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Drawing a circle for the livestock and agrifood sector: fundamentals to a sustainable supply chain

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The classical linear food supply chain exacerbates environmental and socioeconomic vulnerabilities, undermining future food security. In contrast, retaining and reintegrating biomass or valorizing by-products and residues for other applications within or outside the sector (i.e., feed, compost, bioenergy, and bioproducts) allows disentangling the agrifood sector from the accompanying environmental and social issues. Circular practices and circular agrifood models may reconcile productivity, sustainability, and social wellbeing, creating new value chains, diversifying revenue options, and reducing input costs. At the same time, they strengthen local food systems' resilience and promote equitable access to nutritious food. The present literature review brings a critical holistic outlook on the reshaping of the livestock system toward a circular paradigm. It emphasizes the timeliness and relevance of a circular approach to livestock management in order to design a greener and cost-effective agrifood system able to maintain such productivity to keep providing food to a growing global population. Here, the resource flow and valorization pathways are integrated to present a comprehensive circular framework feasible across diverse livestock production contexts, filling the gap where previous assessments focused on single resource flows or case-specific reports (e.g., waste-to-feed or manure-to-fertilizer pathways). Therein, the present review proposes a structured roadmap to improve resource use efficiency and reduce environmental impacts, guiding the transition toward more sustainable and resilient agrifood and livestock systems.

KEYWORDS

animal production, by-products, circular economy, feed, sustainability

1 Introduction

The urgent call for a transition to a more sustainable and circular global food system stems from the need to reduce the pressure exerted by human activities on Earth's resources (Steinfeld et al., 2006; Cammarata et al., 2021; Hassoun et al., 2022; Harchaoui et al., 2023; McAllister et al., 2025a). Although agriculture and, in particular, livestock are central in modern global economy (FAO, 2021), with livestock farming providing 40% to the human protein supply and 18% to the human energy requirements (FAOSTAT, 2022), they have substantial impacts on the environment. Globally, the agrifood sector exploits considerable amounts of the world's arable lands and freshwater (Li, 2021), accounts for 26% of the global greenhouse gas (GHG) emissions (Poore and Nemecek, 2018; Van Zanten et al., 2019; FAO, 2025b), and relies on significant requirements of inputs that are not fully converted into edible products, thus resulting in by-products and waste losses along the food supply chain (Marku et al., 2024). Similarly, geographical decoupling of crop and livestock productions leads to an unequal distribution of lands (Harchaoui et al., 2023; Marku et al., 2024) and an imbalance in the nutrient cycle (Kleinpeter et al., 2023). In addition, the growing global population brings the challenge of increasing efficiency while adopting sustainable practices (Cantorani et al., 2025), placing the sector at the core of the One Health concept, which encompasses the threats associated with population growth, food security, climate change, and resource scarcity (Kleinpeter et al., 2023).

Therefore, embracing circular approaches is imperative to creating a sustainable livestock system. The application of sustainable development principles is gaining momentum as a key element to consider when designing strategies to provide food while enhancing the sector's resilience, maintaining rentability, and reducing pressure on the environment (Ramirez et al., 2021). Indeed, the search for a more sustainable agrifood system, following circular principles, is focused on the adoption of practices and technologies that reduce the input of finite resources (i.e., water, land, and fertilizers) and that increase nutrient circularity and use efficiency in a manner that transforms unavoidable food system residues in added-value products (Ghisellini et al., 2016; Jurgilevich et al., 2016; Corona et al., 2019; Kleinpeter et al., 2023; Valls-Val et al., 2023). In particular, the circular principles foster a more efficient use of resources and energy through the reuse and recycling of residuals, which decrease the waste production and environmental impacts of human activities. Accordingly, reshaping livestock systems to comply with circular approaches (FAO, 2025b) could support the green innovation and boost the competitiveness within the sector (Šperanda et al., 2019), and sustainable farming practices may contribute to facilitating the accomplishment of the Sustainable Development Goals (SDGs) defined by the United Nations. Moreover, it is widely accepted that the livestock sector may have a decisive socioeconomic role in supporting sustainability through circularity (Paul et al., 2020; FAO, 2025a). Hence, the adoption of eco-friendly farming practices in the food supply chain could aid in closing nutrient loops, reduce environmental footprints, and minimize resource consumption, instead promoting resource conservation and, overall, strengthening circularity within the livestock sector.

Thus, the present paper discusses the key processes of animal-based production that impact the environment and the current challenges and limitations faced by the sector in order to achieve environmentally responsible management. In particular, our aim was to identify main intervention areas for circular economy (CE) principles to comprehensively characterize the main frameworks that may enable the implementation of CE principles and allow minimizing the waste stream and maximizing biomass use efficiency. To the best of our knowledge, this is the first study synthesizing the body of research on CE applications in livestock systems from conceptual, empirical, and policy-oriented sources. CE principles are increasingly explored in livestock systems under a multidisciplinary approach, spanning environmental science, animal production, waste valorization, bioenergy, and sustainability governance. However, this work reaches beyond existing studies, which tended to focus on isolated valorization pathways, species-specific analyses, or conceptual discussions. It integrates resource flows and valorization pathways to propose a more comprehensive and actionable understanding of how circularity can be implemented across the livestock sector in order to sustainably improve resource use efficiency, reduce environmental impacts, and guide the transition toward more circular and resilient livestock systems.

2 Methodological framework

Scientific databases (i.e., Scopus, Google Scholar, and PubMed) served as resources for procuring original papers that fitted the scope of the present review, conducted between June and November 2025. The scope was confined to peer-reviewed articles released between January 1, 2013, and September 30, 2025, to which were added also relevant previous studies cited in the primary studies selected. Finally, the main inclusion criteria were: 1) inherence with the topic; 2) publication year; 3) article relevance in terms of number of citations; and 4) study design (conceptual or practical). Nevertheless, no numerical citation count threshold was applied as an exclusion criterion so as to prevent the bias of hindering recent or specialized contributions.

The available literature on CE in the livestock sector is broad, fragmented, and often conceptual. Hence, the search criteria were primarily focused on the basic principles of CE and bioeconomy and the role of livestock in CE systems. More specifically, early search terms included "circular economy," "circular bioeconomy," "sustainability," "livestock systems," "agrifood systems," and "food supply chain.

Furthermore, to deepen the potential of livestock in circularity, the main livestock production flows (i.e., primary production, processing, distribution, and waste management) and their interconnection within the food supply chain frameworks were analyzed. To refine the selection of target papers, the search criteria were framed as: "circular economy" AND "livestock"; "bioeconomy" AND "livestock"; "circular economy" AND "food systems"; "circular economy" AND "livestock polices"; "environment" AND "circular livestock system"; "livestock" AND "resource efficiency" AND "circular"; "livestock" AND "nutrient cycling"; "circular" AND "waste management"; "livestock" AND "animal by-products" AND "circular"; "integrated crop and livestock systems"; "technology" AND "circular livestock systems"; "energy" AND "circular livestock system"; and "socioeconomic" AND "circular livestock system.

The included papers were examined to identify recurring themes involved in the essential transition of the sector to a more environmentally and socioeconomically sustainable and efficient production. The primary areas of investigation were: i) resource use efficiency; ii) nutrient cycling or manure management; and iii) animal by-product (ABP) valorization. Moreover, to pursue relevance-driven principle selection, we favored studies that provide insights into resource flows and common valorization routes, system-level synergies and limitations, environmental and socioeconomic implications, or governance conditions shaping CE adoption. On the other hand, works focused solely on linear production models or unrelated agricultural domains were excluded. Eventually, after manual screening process to only include, discuss, and link meaningful studies, a total of 263 papers were deemed relevant and were selected for extensive dissertation.

3 From linear to circular economy: the role of livestock and technological enablers

Over the last 150 years, the global economy has been dominated by a linear business model that relies on hardly sustainable and wasteful patterns that may be profiled with the expression "take–make–dispose" (Sariatli, 2017). Hence, linear patterns consist in the unbearable exploitation of natural resources and energy for the production of goods, which are disposed of in the final stages of their lifetime, resulting in a progressive waste production (Milovic et al, 2024).

Similarly, the agrifood system is founded on the exploitation of natural resources to ensure the production of food, feed, materials, and energy. Nevertheless, the harvesting biomass required for production flows and the waste streams significantly contribute to land overuse, biodiversity loss, and climate change (Krausmann et al., 2013). As a result, the sector is currently facing an unprecedented array of networked environmental, social, and economic issues that affect all actors in the food supply chain, as well as policymakers and global economic systems. These pressures invariably lead to increased costs and related challenges to ensure both economic and social sustainability. Moreover, as these global crises directly threaten food security and safety, to avoid further damage, novel scientific and technological approaches for building a circular agrifood model are paramount (Steffen et al., 2015; Shah and Wu, 2019; Hassoun et al., 2022; Kumar et al., 2022a; Akanmu et al., 2023; Richardson et al., 2023).

