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The future of protein sources in livestock feeds: implications for sustainability and food safety

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The feed-food competition for environmental and economic resources raises increasing concerns about the production and supply of protein for the global livestock sector. Risks to food-security and approaching deadlines for global sustainable development, means exploring alternative protein feed ingredients is imperative. This *Review* discusses the potential for soilless, local and circular protein feed sources to provide solutions for key sustainability and food-security threats to the global livestock sector, through their partial incorporation in future livestock feeds and feeding systems. In doing so, it offers a holistic insight into the potential opportunities, but also risks associated with such alternatives. Through this analysis, a four-point strategic plan is synthesized to facilitate higher-level policy making that may enable implementation of these alternative ingredients at commercial scales, building toward a more sustainable and resilient livestock industry.

KEYWORDS
alternative protein sources, cellular agriculture, circular agriculture, environmental impact, food policy, food safety, soya production, sustainable development

1. Introduction

Animal-sourced foods, including livestock products are generally considered protein-rich and essential for human nutrition due to their enhanced bioavailability of many beneficial nutrients and superior protein quality (Leroy et al., 2022). Sustainable livestock systems are essential to human and planetary existence, helping secure full human growth especially in areas where fortification and/or supplementation is not feasible, as well as ensuring management of lands and conservation of agricultural biodiversity (Robinson et al., 2011).

However, significant concerns have been raised regarding the efficiency of resource use and environmental impacts of conventional livestock production systems, particularly considering the feed-food competition for land and energy resources (Ertl et al., 2016). For this reason, the future of livestock feeds is of major concern to all stakeholders of the agri-food system, including policy makers, industry, regulatory authorities, and consumers (Makkar, 2018; Gurgel et al., 2021). The conversations around the feed-food competition for resources have become particularly relevant in recent years, considering planet limited biophysical capacity and uncertainties associated with macroeconomic, geopolitical, and socioeconomic developments that threaten feed availability and food-security; such uncertainties include the on-going Ukraine-Russia conflict, Brexit, disparity in household incomes experienced globally, inflation, and energy shortages (van Hal et al., 2019). Emphasis has been given on soy production, which constitutes one of the major sources of protein for livestock. Governmental authorities, non-governmental organizations and policy makers globally acknowledge the potentially damaging effects of soy production on endangered ecosystems (e.g., the Cerrado) and local rural communities (Cabezas et al., 2019; Kusumaningtyas and van Gelder, 2019). Such impacts may become relevant for other conventional protein crops too that are widely used as livestock feed protein sources and take up to 15% of the animal diet compositions, such as oilseed crops (e.g., sunflower seed, rapeseed), particularly considering the global demand for sustainable intensification of livestock production (Ben Hassen and El Bilali, 2022). Furthermore, increases in adoption of plant-based diets by humans is expected to intensify land-related feed-food competition and unintended negative sustainability impacts associated with protein crops even in countries with established boundaries for arable land (e.g., USA) (de Visser et al., 2014; US Soybean Export Council, 2018).

In this *Review*, we call for a focused discussion regarding the diversification of protein sources in livestock feeds as imperative to reducing the production of unsustainable production of protein crops. We propose the exploration of a partial substitution of soy in feeds by soilless, local and circular alternatives, that could cover livestock nutritional needs while addressing key sustainability issues and securing food safety. To facilitate future discussions regarding their implementation and because it is not always possible to discuss in too much detail the potential differences between variations of alternatives (e.g., comparing between the effectiveness of different microalgae species), we classify the alternatives in a systematic way that aligns with literature and represents the four protein production systems that have been investigated in most depth:

Alternative plant-based sources and crop growing methods: representing genetically modified/edited crops (GM/GE), local/home-grown crops (e.g., legumes), hydroponics, and seaweed farming:

i. Cellular agriculture: representing protein extraction at a microscopic level from bacterial, fungal and micro-algal organisms.
ii. Circular agriculture: representing protein sourcing from processed food wastes (e.g., restaurants, hotels, retailers), former foods (e.g., bakery and confectionery) and by-products of other industries (e.g., brewing, biofuel).
iii. Animal by-products: representing the sourcing of Processed Animal Proteins (PAPs) from swine, poultry and ruminant by-products or from insect farming.

This *Review* provides a lens into the opportunities that such alternatives present to relieve pressures of the feed-food competition across the three sustainability pillars, as defined in the global sustainable development goals of the United Nations (UN) and the Food and Agriculture Organization (FAO) (Food and Agriculture Organization, 2014; United Nations Department of Economic and Social Affairs Sustainable Development, 2022). We address economic and social implications separately and not as socio-economic, while acknowledging the significance of their interrelations throughout. Furthermore, we address issues of animal health and welfare within the social pillar of sustainability, as proposed by recent research and policies regarding sustainability of livestock production systems (European Commission, 2017; Tallentire et al., 2019). Finally, we present emerging threats and risks associated with the implementation of alternative protein sources to synthesize pragmatic recommendations for a guided conversation and actions toward sustainable livestock diets. While this *Review* briefly discusses issues of scalability, it is our position that the potential sustainability implications and trade-offs of alternative protein feeds need to be resolved through future research that overcomes significant primary data limitations, prior to discussions regarding their implementation at large scales.

1.1. The problem of unsustainable protein sourcing in livestock feeds

The majority of global livestock production systems rely heavily on unsustainable, plant-based sources to cover the needs for protein in livestock nutrition, the most common of which is soybean meals (Food and Agriculture Organization, 2018). The production of conventional protein crops and soy in particular is directly linked to negative environmental impacts including land degradation and deforestation, fossil fuel depletion, atmospheric pollution and global warming, acidification and eutrophication, and negative impacts to biodiversity (Semper-Pascual et al., 2019; Andretta et al., 2021; Song et al., 2021). Moreover, the production of protein crops at large scales requires large financial investments mainly associated with synthetic and chemical inputs (e.g., fertilizers, pesticides, herbicides), labor, fossil fuel, and land (e.g., rent) (Food and Agriculture Organization, 2016). Until now, these agri-environmental issues were associated primarily with the production of soy, however an uncontrolled intensification of other types of oilseed crop production to meet global livestock sector and human food requirements may raise similar concerns (Henchion et al., 2017). Therefore, the current and emerging sustainability related issues discussed in this *Review* should not be viewed as specific to soy production, but rather as potential implications related to conventional protein crop production more broadly.

