterials, such as innovative and sustainable packaging to be used in the food and non-food sector.

It has emerged that there is a paucity of studies, which explore the nexus between spent hens' valorization pathways and their environmental or economic sustainability. Environmental accounting methods, such as the life cycle assessment or the carbon footprint, have investigated the egg supply chain from feed to egg production, encompassing some other stages such as egg processing. However, none of the experiments discussing the spent hens' valorization pathways has investigated the environmental benefits and/or burdens, as well as the economic ones, associated with functional food or biomaterials production. It means that transversal studies, which blend laboratory experiments and environmental accounting, must be implemented to obtain a transparent overview of the entire egg industry, from feed production to spent hens' disposal. Considering the theoretical benefits coming from spent hens' valorization, both in the field of material and energy recovery, advanced and specific research is required, with particular attention to waste-to-bioproducts and waste-to-energy technologies. Also, these studies are required to achieve the key objectives of the National Recovery and Resilience Plan (NRRP), which asks for a green, ecological and inclusive transition by promoting the circular economy, the development of renewable energy sources and a more sustainable agriculture [69], and organic waste valorization, and the proposals of the Common Agricultural Policy (CAP) [70].

The present research, on the basis of the provided inventory analysis, intends to be applied in the future to the life cycle assessment of the entire egg industry in Italy, discussing alternative spent hens' valorization pathways under the environmental perspective and highlighting the most and the least impacting pathways to the environment. Furthermore, considering the opportunities offered by other accounting methods, such as the life cycle costing, future research directions will explore the economic impacts associated with different valorization pathways.

5. Conclusions

This work addresses some challenges of the Italian egg industry, focusing on the spent hens' valorization pathways to recover proteins into sustainable and innovative biomaterials. After having conducted a systematic literature review on the environmental implications of the egg industry and the current spent hens' valorization pathways, the research has included a material flow analysis to quantify and qualify the laying hens' consistency and the proteins' hidden flows included in their co-products and by-products, namely feathers, blood, bones, offal and skin. Under the quantitative perspective, considering the purpose of developing an inventory of spent hens in Italy, the research has highlighted that over 13,948 t of proteins could be extracted, distinguishing between those embedded within offal (2300 t), feathers (1575 t) and blood (998 t). Under the qualitative perspective, the recovery of proteins depends on the efficiency of the extraction method, but the most diffused are based on proteins' solubility at different pHs. The most dominant proteins embedded in spent hens are myofibrillar proteins and collagen, as well as sarcoplasmic proteins, stromal proteins and keratin.

There emerges the need to enhance the efficiency of the egg industry in Italy by enhancing industrial symbiosis and circular economy strategies. On the one hand, it is essential to boost the recovery rate of spent hens in Italy by measuring their material flows. On the other hand, it is required that public authorities provide funds to tackle the linear economy and realize the circular economy. Industrial symbiosis must be interpreted as an approach to reach a circular economy, since waste from one system can be recovered into secondary raw materials for another system.

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