The growing concerns about the downsides of these unsustainable production and consumption patterns marked the initial stage of a new concept of economy, defined as circular economy. This transformative economic pattern aims to implement a cyclical production system instead of the wasteful linear model (Milovic et al, 2024) as a means to ensure the sustainability of human activities considering the finite nature of Earth's resources. The 3-R strategy (reduce–reuse–recycle) represents the backbone of circular principles, emphasizing the central role of responsible resource management (Ghisellini et al., 2016; Ramirez et al., 2021). The circular approach focuses on reducing waste, reusing resources, and recycling residues to generate a closed-loop system in which the residual value is restored or expanded and returned to the value chain to achieve circularity (Gertsakis and Lewis, 2003; Boulding, 2013; Van Buren et al., 2016; Ramirez et al., 2021; Abbasi et al., 2024). Therefore, the basic assumption of circular models is that recovering the value of a product in the long run leads to a reduction of the waste along the productive chain, maximizing the utilization of resources and creating a loop in which products at the end of the cycle return into the production flow as a novel resource that creates further value (European Commission, 2014; Sariatli, 2017; Milovic et al, 2024). Applying circularity in industrial processes has been proven to be a viable strategy to provide tangible benefits and to address modern economic, environmental, and social challenges. In fact, CE principles found applications in multiple productive systems, including the agrifood sector, with distinct strategies tailored to sector-specific peculiarities (Abbasi et al., 2024).

Notably, the recovery of biological resources finalized to close the natural resource loop in the food supply chain is driven by a subset of CE termed circular bioeconomy (FAO, 2025a). According to the International Advisory Council on Global Bioeconomy and Global Bioeconomy Summit (2020), the concept of bioeconomy encompasses "the production, utilization, conservation, and regeneration of biomass, including related knowledge, science, technology, and innovation to provide sustainable solutions (i.e., information, products, processes, and services) within and across all economic sectors to enable transformation to a sustainable economy" (McAllister et al., 2025a). Within this perspective, when examining the agrifood system holistically, the application of a circular bioeconomy represents the convergence of multiple sectors and value-adding activities operating at various levels of the supply chain involved in the production, processing, distribution, consumption, and disposal of food products (FAO, 2025b). In food systems, the implementation of circular bioeconomy principles entails the efficient utilization, recovery, and regeneration of renewable biological materials (e.g., animals, plants, microorganisms, and derived products) providing to convert residuals and co- or by-products into novel added-value products, such as food, feed, bio-based products, services, and bioenergy (Šperanda et al., 2019; Gomez et al., 2022) (Figure 1).

In food systems, achieving circularity implies the introduction of a set of methods and technologies that allow obtaining a circular flow of the natural resources and energy within the production system. In particular, the implementation of circular practices requires different approaches and technologies according to the

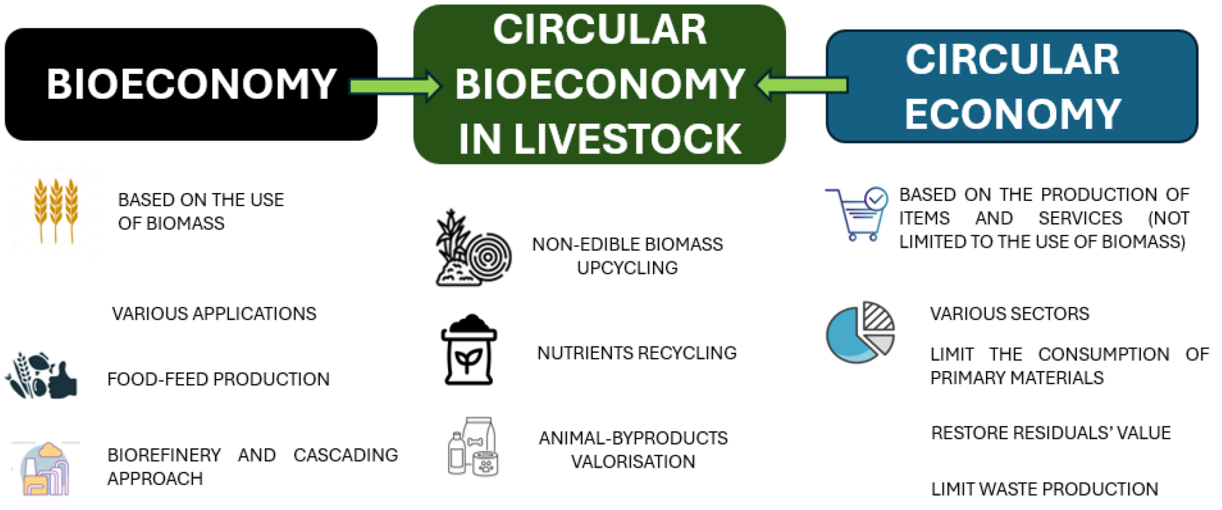

FIGURE 1
Integration of circular livestock bioeconomy into the circular economy and bioeconomy frameworks.

individual residual features, quality, and condition as these properties will control the selection of waste handling and treatment options. Indeed, not all materials can be recycled or reused in the same manner, and in some cases, the number of times certain recycling processes can be repeated is limited because the material becomes worse over time (Ramirez et al., 2021). Moreover, animal or vegetable residuals rich in organic and moisture contents are characterized by rapid physical and biological degradation; therefore, their further processing requires proper handling, sterilization, and decontamination to ensure safe and suitable reuse (Dou et al., 2018). Hence, new technologies are required to reinforce the current strategies aimed at converting agricultural and livestock by-products and waste materials into high-value products (Ramirez et al., 2021). *Inter alia*, advanced technologies may aid in harvesting energy from manure, such as for the generation of biogas while producing sludge as soil amendment or other additional co-products (FAO, 2025a). Agrifood by-products and waste may be a valuable source of biocompounds that can be transformed or extracted throughout a wide range of technologies, conventional or innovative (Brunetti et al., 2022; Roselli et al., 2025). Similarly, eco-friendly farming practices that combine advanced technologies for energy-efficient operations with environment-friendly infrastructure are pivotal to adherence to the CE principles. By adopting these strategies, farming practices can significantly reduce their environmental footprint and resource consumption, increasing the overall resource conservation (Ward et al., 2016; Taifouris and Martin, 2021; Abbasi et al., 2024).

Recent studies have confirmed that the development of a sustainable animal production system is dependent to a large extent on adherence to the CE principles and on the creation of reliable, fit-for-purpose technologies designed to minimize environmental impacts and maximize value (Ramirez et al., 2021; Cantorani et al., 2025).

In line with the emerging technological trends, the modernization of livestock farming practices is driven by the transition to precision livestock farming (PLF). In this background ranks the increased integration of digital technologies (e.g., artificial intelligence, Internet of things, blockchain, and big data) into livestock practices and supply chain management, known as "Agrifood 4.0" (Misra et al., 2020; Torky and Hassanein, 2020). This techno-digital evolution has led to significant improvements in livestock operational efficiency, reducing waste and increasing traceability and transparency, indirectly contributing to the adherence to circular principles (Ward et al., 2016; Misra et al., 2020; Torky and Hassanein, 2020; Gutiérrez-del-Río et al., 2021; Hassoun et al., 2022; Lei et al., 2022; Tapia-Quirós et al., 2022; Pandey and Pandey, 2023). In this framework, the transition of traditional livestock industries toward PLF is characterized by the implementation of novel technologies designed to reshape farm practices in order to cope with the current concerns linked to farm intensification and public debate about food safety and a farm's environmental impact (Pierce et al., 2013; Lindblom et al., 2017; Losacco et al., 2025). In particular, precision farming, as well as precision feeding, which introduces automated technological devices to collect and elaborate on data on livestock resource use (i.e., feed, water, and land), animal feeding behaviors, performance levels (e.g., products yield, and body weight), and environmental conditions (e.g., temperature, humidity, pollutants levels), optimizes the use of inputs by delivering "the right amount, at the right time, in the right place." Thereby, the animal and environmental data collected may ensure the exploitation of minimum levels of resources (e.g., by controlling feed, land, and water exploitation) and promote the recycling of residual streams (e.g., by manure management) while optimizing performance and minimizing the farm's environmental impacts (e.g., through GHG and N emissions control) (Ward et al., 2016; Losacco et al., 2025). Under these paradigms, the livestock sector can inherently represent enormous potential in the CE that may be propelled by resource conversion, nutrient recycling, and by-product valorization.