From an economic perspective, importing and transporting protein feeds over long distances, for example importing soy from South-America to support European livestock production, incurs significant costs and risks especially considering the instabilities in global trading dynamics and volatility of fossil fuel prices (Taghizadeh-Hesary et al., 2019). Considering the social domain, production of conventional protein crops for livestock feed threatens availability of land for food and water resources suitable for human consumption, reduces quality of ecosystem services, and often threatens food safety through accumulation of hazardous chemical contaminants (Figure 1A).

2. Opportunities for sustainability enhancement

2.1. Environmental

Shifting from conventional soy production to local, home-grown protein crops can help reduce land-related environmental pressures in high-risk regions of the global South (i.e., Latin America, Central Africa, Indonesia and Southeast Asia) by up to 11 times (Sasu-Boakye et al., 2014; Stévant et al., 2017). For example, fava beans, peas or lucerne (alfalfa) grown in Western Europe could substitute quantities of imported soy from South-America. Using well-established

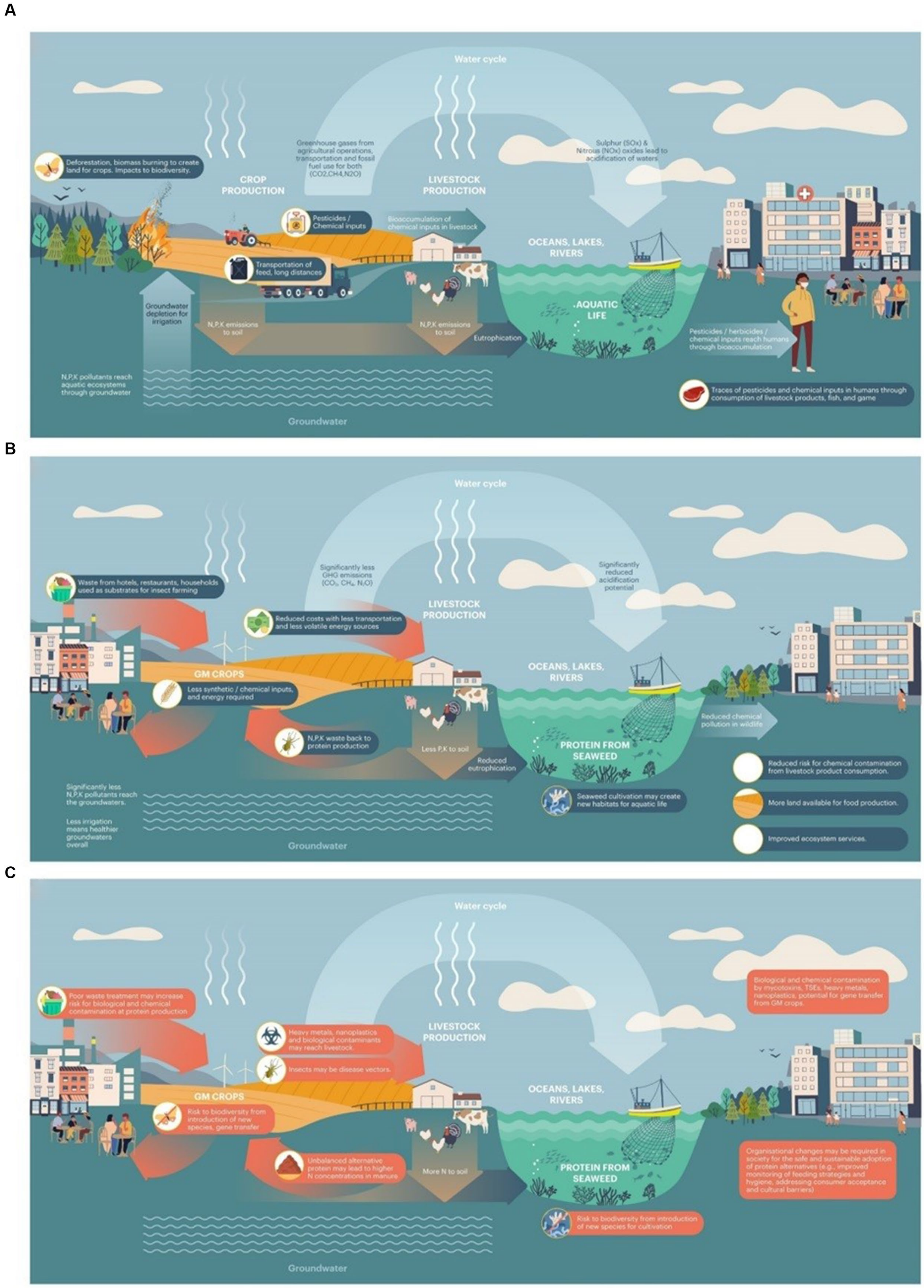

FIGURE 1
Sustainability implications of protein crop production for livestock feeds under different protein sourcing scenarios. **(A)** Conventional crop protein production with associated emissions to atmosphere, soil and aquatic ecosystems and socioeconomic impacts. **(B)** Potential opportunities for sustainability enhancement associated with the incorporation of alternative protein ingredients in livestock feeds at commercial scales, such as protein from insects reared on waste substrates and from farmed seaweed. **(C)** Potential risks to sustainability, such as biological and chemical threats to feed and food safety and threats to biodiversity.

databases, we compared through life cycle analysis the production and transportation of 1 ton of soy imported in a French livestock system from Brazil, against the production of 1 ton of lucerne produced and used within France (Agribalyse, 2022). The results showed that lucerne feed was associated with up to 95% lower impact potential for global warming, 63% for land-use, 97% for freshwater eutrophication and 98% for acidification (for methodological details, see Supplementary material; Agribalyse, 2022). Climate change scenarios project that even major soy producers of the North may suffer yield reductions in the future (e.g., U.S soy 86–92% reduction by 2050), further highlighting a need to diversify protein sources with other local crops (Cordeiro et al., 2019; Yu et al., 2021). Local protein crop production can also help mitigate environmental impacts associated with packaging and transportation of feeds over long distances (e.g., cross-Atlantic), reducing approximately 10% of feed production's total environmental footprint (Figure 1B; Taelman et al., 2015; Herrero et al., 2016).