However, as an actual limitation, the transition toward a circular pattern requires greater investment in research and the development of technologies that enable its application (Sanchez-Garcia et al., 2024). The available literature depicts a transformation trend of the agrifood sector toward the design and implementation of technological solutions and sustainable practices, with a focus on fulfilling the population demands and mitigating environmental impacts. The results emphasized the transformative key role of innovative technologies in enhancing resource efficiency, optimizing supply chains, and improving product life cycle management. In turn, technology implementation offers profound economic and environmental benefits while fostering sustainable production and consumption (Sanchez-Garcia et al., 2024). A bibliometric analysis of the main trends of this sector over the past 47 years confirmed that the central themes of academic productions point to sustainability, CE, and environment, in which greater emphasis is given to interlinked emerging issues such as food waste management and valorization. Notably, the comprehensive study also disclosed the growing importance of technological advancement in the context of sustainability, CE, and global challenges (Borsellino et al., 2020; Mishra et al., 2023; Yadav et al., 2024; Cantorani et al., 2025).

In addition to the important environmental benefits, adopting a CE approach in the livestock sector brings tangible industrial and economic advantages contributing to the reduction of economic losses along the global food chain (McAllister et al., 2025a). For instance, it is estimated that, along the food supply chain, up to 31% of the production for human consumption is wasted and the inefficiency of the global food economy translates into losses amounting between US $1 and $2 trillion per year (Ward et al., 2016; Wang et al., 2024; FAO, 2025b). On the other hand, a circular bioeconomy model may enable obtaining a resource-efficient production system, which is expected to generate profits up to US $7.7 trillion (WBCSD, 2019). In the livestock sector, Šperanda et al. (2019) estimated that the application of CE might help avoid the environmental damage caused by resource misuse and may increase industry competitiveness by creating new business opportunities and more efficient and innovative productive systems.

Therefore, the integration of circular paradigms into the livestock sector requires a systemic approach that redesigns the entire process flow, from primary production to processing and distribution, utilizing systems and advanced technologies that support the strategy of recovering and recycling resources to create new value streams (Ghisellini et al., 2016; Jurgilevich et al., 2016; Corona et al., 2019; Valls-Val et al., 2023; FAO, 2024). From a socioeconomic perspective, a more circular approach to livestock may present significant opportunities.

4 Integration of circular economy approaches into livestock frameworks

Global consumption of animal-derived protein has increased in modern days (FAOSTAT, 2017). At present, society draws more than a third of its protein intake from animal-sourced foods (FAO, 2023). This leads to the expansion of the land used by the livestock production sector, with around 40% of the total global land currently devoted to agricultural activities (OECD/FAO, 2020), which consequently entails environmental burden, *inter alia*, land use change (including forests and grasslands), resultant biodiversity loss (Van Zanten et al., 2018), and the emergence of the feed–food competition phenomenon (Wilkinson and Lee, 2018). As the trend of consuming more animal-sourced foods is expected to continue growing, so will the requirement for arable lands for livestock rearing and feed production activities (OECD-FAO, 2020). Moreover, feed production, together with manure processing and ruminant enteric fermentations, contributes to approximately 57% of the GHG emissions in the whole food systems (Gerber et al., 2013; Smith et al., 2014; Xu et al., 2021), including the transportation of animal feed to livestock buildings (Uwizeye et al., 2020).

To strengthen the sector's sustainability, a shift toward circular livestock industry models can reveal opportunities at all stages: from the use of technology in the primary production with precision farming and feeding to the recycling and the safe use of wasted resources, including manure or processing wastes (i.e., whey, wool, and wastewaters), to obtain products such as feed and fertilizers (Ward et al., 2016). Therefore, each segment of the agrifood chain may be implemented to reach circularity with specific fields of application, in particular with efficient feed utilization strategies that enable resource conversion and upcycling, manure management that aids closing the nutrient cycle, and the valorization of ABPs that reduces food waste throughout the supply chain (Ramirez et al., 2021).

Circularization of the livestock sector may play a key role in resource conversion and the upcycling of non-edible biomass, such as human non-edible plant-based products, grassland, crop residues, and/or food processing by-products. Efficient feed utilization enables reducing the need for additional resource inputs and minimizing food waste generation (Abbasi et al., 2024). It is estimated that up to 86% of the feed consumed by livestock is unsuitable as food for humans (Mottet et al., 2017). Therefore, by resource conversion, animals may convert low-cost biomass (LCB) into high-value animal-based products, organic fertilizers, or renewable energy. By maximizing the efficient utilization of LCB and the safe recovery of ABPs, farmers may create new revenue sources, reduce input costs, and increase their incomes. Moreover, circular-based livestock practices contribute to bolstering food safety and public health by reducing the environmental pressure associated with intensive farming. In addition, circularity promotes cross-sectorial collaborations, bringing together all the actors of the food supply chain, including farmers, food processors, waste management enterprises, and energy companies, creating a more integrated and resilient local economy.

Animal production also contributes to circularity within the integrated crop–livestock systems (ICLS), where crop production and livestock production are combined in the same farm or group of farms, promoting synergies between these systems (Ryschawy et al., 2014; Schut et al., 2021; Harchaoui et al., 2023). In ICLS, for example, grazing animals can thrive on marginal lands unsuitable for crops, utilizing space that would otherwise be wasted. In addition, the inclusion of forages in rotational cropping systems and the provision of manure contribute to carbon sequestration and soil health, improving nutrient cycling (Herrero et al., 2010; Giacometti et al., 2021). Within these frameworks, livestock reduces waste generation and generates added-value products from materials that would otherwise be discarded, avoiding food–feed competition, promoting biodiversity and land regeneration, and closing nutrient cycles.

Recognizing the type of wastes the agrifood sector yields along the production, processing, and distribution stages represents the first step to enhancing sustainability and fostering circular approaches. The type and nature of wastes are numerous, as are the opportunities for sustainable recovery (Galanakis, 2012). Reintroducing into the value chain a product generated from waste creates added revenue and new sustainable development opportunities with a reduced environmental impact, perfectly fitting the CE principles (Ellen MacArthur Foundation, 2019; Ramirez et al., 2021). In this context, the waste hierarchy represents a tool within the European regulatory framework to address waste management and valorization based on sustainability principles (EC, 2008). The waste hierarchy considers five actions to adequately manage food waste: from the reduction of waste generation passing through recovery, reuse, recycle, and, lastly, landfilling. An additional valuable tool that can be integrated within the waste hierarchy is the value pyramid that identifies preferential fields of application as to where to first direct the waste biomass to achieve the most added value (Al-Zohairi et al., 2023).

Consequently, sustainable waste management paths, supported by advanced technology enablers, is crucial to easing the detrimental pressure exerted by the livestock sector (Martín-Hernández et al., 2020; Pires et al., 2021a, Pires et al., 2021b). However, some strategies for the reduction and recovery of waste, even if associated with increased resource efficiency, are also associated with high operational and implementation costs, thereby discouraging large-scale applications (Ramirez et al., 2021). Under these issues, in the livestock sector, the implementation of CE-based systems implies determining practices and technologies that realize efficient resource utilization, manure management, and by-product valorization (Ramirez, et al., 2021).

The following subsections present circular strategies that could be implemented at different levels of the agrifood supply chain. These strategies aim to mitigate the detrimental effects of food production, fostering resource and nutrient circularity that enhances resources use efficiency.

4.1 Livestock role in circular (feed) resource use efficiency

In a circular framework, to improve resource use efficiency and close nutrient loops, crop residues and agro-industrial by-products should be considered first as animal feed. Apart from crop residues such as straw, stover, or olive leaf that are primarily used as economical sources of fiber in ruminant nutrition (Bhandari, 2019; Habeeb et al., 2017; de Blas Beorlegui et al., 2021), the strategic use of agro-industrial by-products in livestock feeding addresses three interlinked challenges: rising feed costs, environmental burdens from the processing and disposal of by-products, and the need for more circular nutrient flows within livestock systems that target resource use efficiency (FAO, 2025b).