In addition to shifting to alternative protein crops, incorporating GM/GE climate-resilient variants of soy or other oilseed crops may help improve resource efficiency in protein feed production (28% less fossil fuel and renewable energy) and reduce negative impacts, including global warming potential by up to 28% and freshwater toxicity and eutrophication by 72 and 51%, respectively (Alig and Ahearn, 2017; Eriksson et al., 2018; Paiva et al., 2020).

Protein production from alternative cultivation methods, such as seaweed (macroalgae) farming and hydroponics, may have close-to-zero requirements regarding land and water (Parsons et al., 2019; Koesling et al., 2021) and require 74–100% less fossil-fuel compared to conventional soy production (Stévant et al., 2017). Such alternatives also make minimal use of synthetic and chemical fertilizers, the production and use of which accounts for up to 95% of the environmental footprint of conventional crop production for impacts including aquatic acidification and eutrophication, and land transformation (Niero et al., 2015; Paul et al., 2018; Chen et al., 2020).

Cellular agriculture within the livestock feed production context, is defined by the use of cell-culturing biotechnologies to produce protein feeds from bacterial, fungal, or micro-algal cellular organisms. Widely used examples of cellular protein sources include yeast protein (*Saccharomyces cerevisiae*), protein from filamentous fungi (*Fusarium graminearum*), and protein from methane eating bacterial (*Methylophilus methylotrophus*). It requires facilities that occupy primarily urban land (e.g., laboratories, vertical farms) and therefore can help free-up large areas of arable land depending on the amounts of soy or other oilseed crops that cellular protein substitutes, while largely minimizing impacts associated with transportation of protein feeds, since they can be located close to feed manufacturers and transport hubs. Protein extraction from yeast, for example, is associated with 71% lower land-use related impacts, 34% lower global warming potential, and 67% lower eutrophication potential (Agribalyse, 2022). Furthermore, cellular-protein extraction facilities use electricity for their operations, which can be sourced more sustainably than fossil fuel used for conventional soy production. With advancements in the renewable energy sector, the environmental impacts of cellular agriculture can be minimized further, since currently the production of electricity accounts for 83–94% of global warming potential, freshwater eutrophication and terrestrial acidification associated with its implementation at large scales (Kobayashi et al., 2022).

Environmental benefits of circular agriculture approaches may hold even more potential than cellular protein. Generating protein feeds from food waste, former foods and industry by-products not only bypasses the need for arable land, but also reduces land requirements for waste disposal. For example, sourcing 1 ton of bread or biscuit meal from food waste does not involve land-use (zero impact). Moreover, depending on the treatment method of waste streams, these alternatives can generate up to 99% less global warming and acidification related emissions, and have up to 83% lower eutrophication potential compared to soy (Agribalyse, 2022). On a system level, incorporating food waste in feeds for European pork production could reduce its overall land footprint by approximately 21% and the greenhouse gases associated with relevant protein feed production by almost 12 times (Zu Ermgassen et al., 2016; Dou et al., 2018).

PAPs from insects present another environmentally sustainable alternative compared to conventional protein sources. Currently, the production and use of seven insect species (*Musca domestica*, *Alphitobius diaperinus*, *Hermetia illucens*, *Gryllodes sigillatus*, *Gryllus assimilis*, *Tenebrio molitor*, and *Acheta domesticus*) has been explored in-depth and legally enabled in the EU for commercial exploitation in farmed fish feeds and pet feeds (Madau et al., 2020). However, the commercial implementation of insect meals at much larger scales to support global livestock production requires further research to optimize mass rearing processes (Madau et al., 2020). Insect farming relies almost exclusively on energy that can be sourced renewably (i.e., electricity as opposed to diesel), therefore significantly reducing the energy footprint of livestock protein feeds (Asdrubali et al., 2015; Madau et al., 2020). Furthermore, it can reduce land-use related impacts by 98% and GHG emissions by 60% when compared to soy and other conventional protein meals (Figure 1B; van Zanten et al., 2015; van Huis and Oonincx, 2017; Smetana et al., 2021). Using waste streams (e.g., manure) to rear insects mitigates unintended impacts from waste disposal systems, further reducing eutrophication and acidification of ecosystems, and impacts on biodiversity (Zheng et al., 2019; Gao et al., 2021). Such strategies can reduce total nitrogen related emissions from livestock systems by up to 62% (Figure 1B; Elahi et al., 2022).

PAPs from swine and poultry by-products can achieve comparable environmental performance with insect meals (Parker, 2018). An important factor that may affect the environmental benefits of such alternatives is whether they are obtained from the slaughterhouse (as animal by-products) or retailers (e.g., market's butcher, as food waste), due to packaging and transportation related emissions. For example, animal fat meals at the retailer are associated with up to 82% lower global warming potential compared to soy, whereas obtaining them at slaughterhouse can achieve up to 95% lower impact (Agribalyse, 2022).

2.2. Economic

Circular and local protein sourcing can significantly drive production and lower supply costs. Large reductions can be achieved immediately by minimizing the use of costly inputs used in conventional protein crops, such as fertilizers, irrigation water, pesticides/herbicides and fossil fuel (Kumar et al., 2020). Localizing and diversifying protein can help reduce transportation costs if more protein feeds are produced closer to the receiving markets or to transportation hubs (Lo et al., 2021). Because circular and soilless alternatives are less affected by the volatility of fossil fuel and synthetic input prices, they may offer relative stability for the global livestock feed market and help secure availability of feed worldwide (Lioutas and Charatsari, 2021).