There is a wide range of available plant-based by-products (PBPs), and their nutrient contents vary dependent on the crop cultivar, seasonal factors, and the degree of processing, which, in turn, influence their digestibility, feeding value, and dietary inclusion rate (Tufarelli et al., 2013; Fang et al., 2023). However, the body of research on the implementation of PBPs in animal nutrition is conspicuous (Tufarelli et al., 2013; Habeeb et al., 2017; Costa et al., 2022; Vastolo et al., 2022; Georganas et al., 2023; Muhammad et al., 2023; Pugliese et al., 2024a; Pugliese et al., 2024b). It has been proven that fruit and vegetable by-products can be exploited in a highly beneficial manner for animal nutrition and health, specifically in the livestock industry. In addition, phytochemicals obtained from PBPs have been proven to exhibit nutraceutical properties (Reguengo et al., 2022; Galanakis, 2012; Brunetti et al., 2022). Hence, their inclusion into the livestock diet might provide them with bioactive compounds that exert various biological functions such as antioxidant, anti-inflammatory, and gut microflora regulation (Tufarelli et al., 2017). Furthermore, innovative feeding strategies that incorporate PBPs into ruminant diet have shown potential to reduce enteric methane and nitrogen emissions while improving the fatty acid profile and shelf-life of meat (Salami et al., 2019). Recent findings report that the bioactive constituents of plants (e.g., essential oils, tannins, and polyphenols) interact with ruminal microorganisms, resulting in a modulation of the ruminal microbiota and fermentative patterns (Patra and Saxena, 2011).

Indeed, dietary supplementation with polyphenol-rich feedstuffs has been reported to diminish the methanogenesis rate and the methane yield by around 20% by influencing the proliferation and activity of methanogenic archaea when 5 kg/day grape marc was included into dairy cattle ration (Moate et al., 2014). In any case, when assessing PBP inclusion as alternative feed components, their effects are always compared with those of isocaloric and isonitrogenous control diets.

Among the PBPs, olive oil extraction yields various by-products, including olive cake, the first raw resulting material from which partially destoned olive cake and olive pomace results, respectively, from partial or complete stones removal. Lastly, the term “exhausted” is used when the leftover oil content is solvent-extracted (Alburquerque et al., 2004; Secades et al., 2017). Nevertheless, the high moisture content and the variable composition of different olive by-products, coupled with their restricted seasonal accessibility, add complexity to the storage and practical implementation of these feed resources all-year around. Olive by-products are typically more well suited for applications in ruminant diet compared with monogastric species, being characterized by high fiber fractions, low protein, and metabolizable energy content (Sadeghi et al., 2009; Tufarelli et al., 2013; Heuzé et al., 2015; Habeeb et al., 2017). However, a review on its supplementation in rabbit diet concluded how this would be a sustainable solution to improve the meat quality and reduce the cost of feeding (Losacco et al., 2023). Similarly, in swine, 12% dietary olive pomace inclusion into pellet feed positively influenced the monounsaturated fatty acid (MUFA) content of subcutaneous fat and resulted in growth performance comparable to that of the control diet (Ferrer et al., 2020). Olive by-product feeding trial in ruminants assessed that their inclusion covers the maintenance requirements of animals (Heuzé et al., 2015; Bionda et al., 2022). In addition, several investigations have reported that the inclusion of up to 10%–20%, depending on the olive by-product, into the diet considerably bolstered the milk yield and the MUFA content of both milk and meat (Habeeb et al., 2017; Tzamaloukas et al., 2021). In lambs, diet supplementation with 20% of partly destoned olive cake did not impair animal productivity or health and has been shown to improve certain carcass parameters, such as hot and cold carcass yield, albeit reducing the apparent dry matter and nutrient digestibility when compared with the control diet (Tufarelli et al., 2013).

Tomato industrial processing yields between 3% and 5% of the total fruit processed as by-products (Eslami et al., 2022). Tomato pomace supplementation has been investigated in several livestock species (e.g., poultry, rabbits, swine, and ruminants), with no detrimental effects on health or productivity. The mixed results reported are perhaps due to the variable composition of the by-product or the different inclusion levels (Lu et al., 2022). For example, in pig diet, 15% substitution of corn for tomato pomace led to a decrease in the saturated fatty acid (SFA) and MUFA contents in favor of the polyunsaturated fatty acid (PUFA) *n*-3 and *n*-6 series (Biondi et al., 2020). Similarly, compared with the control diet, up to 6% tomato pomace inclusion in rabbit led to a significant increase in both live and chilled carcass weights while reducing the SFA and enhancing the MUFA and PUFA contents of meat and perirenal fat (Peiretti et al., 2013). To conclude, with monogastric species, the antioxidant potential of tomato pomace bioactives has been proven useful to alleviate heat stress in poultry, lowering the plasma malondialdehyde levels and improving immune functions when supplemented at doses of 10 and 20 g/kg of feed (Muhammad et al., 2023). On the other hand, in ruminants, 30% substitution of concentrate for tomato pomace slightly reduced the milk yield (−10%), but significantly enhanced the milk fat content and its *n*-6/*n*-3 ratio (Abbeddou et al., 2015) or decreased the enteric methane emissions and feed costs when included at 12.5% (Romero-Huelva et al., 2012).

Grape-derived by-products from winemaking and juice production constitute a nutritionally and biochemically valuable fraction of agro-industrial waste streams that can be valorized in circular livestock feeding systems (Vastolo et al., 2022). Their nutrient profiles present moderate protein, high residual oil content (mostly from the seeds), and appropriate levels of structural carbohydrates only slightly lignified (Chedea et al., 2017; Olivo et al., 2017). However, grape by-products are particularly notable for their high concentrations of polyphenols, flavonoids, and other antioxidant compounds with nutraceutical potential and potential effects on rumen fermentation and microbial ecology (Atalay, 2020). Dietary incorporation of grape by-products in ruminants can supply fiber and energy while delivering unsaturated fatty acids and bioactive phenolics, which may positively modulate methanogenesis, milk yield, and the fatty acid profile, although discrepancies among findings exist (Correddu et al., 2020). Dried grape marc incorporation into dairy cattle diet led to comparable milk production influenced by the fat content, with the supplemented group showing reduced SFA and enhanced MUFA and PUFA contents compared with the control (Moate et al., 2014). In monogastric species, the administration of grape by-products positively enhanced the growth performance and fatty acid profile by up to 9% in pig diet and by 3% in poultry diet (Costa et al., 2022). In addition, Georganas et al. (2023), reviewing grape by-product administration in poultry diet, concluded that inclusion levels between 2% and 5%, dependent on the by-product type, lead to significant enhancement of the meat PUFA content and oxidative stability. When compared with a control diet, raw or fermented grape pomace supplementation at 15 g/kg of diet allowed birds to better cope in heat stress situations, recording considerable enhancement of the antioxidant markers and intestinal morphology. Notably, the effects of fermented grapes were almost similar to those of a synthetic antioxidant (Gungor et al., 2021). Moreover, always in heat-challenged birds, up to 60 g of grape pomace per kilogram diet reduced the plasma cholesterol and low-density lipoprotein (LDL) contents (Hosseini-Vashan et al., 2020). On the other hand, inclusion of 5% pomace into the diet of weaned pigs promoted beneficial bacteria colonization of the cecum and boosted immunity, with no significant alterations in the growth parameters (Wang et al., 2020).

Pulse by-products from crop harvesting and processing, such as straw, screenings, hulls, and pods, represent an abundant source of human-inedible plant biomass that can be integrated into livestock rations to improve resource efficiency and relieve pressure on human-edible feed resources (Pugliese et al., 2024a). The nutritive value of pulse residues is influenced by species, cultivar, and processing, generally providing appreciable fiber and, dependent on the fraction, beneficial amounts of residual protein and fermentable carbohydrates (Sharasia et al., 2017; Wang et al., 2022). Moreover, the anti-nutritional contents can be overcome by pretreatment (Laudadio and Tufarelli, 2011). Ruminants can benefit from the straw as roughage for fiber and nitrogenous substrates for rumen microbes, and *ad libitum* consumption has been shown to support maintenance and productive functions in balanced diets (Mudgal et al., 2018; Damte and Tafes, 2023).

For monogastric species, when soybean meal was substituted for two different cultivars of lentils included in up to 400 g/kg of diet, no detrimental effects on the poultry growth performance or productivity were reported (Ciurescu et al., 2017). In rabbit, dietary inclusion up to 10% of lentil screening by-product resulted in improved meat traits and serum antioxidant capacity, supporting also gut health (Pugliese et al., 2024a).

Harnessing locally abundant agro-industrial by-products might represent a promising low-cost feed resource for livestock (Berbel and Posadillo, 2018; Habeeb et al., 2017). Recycling this valuable biomass is of great importance in a circular model so as not to lose its valuable nutrient content along with the bioactive compounds (Lu et al., 2022). Furthermore, the inclusion of PBPs into livestock diet, owing to their generally lower price as feed ingredients, enables decreasing the feeding costs, which could possibly help farmers improve their profit margins (Romero-Huelva et al., 2019; Salami et al., 2019). Nonetheless, practical use of agricultural by-products requires attention to the variabilities in the moisture and chemical composition across cultivars, processing methods, and seasonal factors, which may benefit from pre-treatments (i.e., drying or ensiling) that stabilize the nutrient quality and reduce the anti-nutritional effects (Vastolo et al., 2022), thereby increasing their suitability as low-competing feedstuffs (LCFs) within circular livestock production models. Taking advantage of LCFs aligns with the circular bioeconomy objectives by converting otherwise underused biomass into livestock-derived food while diminishing direct competition with human food.

4.2 Nutrient circularity: manure management

Under a circular perspective, the livestock sector may play a vital role in nutrient cycling (McAllister et al., 2025b). Accordingly, through circularization, manure, which is often viewed as a problematic waste product, emerges as a cornerstone resource, and its management has become a crucial component in farming planning (McAllister et al., 2025b). Proper handling of animal excreta allows the recovery of their organic matter contents into safe and valuable resources (i.e., organic fertilizers and biogas), enhancing the overall resource efficiency within the sector (Arsic et al., 2025). In circular livestock systems, the primary aim of manure processing is to close the nutrient loop by recycling macronutrients (mainly N and P) for crop use (Jensen, 2013; Sutton et al., 2022) and, where possible, to recover energy. For instance, conventional composting transforms manure into an organic fertilizer that returns nutrients and carbon to soils (Arsic et al., 2025). Thus, this closed-loop approach enhances nutrient cycling and provides viable opportunities to maintain soil fertility and health, improve long-term crop productivity, minimize the environmental footprint associated with landfilled waste, and potentially generate favorable economic outcomes. Moreover, the circularization of solid and liquid excreta supports the safe reintegration of stabilized materials into agricultural systems, thereby mitigating human, animal, and environmental risks such as biological and chemical hazards, nutrient leaching, antimicrobial resistance, and GHG emissions (Menzi et al., 2010; Arsic et al., 2025).

Manure characteristics are highly variable, dependent on the species (e.g., ruminants, pigs, or poultry), feeding regimes, rearing conditions, and management practices (Leip et al., 2019; FAO, 2024). In particular, the composition and the agronomic value of raw and processed manure are shaped by the considered livestock system as each species differs in nutritional requirements for protein and energy, feed efficiency, and pathways of manure excretion (Leip et al., 2019; FAO, 2024).

Animal manure constitutes a major component of the organic residue streams in the livestock sector (Ramirez et al., 2021). However, the spatial segregation between crop-intensive and livestock-intensive regions generates an uneven distribution of animal waste, creating nutrient-deficient areas and nutrient "hotspots." This, in turn, increases the need for nutrient redistribution and raised costs due to transportation expenses from the production site to the processing or disposal facilities (Jones et al., 2013; Buckwell and Nadeu, 2016; Willems et al., 2016; van Grinsven et al., 2018; Jin et al., 2021; Lorick et al., 2020; Arsic et al., 2025). Consequently, in high-density livestock systems, substantial nutrient surpluses have become concentrated within limited geographical areas, inducing environmental pressures that make manure recycling practices indispensable. The identification and the deployment of cost-effective manure processing technologies that facilitate nutrient redistribution between regions and convert organic waste streams into safe and stable products represent key prerequisites for achieving a circular livestock sector (McCrackin et al., 2018; Lorick et al., 2020). For example, in Australia, the costs of treatment and disposal of solid and liquid wastes from feedlots and red meat processing have been estimated to exceed AU $100–200 million per year. However, implementing circular waste management technologies capable of transforming livestock manure into novel value-added products could generate up to AU $ 140 million in additional revenue (O'Hara et al., 2016; Ramirez et al., 2021).

Manure management comprises the collection, storage, treatment, and utilization steps, all of which help prevent excessive nutrient accumulation or leakage of nutrients in high-animal-density areas and limit GHG and ammonia (NH_3) emissions from manure, protecting surface and groundwater from being polluted with N, P, or other potentially harmful compounds. Furthermore, reducing the pressure on the environment caused by animal organic streams also requires management and prevention of GHG and NH_3 emissions from this waste. These include methane (CH_4) emissions from enteric fermentation and manure management and nitrous oxide (N_2O) emissions from manure storage and the subsequent manure applications to soils or on pasture by grazing animals (Sha et al., 2021). At present, a wide range of technologies have been developed for mitigating GHG and NH_3 emissions from manure management (Chadwick et al., 2011). Among them, upstream technologies include livestock dietary modifications such as modulation of the crude protein or non-starch carbohydrate content in formulated diets (Swensson, 2003; Feilberg and Sommer, 2013; Sutton et al., 2022) and the integration of dietary acidifier to reduce the pH of slurries and urine (Kim et al., 2004; Murphy et al., 2011). In addition, livestock housing conditions are pivotal to reducing emissions. For example, smart barns can decrease emissions, optimizing environmental conditions and promoting air flow while bedding by absorbing urine and increasing the bulk density of manure (Sutton et al., 2022). Notably, increasing the frequency of manure removal or reducing the slurry storage temperatures can lessen NH_3 emissions (Cai et al., 2015).

Traditional methods and novel technologies can significantly reduce GHG and NH_3. *Inter alia*, practices such as acidification; the application of absorbents, biofilters, or urease inhibitors; and the use of bacterial cultures or enzymes can modulate the biodegradability of manure. In particular, certain absorbents such as ammonium salts can retain ammonia, thereby reducing NH_3 emissions and indirectly mitigating N_2O emissions. Recent developments also include physical (e.g., pulse combination drying, air ammonia stripping, and ceramic membrane distillation), chemical (e.g., plasma recovery), and biological technologies (e.g., microalgae and phototrophic purple bacteria) (FAO, 2024). In circular livestock systems, however, the primary objective of manure processing remains the closure of the nutrient loop through the recycling of macronutrients (mainly N and P) in order to make them available for crop uptake (Jensen, 2013; Sutton et al., 2022) or, alternatively, through energy recovery.

Composting represents a key manure management strategy based on the aerobic decomposition of organic matter mediated by diverse microorganisms, primarily bacteria and fungi, which generates sustainable thermal energy and yields compost with suitable agricultural quality (Lin et al., 2018; Pajura, 2024; Valverde-Orozco et al., 2024). In particular, the appropriate regulation of composting parameters can exert a significant hygienic effect on manure by reducing pathogen risk and facilitating the breakdown of chemical contaminants such as antibiotics, pesticides, hormones, and drug residues (Onwosi et al., 2017; Manyi-Loh et al., 2018; Sołowiej et al., 2021; Pajura, 2024). Although this method is relatively inexpensive, it may require considerable land area and, if improperly managed, can lead to GHG emissions or the generation of leachates. These drawbacks can be mitigated through careful composting system design or through the incorporation of physicochemical and biological additives such as biochar, nitrification inhibitors, mineral sorbents, or microbial inoculants (Shan et al., 2021; Zhao et al., 2022).

Precision compost strategies in which suitable composts and application methods are matched with defined crop types and growth environments have been shown to improve crop yield by up to 40% in dry and warm areas and on acidic and sandy soils, thus advancing sustainable food production (Zhao et al., 2022). Several studies have demonstrated that the application of compost enhances soil fertility and health, as well as vegetable quality and productivity. For instance, composted cattle manure has been shown to improve soil fertility by regulating the soil pH and increasing the plant uptake of both macro- and micronutrients (Anwar et al., 2017; Das et al., 2017). Similarly, composted cow manure contributes to soil carbon sequestration; improves the water holding capacity, aeration, and infiltration; and reduces soil compaction and erosion (Xu and Mou, 2016). McClelland et al. (2022) evaluated the effect of cow manure-derived compost amendments on different forage grasses (i.e., alfalfa, brome grass, and orchard grass) and reported a 40% increase in areal biomass in irrigated pastures. In addition, when used as a soil amendment, such composts promote the synthesis of biostimulant compounds involved in plant growth and disease protection, thereby reducing the need for soil and plant pesticides (Das et al., 2017; Pergola et al., 2018a, Pergola et al., 2018b, Pergola et al., 2020; Goldan et al., 2023). Beyond conventional composting, emerging biofertilizer technologies are being developed to support scalable manure management solutions and strengthen circularity within the livestock sector. A particularly innovative approach involves vermicomposting and biochar. Vermicomposting further diversifies manure valorization by employing larvae and earthworms to accelerate the decomposition of organic matter, reduce odors, and potentially inactivate pathogens. In terms of efficiency, vermicomposting has been reported to reduce solid residue volumes by up to 50% while generating both solid (vermicast) and liquid (vermiwash) fractions rich in nutrients that may serve as valuable inputs in animal feed (Raza et al., 2022). Moreover, studies have shown that this organic waste treatment reduces the manure processing time and produces compost with better fertilizing properties with respect to traditional composts (Awasthi et al., 2019; Das et al., 2020; Ddiba et al., 2022; Kumar et al., 2022b). The use of larvae to turn manure into valuable products has shown a wide range of benefits: manure can be converted into safe compost, and larval fat and rearing residues can be used to generate biofuels or to isolate secondary materials such as proteins, lipids, chitin, and chitosan (Arsic et al., 2025), and finally, larvae can be included as an alternative protein feed for livestock (Chia et al., 2021; Duan et al., 2019; Wang et al., 2021) and aquaculture (Čengić-Džomba et al., 2020; Jiang et al., 2019; Awasthi et al., 2022). Lastly, advanced manure processing (ammonia stripping or struvite precipitation) enables the specific recovery of N and P for use as concentrated fertilizers (Taifouris and Martin, 2021).