Coupling local protein production with local energy sources may allow governmental authorities to gain better control over the input requirements for production and market needs of the livestock feed sector. Shifting from imported fossil fuel to local renewable energy for protein production may present a viable and more resilient future pathway for future feeds (Punzi, 2019). Furthermore, diversifying protein sources may also help avoid incidents where feed producers shift to more profitable alternatives for their land (e.g., energy crops for biofuel) in times of crises, therefore leading to a more robust livestock sector overall (United States Department of Agriculture, Foreign Agricultural Service, 2022). All these are important opportunities for economic viability of the industry, especially considering the uncertainties in on-going global trading dynamics (e.g., Brexit) and geopolitical developments (e.g., Ukraine-Russia conflict) (Taghizadeh-Hesary et al., 2019; Choi et al., 2021; Yao et al., 2021; Schiffling and Valantasis Kanellos, 2022).

While current literature identifies large gaps and uncertainties regarding the economic inputs and outputs associated with alternative protein feed production (e.g., economies of scale in mass insect rearing of different species, recycled food waste streams), some evidence points toward their economic viability and profitability (Shurson, 2020; Niyonsaba et al., 2021; Rzymski et al., 2021). A number of studies also suggests that future advancements in biotechnology may further increase cost-effectiveness through synergies between waste streams of industries that can be used as resources for protein production (e.g., food waste from restaurants, former foods from bakery, manure from livestock) (Ritala et al., 2017; Jones et al., 2020).

Furthermore, the Covid-19 pandemic has raised awareness about the investment in developing automation technologies and has driven advancements in treatment practices that eliminate the risks of pathogen and disease dispersal, which may drive growth, increasing acceptance and popularity of circular alternatives (Henry, 2020).

2.3. Social

Social sustainability in the context of sustainable livestock production commonly refers to potential issues associated with impacts on human health and safety related to livestock farming activities, human rights, working conditions, and social development as reflected through customers and local communities' perspectives. In this *Review*, we follow the suggestion of recent literature, and additionally consider the potential impacts of protein feed ingredients choices on animal health and welfare, on animal growth and performance, and in relation to the acceptability and digestibility of alternative feeds (Tallentire et al., 2019). These latter implications are discussed primarily through the scope of nutritional suitability because they are mainly associated with the presence of anti-nutritional factors and metabolites in alternative protein feeds.

From a nutritional perspective, the alternative protein sources presented here can provide animals with protein that is comparable to conventional soy (Table 1). Furthermore, they can introduce to their diets important bioactive compounds that can improve gut health, such as antimicrobial peptides, chitin, and lauric acid (Gasco et al., 2018). Algae in poultry diets can improve growth performance, laying rates and product quality (Coudert et al., 2020). GM/GE protein crops often improve feed nutrient profiles without compromising animal and human health (Buzoianu et al., 2013; Naegeli et al., 2020). Food waste can also be a good source of amino acids, minerals, fatty acids, and vitamins essential for animal growth, however there is no clear evidence that it can significantly improve animal performance. Literature suggests that food waste does not affect meat quality, while some studies propose it may even improve it (Dou et al., 2018).

Local protein solutions can also stimulate economic and social growth in local rural communities mitigating the negative impacts of urbanization. By diversifying protein production, local producers and smallholders may acquire a more central role in the agricultural sector (Swain and Teufel, 2017). The potential synergies to funnel waste streams from various industries as resources for livestock feeds can promote cross-sectoral knowledge sharing and collaborations, and opportunities for education as the demand for more specialized on-farm labor may increase (Marinoudi et al., 2019). On-farm work safety can be reduced significantly through production methods that minimize the use of hazardous agrochemicals (e.g., pesticides, herbicides, chemical fertilizers) and that rely on automated technologies as opposed to conventional crop production (Elahi et al., 2019). Furthermore, the potential to preserve ecosystem services and avoid negative environmental impacts contributes to improved human wellbeing and quality of life (Rukundo et al., 2018; Flach et al., 2021).

2.3.1. Food safety

Damages or decay of grains and seeds due to poor conditions of transportation and storage can largely increase the potential risks for biological contaminations of humans through the food chain, such as outbreaks of mycotoxins or viral diseases that can cause severe human health impairments. Climate change (increased ambient temperatures and humidity in particular) and instabilities in global trading of feeds (e.g., significant delays in transportation of feeds due to Brexit or the Ukraine-Russia conflict) have further increased such risks, especially in the absence of state-of-the-art storage and transportation technologies.

Diversifying protein sources in livestock feeds through local, circular, and soilless alternatives could help reduce reliance on imported protein feeds (i.e., grains, seeds), thus reducing food and feed safety risks associated with international transportation and long duration storage, as the ones discussed above. For example, UK livestock production systems importing sunflower seeds from Ukraine, a major producer worldwide, have experienced significant disruptions in the past 2 years and have often received severely damaged and contaminated grains due to the deteriorated storage conditions in Ukraine and extremely long delays at the customs during transportation (unintended consequences of the conflict and relevant trading deals post-Brexit). Therefore, in such cases supplementing livestock diets with protein feeds sourced within the UK (e.g., fava beans, peas, protein through circular streams) could enhance livestock system resilience while largely mitigating risks to human health (Figure 1B; Becton et al., 2022).

Incorporating several of the alternative ingredients discussed here in livestock feeds, could also potentially increase human health risks

TABLE 1 Examples of potential alternative proteins used in livestock feeds that could substitute conventional protein crop production as more sustainable protein sources.