In circular-based livestock systems, manure management not only provides biofertilizers but also produces renewable energy through the extraction of heat- and manure-based biogas. Currently, the successful adoption of these practices relies on novel circular bioenergy technologies such as advanced biorefinery and thermochemical platforms. These facilities are central to the valorization of manure, transforming organic waste streams into a wide range of high-value products: from biogas and biofuels to bioplastics and biochemicals.

Bioenergy can be produced using manures, processing residues, and wastewaters as inputs (Ramirez et al., 2021). The exothermic activity of microorganisms during composting yields a large quantity of thermal energy, which is typically lost as heat in the environment (Smith et al., 2017). In the wake of the current global energy and climate crises, recovery of this heat may be considered a sustainable method for energy production (Malesani et al., 2021). Heat recovery from composting can be achieved using different methods, one of which is the direct retake of heat from the water vapor generated in the composting process (Smith et al., 2017). Furthermore, suitable technologies such as heat absorption pumps and heat capture or thermoelectric generators enable transforming heat into electricity (Sołowiej et al., 2021).

Anaerobic digestion (AD) represents the most widely used commercial technology for the production of bioenergy from manure. AD is a biological process in which microorganisms break down organic matter under anaerobic conditions to produce biogas primarily composed of CH_4 and CO_2 (Uddin et al., 2021). Microbial fermentation may also be applied on a mixture of manure and other agricultural by-products, optimizing the CH_4 yields in a process called anaerobic co-digestion (AcoD) (Tsapekos et al., 2017). Biogas produced by AD and AcoD may be exploited not only to generate electricity in large industrial farms but also may be sold to smaller, community-scale facilities that serve multiple farms or at the household level in low- and middle-income countries, thus reducing reliance on fossil fuels and making rural communities more self-sufficient and resilient (Rupf et al., 2015). Together with biogas, AD processes result in the production of a nutrient-rich slurry, the digestate, which may be utilized as a biofertilizer or a soil amendment as it contains high N and P concentrations (Lamolinara et al., 2022).

Modern thermochemical processes (e.g., combustion, pyrolysis, gasification, and hydrothermal liquefaction) enables converting manure in heat and electricity. Among these systems, pyrolysis also enables the production of bio-oil and biochar. Notably, biochar has recently emerged as a valuable solution for enhancing circularity in animal husbandry (Kazemi, 2025). This co-product, which is rich in carbon, is investigated for a range of purposes, such as feed supplement, litter and bedding material, and soil amendment. Some biochar products have been promoted as promising soil additives into circular agricultural systems (Joseph et al., 2021). In addition, when combined with dairy cattle manure, biochar improves the soil pH, porosity, water holding capacity, and microbial activity in both semiarid and calcareous soils (Elzobair et al., 2016; Ippolito et al., 2016; Joseph et al., 2021; Romero et al., 2021).

Emerging evidence suggests the potential benefits of the integration of biochar into animal production systems both for improving the soil quality and for animal feed (Romero et al., 2021). There are literature reports on the use of biochar as a feed additive for several livestock species and fish, which may significantly reduce feed costs while improving the overall animal health (Man et al., 2021; Kazemi, 2025). The adsorption ability of biochar is a key feature that makes it effective in livestock production (Farooq et al., 2023). In particular, it enables both enhancement of nutrient availability and reduction of digestive emissions of harmful compounds (Wen et al., 2023). Indeed, dietary integration with biochar was found to improve the growth performance and feed efficiency while mitigating the environmental impacts of manure management by reducing CH_4 and NH_3 emissions (Saleem et al., 2018; Schmidt et al., 2019; Konduri et al., 2024). For example, Bagherpoor et al. (2023) provided proof that the integration of biochar into probiotic-added diets in sheep improved the digestibility and microbial biomass while reducing the methane and ammonia production. On the other hand, in poultry, biochar was found to retain nitrogenous compounds in the digestive tract and improve the nitrogen utilization efficiency while reducing nitrogen emissions, contributing to environmental sustainability (Prasai et al., 2018).

The management of livestock manure occupies a pivotal position in the transition from linear to circular agrifood systems as it simultaneously influences GHG emissions, nutrient balance, soil health, and the economic viability of farms. Manure constitutes both a source of pollution and a means for resource recovery, and its proper management can extend benefits beyond the farm level to the regional and national scales (FAO, 2025b).

At the farm level, the type of practice (i.e., composting and AD) influences the quantity of emissions and pathogen loads that are released into the surrounding environment (Leip et al., 2019). From a system-wide perspective, their cumulative positive effect may become evident in global nutrient balance, the demand for synthetic fertilizers, and the general resilience of the agrifood sector. However, from the sanitary point of view, inadequate treatment may fail to inactivate pathogens (e.g., *Salmonella* or *Escherichia coli*), and zoonotic agents harbored in manure may be transmitted to crops or grazing animals, posing animal and human health hazards and thereby jeopardizing public health (Jensen, 2013; FAO, 2025a). Thus, consistent monitoring protocols and compliance with regulatory standards (e.g., EU Regulation 1069/2009) are required to ensure biosecurity.

The application of manure for the recycling of nutrients has been shown to reduce fertilizer use (Fang et al., 2023) and decrease the need for additional arable land to produce mineral fertilizers, mitigating land use change and biodiversity loss (Van Zanten et al., 2018). On the other hand, AD generates organic amendments and can reduce emissions while generating biogas that displaces fossil-derived energy as manure-derived biogas may contribute to national decarbonization targets (Ghisellini et al., 2016). Nevertheless, despite supporting soil carbon sequestration and soil microbial activity, the improper application of digestate or compost can increase ammonia volatilization or lead to N leaching and P accumulation, exacerbating eutrophication of aquatic ecosystems (Gerber et al., 2013; Romero et al., 2021; Shan et al., 2021). Hence, decision support tools and site-specific nutrient recommendations are therefore essential to align the application rates with the crop demand (Ward et al., 2016; Fang et al., 2023).

International guidelines (e.g., EU Regulation 1069/2009) and national strategies increasingly incentivize circular nutrient practices to encourage the adoption of integrated manure management systems that combine nutrient recycling, emission reduction, and energy recovery (FAO, 2024; WBCSD, 2019). Thus, the assessment of each manure management pathway must balance the agronomic benefits with potential environmental trade-offs, considering the local climate, soil type, and the existing nutrient budget. Following the application of circular manure management strategies, the livestock sector can transform manure from an environmental liability into a multifunctional resource able to close nutrient loops, reduce GHG footprints, and enhance the overall farm sustainability.

4.3 Animal by-product valorization

The processing of animal-based food such as meat, milk, or eggs for human consumption inevitably yields million of tonnes of ABPs along the European food supply chain (EFPRA, 2023). Fostering the adoption of a circular bioeconomy model in the agrifood sector means encountering solutions to fully exploit the potential of this biomass by harnessing them to generate added value. This could lead to new potential income revenues, reduce the disposal rates, and encourage the upcycling of by-products, in turn favoring economic growth and sustainable development (Lee et al., 2025). Regardless, improper handling of ABPs poses severe hazards to the environment and public health. For instance, the outbreak of food-borne diseases, such as bovine spongiform encephalopathy (BSE), resulted in Regulation (EC) 1774/2002, and subsequent modifications, to limit the use of some ABPs, such as meat and bone meals (Reg. EC 1069/2009). An ABP is considered safe only following specific inspections to rule out contamination hazards, which might negatively affect all derived products (Milani et al., 2011; Lynch et al., 2017). According to the current regulation, ABPs are classified into three risk categories with descending risk rates, in turn affecting the handling, storage, and processing procedures. The higher-risk category (category 1) requires incineration with no possibility of recovery. Remarkably, as confirmed in scientific surveys, advanced rendering techniques have led to modifications of their regulation, such as a change in the risk category or the readmission of the use of certain ABPs. For example, while the use of ruminant-derived ABPs is restricted to only pet food, pig- and poultry-derived meals are allowed as livestock feed, including aquafeed; however, the ban on intraspecies consumption still remains (Woodgate et al., 2022; Lee et al., 2025).

In the meat industry, carcass processing by-products are categorized as edible (offal), the major share, or non-edible parts (i.e., hooves, feathers, and blood) (Alao et al., 2017). Strictness of the regulation with regard to ABP use as fertilizers or animal feed has hindered the recovery of nutrients from this biomass, urging researchers to discover new opportunities for safe alternative recovery paths (Buckwell and Nadeu, 2016). Identifying alternative methods to retrieve value from ABPs perfectly fits the circular bioeconomy concept and supports their reallocation from the waste stream to the valuable resource flow (Lee et al., 2025). Moreover, increasing operational costs and the need to minimize waste generation have also triggered an increased trend in investigating new processes to retrieve the most value from carcass in order to boost efficiency and economic returns (Drummond et al., 2019; Ramirez et al., 2021). Offal, an edible by-product, represents a rich source of key nutrients (e.g., minerals, vitamins, and essential amino acids) and a traditional gastronomic speciality in several countries (Nollet and Toldra, 2011). Moreover, the promotion of offal consumption may be a crucial strategy in supporting the nutritional requirements of vulnerable individuals, especially within developing countries, also supporting Goal 2 (Zero Hunger) of the SDGs (Fayemi et al., 2018).

With regard to the inedible parts, their repurposing allows reducing waste generation, following circular principles. Production and tanning of leather for garment manufacturing, for example, represents a longstanding human method of recovering animal hide (Alao et al., 2017). In addition to its traditional use as stuffing material, feathers can be processed to obtain energy or undergo hydrolysis for use as feed (Alao et al., 2017). Novel processes allow the conversion of by-products into more valuable ones (Lee et al., 2025). For example, collagen, which is typically used in gelatine production, has been recently evaluated as a recovery medium for bioactive peptides to supplement animal feed (Drummond et al., 2019). On the other hand, wool, feathers, and hooves are keratin-rich ABPs; thus, their disposal might be prevented, leveraging them as natural sources of this molecule for cosmetic or biomedical applications (Sharma and Gupta, 2016; Enciso-Tenorio et al., 2025). Various human and veterinary medicinal products such as hormones and enzymes can be sourced from inedible ABPs, as in the case of the anticoagulant heparin, which is retrieved from livestock mucosal tissues (Middeldorp, 2008; Marti et al., 2012; Lee et al., 2025). As for blood, there are numerous techniques able to separate the different fractions and obtain products with several distinct pharmaceutical applications, serving as a source of bovine serum albumin or other molecules involved in blood clotting or employed as a cell culture medium (Lee et al., 2025). Otherwise, blood can be converted into fertilizer or animal feed as blood meal (Lynch et al., 2017).

A circular model in line with the waste hierarchy model should be preferred to maintain the value of an ABP within its source sector (Lee et al., 2025). In this way, prioritizing the rendering of inedible ABPs into livestock feed fosters circularity, fulfilling four key functions: to close the nutrient loop, to reintroduce valuable nutrients within the food chain, to replace vegetable or mineral nutrient sources, and to reduce feed costs (Azarkamand et al., 2024; Lee et al., 2025). Owing to their valuable nutrient profiles and high-biological-value proteins, meat and bone meal are still widely adopted as livestock feed outside of Europe (Alao et al., 2017; Leiva et al., 2018). On the other hand, following BSE outbreak, Europe has banned their use to prevent public health implications (Leoci, 2014). However, in accordance with new scientific evidence, amendments of Regulation 1069/2009 readmitted the conversion of ABPs to formulate a safe feed suitable for monogastric animals and aquaculture (Leiva et al., 2018; Ramirez et al., 2021; Woodgate et al., 2022; Lee et al., 2025). Aside from protein, ABPs also represent a rich source of minerals, which play pivotal roles in skeletal development, nervous signal transmission, and animal production. In laying hens' diet, the inclusion of meat and bone meal as substitute inorganic mineral sources resulted in improved eggshell quality parameters (Bozkurt et al., 2004). However, when employed as feed, the inclusion rate has to be carefully considered in order to avoid formulating unbalanced diets that could affect the health and productivity of animals (Solà-Oriol et al., 2011). In the pet food sector, ABPs are either used as treats or for diet formulations. For instance, they are typically employed to provide functional ingredients or essential nutrients (i.e., taurine in cat species) that are lacking in vegetables (Boskot, 2009; Martínez-Alvarez et al., 2015; Bampidis et al., 2023).

Another promising but inexpensive feedstuff analyzed for inclusion into different livestock species diets is the undigested rumen content, i.e., rumen digesta, supplemented alone or in combination with dried blood (Togun et al., 2009; Esonu et al., 2011; Mohammed et al., 2011; Mondal et al., 2013; Alao et al., 2017). In poultry and rabbit, 30% dietary inclusion of a mixture of rumen digesta and dried blood has been proven to enhance productive traits and boost economic rentability while reducing feed costs (Togun et al., 2009; Esonu et al., 2011; Mohammed et al., 2011; Mishra et al., 2015).

As a brief dive into aquaculture, carnivorous farmed fish diet highly relies on fishmeal and fish oil as feed obtained from wild fish stocks (Oliva-Teles et al., 2015). For this reason, recent investigations into aquafeed delved into suitable, safe, and more sustainable alternatives to replace the low-economic-return feedstuffs (Cottrell et al., 2020). Here, the inclusion of ABPs might serve the sector's need to enhance both profitability and sustainability with possible practical applications (Woodgate et al., 2022).

Other upcycling opportunities to recover inedible ABPs, one part for use as feed, include processing and safely reusing as soil amendment or conversion into biogas (McCabe et al., 2016, McCabe et al., 2020; Alao et al., 2017; Ramirez et al., 2021). Technological advances in rendering techniques, e.g., aerobic and

AD, paved the way to recovering value from this waste and limiting the dependence on synthetic fertilizers and fossil fuel. Energy and biofuel production from ABPs might ultimately decrease GHG emissions and enable cost reductions, in particular if employed to fuel on-farm requirements or animal processing facilities (Ramirez et al., 2021; O'Hara et al., 2016; Fredheim et al., 2017).

For the meat industry, dairy manufacturing also implies a significant number of by-products (dairy by-products, DBPs) that stand as environmental hazards if not properly treated (Milani et al., 2011; Carvalho et al., 2013). The sheer volumes produced, combined with the favorable composition of DBPs, makes systematic valorization both an environmental priority and an economic opportunity (Yadav et al., 2015; Meo Zilio and Vasmara, 2025). Direct disposal of DBPs could pose environmental concerns for soil and water pollution owing to the high biological and chemical oxygen demand (BOD and COD, respectively) associated with their organic contents (Yadav et al., 2015; Mann et al., 2019). The lack of technological investments and the distance between dairy manufacturing and DBP-exploiting industries impact on the capacity of local wastewater treatment plants and on the overall transformation costs, possibly explaining the limited reuse rates among cheese producers (Milani et al., 2011; Trindade et al., 2019; Pires et al., 2021b).

Cheese whey (CW), the primary milk-based by-product, is a yellowish liquid that still retains a portion of the milk components or solids, with possible further applications for human or livestock (Meo Zilio and Vasmara, 2025). The composition of CW is variable and is dependent on the milk origin and its processing flow. Within some productive realities, CW is considered a co-product processed to make whey cheeses (i.e., Ricotta in Italy), a solution to recovering value from this discarded fraction (Pires et al., 2021a, Pires et al., 2021b; Meo Zilio and Vasmara, 2025). Following whey cheese production, another by-product, i.e., second cheese whey (SCW), still remains. The recovery or reuse of this DPB is still under investigation (Pires et al., 2021a; Fancello et al., 2024). Nevertheless, recent research delving into possible recovery options detailed the peptide profile of SCW, pointing out its health-supporting properties and its value in the production of functional foods (Sommella et al., 2016).

Both CW and SCW are rich in denatured proteins, soluble peptides, oligosaccharides, lactose, minerals, vitamins, and free amino acids, providing a natural matrix of essential nutrients and functional compounds that can be recovered or transformed into higher-value products (Olvera-Rosales et al., 2023; Kilic, 2024). These components have documented functional properties hinting at their use as nutraceuticals (Olvera-Rosales et al., 2023; Santa and Srbinovska, 2023). Whey-derived bioactive peptides exhibit anti-hypertensive, antioxidant, and antimicrobial activities (Brandelli et al., 2015), while the non-digestible oligosaccharides act as dietary fibers and prebiotics, supporting gut health (Santa and Srbinovska, 2023). Due to this compositional richness, DBPs are also widely used as livestock feed; however, the organic load also makes them an attractive substrate for biotechnological processes to yield biofuels (Carvalho et al., 2013; Osorio-Gonzalez et al., 2022). Leveraging these attributes enables their valorization, reducing environmental disposal concerns and expanding its application spectrum from feed supplementation to innovative food formulations and bioproducts (Pires et al., 2021b).