Protein source	Examples	Implementation as livestock feed	Crude protein content	References
Conventional protein crop	Brazilian soy	Commercial worldwide	20–55%	Sauvant et al. (2004)
Alternative plant-based sources and crop growing methods				
GM/GE protein crops	Soybean Mon87701	Commercial worldwide	48–63%	Edwards et al. (2000) and Giraldo et al. (2019)
Homegrown legumes	Fava beans, lupins, peas	Small worldwide	21–31%	Sońta et al. (2021)
Duckweed	*Lemna* spp.	Small worldwide	20–45%	Sońta et al. (2019)
Seaweed	*Porphyra* sp., *Palmaria palmata*	Small worldwide	3–47%	Morais et al. (2020)
Cellular agriculture				
Fungal protein	*Saccharomyces cerevisiae*	Commercial worldwide	33–47%	Glencross et al. (2020)
Bacterial protein	*Arthrospira plantensis*	Commercial worldwide	51–81%	Glencross et al. (2020)
Micro-algae	*Chlorella vulgaris*, *Tetraselmis suecica*	Small worldwide	7–59%	Pignolet et al. (2013) and Roques et al. (2022)
Circular agriculture				
Food waste	Hotel and restaurant food waste	Small EU, US, Southeast Asia	3–33%	Kamal et al. (2021)
Former foods	Bakery and confectionery	Small EU, US, Southeast Asia	11–84%	Pilarska et al. (2018)
By-products of agroforestry	Crop residues, fruits, vegetables	Small worldwide	1–41%	del Mar Contreras et al. (2019)
By-products of biorefinery	Canola, palm, wheat	Small EU, US, Southeast Asia	14–62%	del Mar Contreras et al. (2019) and Khoshnevisan et al. (2020)
By-products of brewing industry	Barley, distillers grain, rice	Small EU, US, Southeast Asia	2–62%	del Mar Contreras et al. (2019)
Animal by-products				
Insect PAPs	*Musca domestica*, *Tenebrio molitor*	Small worldwide	35–82%	Asdrubali et al. (2015) and European Fat Processors and Renderers (2022)
Swine PAPs	Fats, greaves, blood, bone meals	Commercial in EU	42–61%	DiGiacomo and Leury (2019)
Poultry PAPs	Fats, greaves, blood, bone meals	Commercial in EU	53–93%	DiGiacomo and Leury (2019)
Ruminant PAPs	Strictly only collagen, gelatine, milk	Commercial in EU	90–99%	DiGiacomo and Leury (2019)

GM, genetically modified; GE, genetically edited, PAPs, processed animal proteins.

through exposure to allergens and additives. For example, food waste from households, restaurants, retailers, and former foods from bakery and confectionery often contains small quantities of the majority of all 14 known allergens, such as traces of nuts, and various artificial sweeteners (e.g., sucralose) and artificial coloring agents (e.g., tartrazine). These substances can reach humans through bioaccumulation in livestock tissues, and can cause allergic reactions manifested through various symptoms ranging from skin rashes to gastrointestinal issues. However, there are also several advantages to using alternative feeds in this aspect. For example, GM/GE variants may suppress the expression of potential allergenic proteins in plant development, therefore enhancing their acceptability (Dubois et al., 2015).

3. Risks to sustainability

3.1. Environmental

Incorporating alternative protein sources at large scales may present opportunities for sustainable development; however, they may also give rise to potential unintended consequences (Table 2). In some cases, and while home-grown crops like fava beans and peas can relieve land-use related impacts in vulnerable ecosystems of the global South, their total land footprint can be higher by up to 7.6% and their marine eutrophication potential by up to 43% compared to conventional soy (Agribalyse, 2022). Furthermore, shifting protein crop production rapidly may cause a displacement of local crops and

TABLE 2 Summary of key opportunities and risks to sustainability and food safety associated with the implementation of alternative protein feed ingredients.

Alternative protein sources	Environmental opportunities	Environmental risks
Alternative plant-based sources and crop growing methods	Lucerne up to 63% lower land-use related impacts; healthier/more stable soils; lower GWP by 86–95%; lower FEP by 52–97%; lower AP by 62–97%; lucerne lower MEP by 56%	Poor management of former arable areas, leading to abandoned and deserted land; some local crops have higher MEP by 40–150%; invasiveness/weediness of genetically modified/edited crops; edited gene flow threatening wild genotypes and biodiversity
Cellular agriculture	Alternatives relying more on electricity than fossil fuel; protein from yeast up to 62% lower land-use related impacts; lower GWP by 19%; lower FEP by up to 57%	Lack of electricity from renewable sources leading to higher energy and carbon footprint up to 163%; higher AP by 2–17%
Circular agriculture	Reduced chemical inputs improving conditions for terrestrial and aquatic life; reduced habitat fragmentation; lower land-use impacts by 55–100%; lower GWP by 64–100%; lower FEP by 43–100%; lower AP by 97–99%; lower MEP by 2–72%	Toxicity related impacts may be significantly increased due to bioaccumulation of biological and chemical contaminants; threats to biodiversity
Animal by-products	Lower land-use related impacts by 84–99%; lower GWP by 66–95%; lower EP by 82–99%; lower AP by 16–93%; lower MEP by 75–100%	Poor protein utilization from alternatives leading to higher N concentrations in animal manure; uptake of heavy metals due to wastewater as substrate; more effective use of wastewater in other industries
	Economic opportunities	Economic risks
Alternative plant-based sources and crop growing methods	Reduced costs for transportation, fossil fuel, chemical inputs; automated/efficient production and supply	High capital/start-up costs at larger scales; high processing costs; additional processing to inactivate anti-nutritional factors
Cellular agriculture	Improved and uninterrupted supply of feeds from diverse sources; resilience to global trading dynamics	Renewable energy prices remain high; reduced availability of novel technologies required for commercialization
Circular agriculture	Reduced costs associated with waste disposal; reduced labor requirements; wastes and by-products acquire economic value	Increased costs for hygienic processing of wastes and industry by-products; additional processing to inactivate anti-nutritional factors
Animal by-products	Animal by-products acquire economic value; reduced labor requirements	Cross-feeding strategies may incur additional costs at livestock production
	Social opportunities	Social risks
Alternative plant-based sources and crop growing methods	Good sources of protein, fats, and bioactive compounds that promote animal gut health and growth	Disease outbreaks; feed fraud; bioaccumulation of biological (e.g., mycotoxins) and chemical (e.g., pesticides) contaminants; anti-nutritional factors
Cellular agriculture	Growth of local rural communities; reduced heavy-duty on-farm labor; innovation in production/supply chains	Consumer acceptance when cell protein is produced using waste substrates or GM/GE—bioengineering techniques; anti-nutritional factors
Circular agriculture	Sustainable alternatives promote a “Feel good” factor	Cultural barriers; consumer acceptance—“Disgust” factor; misinformation through media; anti-nutritional factors
Animal by-products	Enhanced bioavailability of protein and nutrients compared to plant-based sources	Disease outbreaks; bioaccumulation of biological and chemical contaminants, especially when insects are reared on wastes
	Food safety opportunities	Food safety risks
Alternative plant-based sources and crop growing methods	GM/GE variants can reduce the expression of proteins with potential allergenic action	GM/GE genome of protein feed variants has not yet been fully mapped, therefore uncertainty about GM/GE effects on long term human health
Cellular agriculture		Potential biological contamination (e.g., mycotoxins) and chemical contamination (e.g., nanoplastics) when wastewater is used to rear cultivations
Circular agriculture		Potential biological contamination (e.g., mycotoxins) and chemical contamination (e.g., nanoplastics) due to poor hygienic processing of wastes and industry by-products
Animal by-products		Viral outbreaks (e.g., BSE/TSEs); insects as disease or heavy metal vectors when reared on waste

For the environmental opportunities and risks, the table presents the relative difference (%) in environmental impacts associated with the production of 1,000 kg dry matter of alternative protein feeds, against 1,000 kg soybean meal produced in Brazil. The comparisons are based on the ReCiPe Midpoint (H) impact calculation method, 1,000 Monte Carlo iterations for uncertainty propagation, and data sourced from literature and the Agribalyse v3.1 database (for methodological details, see Supplementary material; Agribalyse, 2022). GWP, global warming potential; FEP, freshwater eutrophication potential; MEP, marine eutrophication potential; AP, acidification potential.

wildlife, and have potential knock-on effects on land-use (Eriksson et al., 2018). Therefore, local solutions should not be viewed as a panacea, and it is critical choosing specific home-grown crop feeds is done considering also regional vulnerabilities, for example the existence of Nitrogen Vulnerable Zones, as well as the capacity, potential, and needs of different regions for production and trading of livestock feeds and other agricultural produce that requires similar resources (e.g., crops for human food). Future research should try to provide answers to what the land-use implications in the global North would be, if the majority of livestock producers made the switch to home-grown protein, and what the production limit would be before this resulted to new, local land-related impacts.

It is important to consider that circular and soilless alternatives, such as insect farming or food waste for feed, may also have unintended impacts on land-use change especially as the scale and size of production systems increase (Shah and Wu, 2019; Doi and Mulia, 2021). Soilless systems require a robust management plan to avoid the abandonment of crop land, which in combination with effects of climate change in the South, including increasing temperatures and frequencies of extreme droughts, can exert pressures on soil organic carbon and biodiversity (Pacheco et al., 2018; Olsson et al., 2019; Winkler et al., 2021).

In the aquatic ecosystems, seaweed farming can also create competition for light and nutrients between cultivated and wild species (e.g., planktonic communities), pollution from artificial material as farming infrastructure, noise disturbances to animals due to increased vessel activity in the area and may significantly alter the geomorphology of coastal ecosystems (Figure 1C; Campbell et al., 2019).

Finally, while there is a strong case for the GHG emission reductions that alternative protein feeds can achieve, there may be unintended increases in N and P concentrations in the manure and urea of livestock animals if they are fed alternatives that provide more imbalanced protein compared to soy and other conventional feeds (Trabue et al., 2021).

To date, hydroponics appear to be less energy efficient than other conventional crop production methods. For example, the production of 1 ton of hydroponic fodder requires approximately 60% more energy (mainly due to electricity consumption) than 1 ton of soy (Agribalyse, 2022). However, advancements in renewable energy sourcing open up far more opportunities for improvement of energy efficiency for hydroponics than conventional crop production, since the latter relies much more on fossil fuel.

3.2. Economic

Much of literature is conflicted about the economic viability of local, circular and soilless alternatives implemented at large scales. For example, seaweed farming, insect farming and cellular alternatives may be a good solution when implemented in less-developed countries especially as post-harvest processing technologies and biotechnologies become better and more affordable (Duarte et al., 2021), but not a cost-effective industry in the North due to the higher labor and energy related costs (van den Burg et al., 2016; Emblemsvåg et al., 2020). Such economic constraints may present challenges for their marketability as commercial feeds due to the low prices of competing conventional protein sources (Arru et al., 2019).

A critical condition for circular agriculture alternatives to be viable and cost-effective is the proper treatment of waste streams prior to their use as feed or feedstock, to minimize the risks of pathogen and disease outbreaks that may result to severe economic consequences through impaired animal performance (Dou et al., 2018). Ensuring high hygiene standards through timely collection of the waste, thermal treatment, appropriate transportation and handling practices incurs costs that need to be accounted for when evaluating the feasibility of such feeding strategies (Figure 1C; Pinotti et al., 2021; Rajeh et al., 2021).

3.3. Social

While alternative protein sources may not necessarily jeopardize animal growth, there is a risk in achieving a comparable crude protein utilization with conventional protein sources that may affect optimal animal performance (e.g., carcass composition), especially compared to what the more balanced protein sources can offer (e.g., soy) (Gasco et al., 2019; Luciano et al., 2020). It can also be difficult to persuade livestock animals to consume the quantities of alternative protein sources required to achieve optimal growth (Mainardes and DeVries, 2016). Even when palatability is not a critical issue for animal welfare, the inclusion levels of alternative protein sources should be carefully considered due to anti-nutritional factors that can be toxic beyond certain concentrations. For example, leguminous feeds contain mimosine and its metabolites, which can be toxic for most livestock species at high concentrations (Lakshmi et al., 2020). While the development of sweet varieties of lupins have mitigated issues of toxicity caused by high levels of alkaloids, other anti-nutritional factors like non-starch polysaccharides may impair animal performance and are therefore a limiting factor for use at large scales (Olkowski, 2018). Food waste with plant components can contain high concentrations of enzyme inhibitors like tannins and alkaloids, which reduce feed intake and nutrient utilization (Georganas et al., 2020). Food wastes and former foods also may contain secondary metabolites and toxins that can be harmful to animals, such as chocolate residues that are high in theobromine (Makinde et al., 2019; Klein et al., 2021).