Before increased awareness of the potential health-promoting value of CW and SCW (Sommella et al., 2016; Mann et al., 2019), these have been used as animal feed or dismissed as waste. However, extensive feeding of some DBPs to livestock is not always feasible owing to the high lactose content, affecting animals' digestive tracts (Maragkoudakis et al., 2016). With proximity between cheese plants and farms, DBP use either as a feed or as a partial replacement for drinking water has been proven practicable for small traditional farms as the minimal handling only requires lower disposal costs and reduces the environmental footprint of the dairy supply chain (Lutz et al., 2017; Palmieri et al., 2017).

Some other recovery routes for DBPs involve medium- and high-technology solutions based on concentration, separation, and bioconversion (Ahmad et al., 2019; Fancello et al., 2024). Whey-based products are largely adopted as additives within the food industry owing to their technological properties and nutritive value (Mann et al., 2019). For example, lactose recovered from DBPs can be refined to food-grade status and used in infant formula or, alternatively, can be used as a microbial fermentation medium (Sar et al., 2022). Bencresciuto et al. (2024), for example, produced biodiesel that meets the quality standard requirements by aerobic fermentation of lactose from SCW. In addition, to provide a comprehensive overview of the dairy industry wastes, cheese whey wastewater (CWW) has to be mentioned as well (Carvalho et al., 2013). CWW is composed of a mixture of the water employed in the production flow and post-manufacturing cleaning with milk or other DBPs. For this reason, similarly for CW and SCW, several handling procedures allow recovery of CWW, further easing environmental pressure (Carvalho et al., 2013; Tugume et al., 2025). Among the biological treatments for CWW, aerobic or AD represents the most common solution applied for its depuration, further providing biomethane from organic acid fermentation (Yang et al., 2003; Rivas et al., 2010, Rivas et al., 2011; Carvalho et al., 2013) and digestate, which can then be pyrolyzed to produce biochar. This represents a valuable carbon and nutrient source with diverse applications, *inter alia*, soil amendment and carbon sequestration (Tugume et al., 2025). AD demonstrates high detoxification rates, although, in the case of elevated starting values, are still not adequate to fulfill the legal dumping limits (Yang et al., 2003). In this regard, two-step processes have been proven superior over the single-step AD, in CWW management (Yang et al., 2003). Aerobic digestion is considered inferior compared with anaerobic processes owing to its longer operation period, lower COD removal, and its extensive sludge production (Carvalho et al., 2013), despite both being resolved by pre-treating CWW. Moreover, these same authors reported how treated CWW-derived sludge could be used as agricultural fertilizer, with careful consideration of the high salinity, hence preferred for saline-tolerant crops.

Similar to the above categories, the production of eggs for human consumption also implies huge quantities of wastes. In fact, around 10% of an egg's weight is accounted for by the shell and inner membrane, which are not intended for consumption and represent the discarded parts (Rosaiah et al., 2024). Furthermore, infertile eggs constitute a by-product of the egg hatchery industry (Suprayogi et al., 2025). In a favorable circular agrifood framework, the valorization of this biomass is crucial to reducing the environmental burden of waste landfilling, in addition to creating new revenue opportunities (Younas et al., 2025).

In poultry nutrition, upcycling of infertile eggs can partially replace soybean meal in feed composition, serving both to reduce reliance in this feedstuff and to decrease the costs of poultry rations (Suprayogi et al., 2025). In fact, in broilers, up to 6% inclusion effectively enhanced the final body weight and ameliorated the meat lipid profile in α-linolenic acid content (Suprayogi et al., 2025). This recovery solution contributes to adding value to a hatchery by-product, turning a disposal problem into a feed resource, which supports sustainable and circular poultry production by recycling nutrients back into the food chain.

Given the large ash content of eggshell (>90%), egg waste can represent a source of mineral, mainly calcium, phosphorous, and other micronutrients (Ray et al., 2017), with useful applications such as fertilizers for crops (Wijaya, 2019) or dietary supplements for both humans and animals (Waheed et al., 2019). Powdered eggshell applied as a fertilizer improves the soil acidity and provides crops with soluble calcium to foster nutrient uptake; otherwise, it can be coupled with an organic matter source to formulate a slow-release fertilizer to supply crops with both calcium and carbon and to reduce leaching losses (Dayanidhi and Sheik, 2021). Adequate daily uptake of minerals is pivotal in maintaining general health and controlling bone degeneration (Bourassa et al., 2022). As an example, it was found that consuming less than 3 g of eggshell can almost meet the daily calcium requirement (Milbradt et al., 2015) and eventually provide trace minerals, which have been found to counteract osteoporosis (Szeleszczuk et al., 2015). Lastly, the bioavailability of calcium in eggshells is superior to that of other sources, hence its widespread adoption in the biofortification of several food categories to boost dietary mineral intake and combat nutrient deficiencies (Gómez-Alvarez and Montoya, 2024; Younas et al., 2025).

Alternative upcycling paths for eggshell and egg membrane involve their processing for the production of biofuel or, alternatively, as soil and water decontamination tools (Younas et al., 2025). Its calcium carbonate content makes eggshell a valid catalyst driver for biodiesel transesterification (Rajak et al., 2025). In the same way, the calcium carbonate content was successfully employed as an adsorbent for phosphates in a 1:1 combination with rice straw from groundwater, proving its ability to eliminate such pollutants (Lunge et al., 2012). More recently, research on egg waste recycling investigated its conversion into functional materials for thermal energy storage, composite fillers, and precursors for calcium-based compounds, showing technical feasibility for recovery (Ben Aribia et al., 2024; Rosaiah et al., 2024). Eggshell powder can function as a filler in polymers [polyethylene glycol, polypropylene (PP), polylactic acid (PLA), and epoxy] and as a phase change composite matrix (e.g., polyethylene glycol/$CaCO_3$), improving both the thermal stability and the mechanical stiffness. For example, cleaned eggshell powder can be mixed with polymer matrix in thermal energy storage panels or used as a biodegradable polymer composite for packaging (Ben Aribia et al., 2024). Indeed, eggshell could serve as a renewable material in the development of energy storage and conversion tools, which may facilitate the much-needed transition to sustainable energy sources (Rosaiah et al., 2024).

5 Conclusions

Within this review paper, the feasibility for the agrifood, in particular livestock, sector to shift toward a circular bioeconomy model was outlined. Adherence to the principles of circularity could lead to: i) the reduction of the waste generation rates by recycling, either within the same productive process or allowing their transformation as value-added products in other fields (e.g., medical, pharmaceutical, or industrial) and ii) the recovery of the wasted biomass, entailing reduced environmental degradation (GHG emissions, biodiversity loss, and feed–food competition) and decreased reliance on non-renewable resource extraction. This might yield an increased environmental, economic, and social sustainability of the agrifood sector through reduced environmental impact, potential increase of the profitability level, and an enhanced resilience of the sector to improve food security within a rising global population framework. Efficient resource use, nutrient circularization, and ABP valorization constitute the cornerstone of circular livestock systems. Their successful deployment requires careful assessment of the environmental, health, and economic risks, complemented by the exploitation of synergistic benefits such as nutrient recycling, soil improvement, and renewable energy production. The integration of different strategies (e.g., LCF use, precision feeding, and manure management) and robust regulatory support could aid in the sector limiting environmental degradation and nutrient leaching and generating valuable co-products that reinforce farms' profitability and broader sustainability targets. Nevertheless, careful attention to the application rates, pathogen control, economic feasibility, and life cycle accounting is necessary to ensure that the transition yields net environmental and social benefits, helping with the scores of several SDGs. In conclusion, both scientific- and field-based studies have provided strong evidence that the introduction of circular farming practices may be considered a central node to ensure the sustainable growth of the food sector and to address the global challenge of food security by ensuring the efficient use of environmental resources such as nutrients, water, and land, closing the nutrient loop and valorizing ABPs.

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– review & editing. VL: Writing – review & editing, Writing – original draft. AT: Writing – review & editing. LPi: Writing – review & editing. MD: Writing – original draft. SL: Writing – review & editing. VT: Writing – review & editing, Writing – original draft. CL: Writing – review & editing, Writing – original draft.

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