Consumer perception and acceptance has always been a big concern and a barrier to the adoption of alternative proteins for livestock feed (Figure 1C). Although meat consumers and livestock farmers seem to be positive about alternatives such as insects, algae, and lab-grown feeds used in livestock production there is still much to be explored regarding how to maximize marketability and acceptance of livestock fed with protein alternatives (Verbeke et al., 2015; Onwezen et al., 2019). Such opposing attitudes and cultural biases (e.g., disgust factor) are often being developed and maintained through misinformation by media (Altmann et al., 2022; Khaemba et al., 2022). Livestock producers may attempt to overcome such issues of marketability by withholding relevant information, which consists of feed and food fraud and mislabeling violations, and can be often noticed when such alternatives as GM/GE crops, animal by-products, and insect meals are used (Montgomery et al., 2020). Such incidents not only threaten customer trust and acceptance, but also food security since they may often exclude vital information about potential sources of fungal, bacterial, or chemical contamination.

3.3.1. Food safety

A major food safety concern associated with alternatives that upgrade waste streams to protein is that of the bioaccumulation of biological and chemical contaminants (Figure 1C). The EU and US have very strict regulations that require food waste, former foods and wastewater to be thoroughly treated (e.g., hydrothermal treatment at 110°C for an hour) for viral and bacterial contaminants, and require the precise detection and treatment of chemical contaminants including toxic heavy metals, traces of pesticides and nanoplastics (Dou et al., 2018; Pinotti et al., 2019). This is a critical condition that currently limits the use of such alternatives as livestock feeds in wide scales in those regions (EU and US), or even as substrates for insect farming, seaweed farming and cellular protein production (Dou et al., 2018; Pinotti et al., 2019). Other regions, like countries of Southeast Asia (e.g., South Korea) also have started implementing precise protocols for the systematic regulation of food waste hygienic processing to enable their commercial incorporation in livestock feeds (Dou et al., 2018).

Sourcing protein from seaweed that is grown in coastal waters also has been associated with human food safety issues due to the heavy metal accumulation such as arsenic, cadmium and copper (Tirado et al., 2010). Such contaminants can travel from protein feeds to livestock animals and then reach humans where they can cause severe immediate effects like inflammatory responses, disruption on gut microbiota and effects on nutrient absorption, and chronic inflammation that increases the risks for cancer (Smith et al., 2018; Magnoli et al., 2019; Prata et al., 2020).

Another critical biosecurity concern is associated with the re-introduction of PAPs in the EU from swine and poultry. This should be done following strict protocols of cross-species feeding to avoid disease outbreaks similar to the BSE/TSE epidemic of the 1980s that occurred in the UK (Woodgate and Wilkinson, 2021). As a consequence of such past incidents ruminant PAPs are still prohibited in the EU, with the exception of collagen, gelatine, and milk, that should strictly be fed to non-ruminant species. In the US, only a very small number of pig production farms currently uses food waste that contains animal parts as feed, following thorough thermal processing at licensed facilities (Dou et al., 2018).

Insect meals can also be disease vectors or carry harmful heavy metals. The potential for such threats to be realized is largely increased when wastewater and/or waste substrates are used for their rearing, particularly in the absence of precise treatment methods as mentioned above.

Finally, we highlight the importance to consider the introduction of novel allergens in the human as a potential biosecurity threat. Several of the alternatives discussed here contain the majority of all known food allergens (e.g., food waste, home-grown protein, former foods particularly nuts, animal by-products). These allergens may be transferred down the food chain causing severe human allergies and even death (Advisory Committee on Animal Feedingstuffs, 2009; Testa et al., 2017; Bingemann et al., 2019).

4. Discussion on emerging threats and future directions

Substituting conventional soy and other protein crops in livestock feeds with more sustainable alternatives should undoubtedly be a priority of the livestock and agri-food sector (Song et al., 2021; European Parliamentary Research Service, 2022). As we expect to experience several environmental and socioeconomic threats to feed and food security in the next 2–10 years, building a resilient protein supply is critical. The Ukraine-Russia conflict has not only blocked the supply of sunflower meals from one of the largest producers globally (Ukraine), but has also frozen large European investments that aimed to support local Ukrainian soy production aiming to replace unsustainable imports from South America. Other geo-political developments including Brexit and disease outbreaks (African Swine Fever in Southeast Asia) have exacerbated feelings of insecurity of agricultural stakeholders due to uncertainty around future trading partners, impaired production, disrupted supply of labor, import/duty policies and limited support through subsidies. Climate-related impacts and extreme weather events may lead to impaired productivity and poorer nutrient profiles of conventional protein feeds and increased outbreaks of biological contaminants (Alava et al., 2017).

Alternative protein sources have already been used to substitute protein crops in small scales, as in pet feeds or feeds for fish (aquaculture). Among the most popular examples are insect meals, swine and poultry PAPs used in the feeds of domestic canines and felines. While to some extent, this example may be used to illustrate the potential for these alternatives to be used safely for livestock, there are still several obstacles—mainly socioeconomic—to be overcome prior to their being sustainably produced and integrated into livestock feeds at scale. There appears to be no "silver bullet, free from trade-offs" livestock feed formulation that can guarantee global sustainability across all three pillars. Literature has identified stakeholder dialogue as imperative to evaluate the effectiveness of solutions for sustainable development through the understanding and assessment of potential trade-offs associated with their implementation (Hebinck et al., 2021). Through our analysis of the potential opportunities, risks, and trade-offs of solutions for improved livestock feed sustainability, we invite a dialogue between relevant stakeholders and the co-development of a set of livestock diet scenarios specific to the different livestock species. We propose that in the center of this approach needs to be a shift toward more sustainable local, circular and soilless protein sources. Key sustainability trade-offs can then be quantified for each scenario which will inform region-specific policies for sustainable livestock production. We synthesize four key strategic regional policy pathways to guide future livestock feed formulation in consideration of global sustainable development goals (Table 3; United Nations Department of Economic and Social Affairs Sustainable Development, 2022).

- *Decoupling protein production from fossil fuel* by shifting to alternatives that rely almost exclusively on renewable energy (e.g., solar, wind, geothermal) will reduce the overall environmental footprint of livestock feeds. This needs to be supported by a strict regulation monitoring renewable energy price to ensure the economic viability of alternatives and feed market stability, as well as by further research that may enable uninterrupted and abundant supply of energy from such sources.
- *Developing economic strategies for alternative proteins at subnational level*, as opposed to lateral measures and policies may facilitate adoption of these solutions at larger scales, especially considering the geographic variability in labor and direct input costs, taxes, and support through subsidies. We propose that future policies financially incentivize local protein production

TABLE 3 Example of interactions between alternative protein sources for livestock feeds and global sustainable goals.

Sustainability goals	Mechanism
Socio-economic resilience against climate-related, macroeconomic, and geo-political extreme events (SDG 1)	Decoupling protein feed production from fossil fuel and economically volatile energy sources; reduced reliance on imported protein and global trading partnerships
Increase food security and end hunger (SDG 2)	Landless protein sources reducing feed-food competition; increasing protein feed availability and improving accessibility through local markets; reduced protein feed costs through the use of circular agriculture alternatives leading to less expensive/accessible livestock products
Improve water quality and water-use efficiency, supporting the participation of local communities in water security (SDG 6)	Reduced reliance on groundwater resources for irrigation; reduced chemical pollution of water bodies by avoiding synthetic fertilizers/chemical inputs at crop production
Promote job creation, and safe and secure working environments (SDG 8)	More diverse labor input requirements; reduced heavy-duty manual labor compared to conventional crop production
Resilience and adaptive capacity to climate-related hazards (SDG 13) and Carbon Net Zero emissions	Reduced reliance on fossil fuel, more land available for trees; healthier soil organic carbon stocks; reducing pressure on water cycle through reduced irrigation
Nitrogen (N) and Phosphorus (P) Vulnerable zones to reduce eutrophication pressures	Reduced use of synthetic N and P fertilizers reducing nutrient leaching; reduced organic material deposition in water bodies due to healthier/more stable soils
Minimize impacts of ocean acidification (SDG 14)	Reduced nitrogen leaching from soils due to the use of synthetic fertilizer
Ensure the conservation and sustainable use of terrestrial and inland freshwater ecosystems and their services (SDG 15)	Healthier soil horizons; reduced potential for acidification of ecosystems; reduced impacts of habitat fragmentation and degradation for terrestrial and aquatic biodiversity
Combat desertification, land and soil degradation, deforestation (SDG 15)	Reduced land requirements for protein crop production; reduced reliance on protein sources from environmental hotspots
Reducing food waste, carbon, and protecting critical water resources (Courtauld Commitment 2030)	Food waste used directly as feed or substrate; reduced fossil fuel use leading to reduced carbon emissions; landless alternatives using significantly less water

and consumption to help the shift from the less expensive, unsustainable imported alternatives.

- *Understanding and addressing social biases against circular livestock feed solutions* through efficient stakeholder engagement. This is critical to ensure marketability and overall economic viability of circular alternatives, and therefore facilitate their implementation at large scales. Further exploration of stakeholder concerns may help identify additional risks and unintended consequences of such alternatives, thus we propose that the development of future livestock feed scenarios considers all stakeholders perspectives.
- *Further enhancing feed and food safety* with improved protocols regarding the precise and early detection and monitoring of biological and chemical contaminants in alternative feeds. This is imperative for enabling the safe adoption of alternatives like cellular and insect protein reared on waste substrates, food waste and former foods as protein sources, and PAPs. Emerging feed and food security threats, like the impacts of climate change and storage/transportation conditions on biological contaminant blooms, should be considered throughout future livestock feed scenarios.

Immediate action is required to reshape the global livestock feed market and enhance its future resilience to environmental, macro-economic and geopolitical instabilities (e.g., climate change, Ukraine conflict, energy crisis). Future research should focus on the quantification of synergies and trade-offs between sustainable protein solutions and within and between sustainability pillars to enable accurate spatiotemporal comparisons of alternatives and facilitate regionalized decision making. Any discussion regarding sustainability trade-offs in livestock feed production must include a detailed analysis of who benefits when there are benefits, and who losses when there are losses. It is the position of this *Review* that such sustainability concerns should be fully addressed and resolved prior to efforts for implementation at larger scales. Research into alternative sources suggests that the converse, i.e., considering scalability as a priority, is likely to lead to problems of adoption (Marcellin et al., 2022). Anticipatory policies should be in place to compensate for losses through such trade-offs and to scope the future of the livestock sector beyond the time horizon suggested by the current sustainability agendas (e.g., 2030 as in UN SDGs). The relevant discussions should now also focus on how circularity and localization of protein feeds can fit and synergize with relevant sustainability policies about regenerative and transformative agricultural systems to form clear guidelines for a more sustainable agri-food sector.

Author contributions

GP contributed in the study design, performed the literature review and life cycle assessment, analyzed and interpreted all data and information, and was the primary contributor in writing, reviewing, and approving the manuscript also acting as the corresponding author. BD was responsible for funding acquisition, contributed in the study design, supervised the manuscript writing process, and reviewed and approved the final manuscript. IK was responsible for funding acquisition, a major contributor in the study design, supervised the manuscript writing process, and reviewed and approved the final manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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