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Review Paper

Transformation of the meat production chain towards sustainability

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ABSTRACT

The global demand for meat is projected to rise significantly by 2050, necessitating a transformation in traditional meat production systems to address environmental, economic, and ethical concerns. Industrial livestock farming contributes to some extent to greenhouse gasses emissions, deforestation, biodiversity loss, and water pollution, highlighting the urgent need for sustainable practices. Concerns over animal welfare, food safety, public health, environmental health, and economic inequalities further emphasize the need for transformation of the meat chain. This paper briefly explores strategic solutions, such as sustainable farming practices, point-of-care food safety control methods, valorization of animal by-products, regulatory reforms, and consumer awareness initiatives. Addressing industry resistance through financial and technological support is also crucial for a successful transition. A multi-level approach integrating innovative technologies, policy support, and consumer engagement is essential to achieving transformation to resilient, sustainable, and ethically responsible meat production system.

1. Introduction

The global demand for meat is expected to rise significantly by 2050, putting immense pressure on existing traditional meat production systems to transform towards sustainability due to its significant environmental, economic, and ethical impacts (*FAO*, 2017). This presents an urgent need to develop more sustainable practices that reduce greenhouse gas (GHG) emissions, minimize resource consumption (land, water), and ensure ethical treatment of animals (*Dopelt et al.*, 2019).

Two declarations, the Dublin Declaration (2022) and the Denver Call for Action (2024), related to the interconnection between agriculture, livestock and food systems, were issued by a group of scientists advocating for the importance of livestock in sustainable food systems advocating for a more balanced and science-based perspective on livestock's role (*Leroy and Ederer*, 2023). The Dublin Declaration (https://www.dublin-declaration.org/) emphasizes that livestock contributes positively to nutrition, livelihoods, ecosystems, and food security. It argues that eliminating or drastically reducing meat consumption could have unintended negative consequences on human health and rural economies. The Denver Call for action (https://www.dublin-declaration.org/the-denver-call-for-action) advocates recognizing the complex roles that well-managed livestock play in enhancing nutrition, supporting livelihoods, and providing essential ecosystem services such as biodiversity maintenance and soil fertility. It calls for

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policies grounded in comprehensive, evidence-based assessments that consider ethical, economic, social, and environmental dimensions of sustainability. Both declarations advocate a balanced, science-guided discussions on livestock's role in sustainability, rather than blanket reductions in meat consumption. Achieving sustainability in the meat production chain requires systemic changes involving production methods, such as adoption of responsible farming practices, innovation, shortening supply chains, new regulatory frameworks, and including changing consumer behavior (*Caccialanza et al*., 2023). This paper explores the current challenges, barriers, and strategic solutions necessary for creating a more sustainable meat production system.

2. Current challenges in the meat production chain

The conventional meat industry is dominated by large-scale industrial farming, which presents several sustainability challenges, as presented below.

2.1. Environmental impact

The sources of GHG emissions from livestock sector have been divided to seven modules: (i) from livestock biological processes (CH_4 from enteric fermentation), (ii) from land use change, (iii) from livestock feed production, (iv) from manure management (N_2O, CH_4, NH_3), (v) from cultivated soils (N_2O from fertilizer application), (vi) from land degradation and desertification, and (vii) from animal respiration. Industrial livestock farming is believed to be responsible for approximately 11.1% of global anthropogenic GHG emissions based on data from the ruminant supply chain, assuming its contribution to global warming (*FAO*, 2023). Furthermore, emissions of N_2O and CH_4 from livestock manure contribute together around 10% of the total non-CO_2 GHG emissions (*Møller et al*., 2022). A potential solution can be found in effective recycling of livestock manure to reducing the negative impact of livestock-associated GHG emissions (*Liu et al.*, 2023). Deforestation to make way for pastureland and feed crop production further exacerbates carbon emissions, contributing to 17.4 % of all GHG from anthropogenic sources (*IPCC*, 2007). Excessive use of chemical fertilizers and pesticides in feed production contaminates water sources, leading to eutrophication and the degradation of aquatic ecosystems (*Akinnawo*, 2023). Intensive farming leads also to severe biodiversity loss due to habitat destruction and land-use change (*Machovina et al*., 2015). Large-scale meat production operations require vast amounts of land (integrated supply chain 'feed-to-fork'), often obtained by clearing forests, wetlands, and grasslands, displacing wildlife, and disrupting ecosystems (*Kraham et al*., 2017). Water consumption in industrial meat production is also a critical concern, with around 13.16 m^3 of H_2O needed to produce just one kilogram of beef (*Navarrete-Molina et al.*, 2019). The high concentration of animal waste in confined animal feeding operations (CAFOs) contaminates soil and water bodies, causing harmful algal blooms and dead zones in coastal regions (*Burkholder et al*., 2006).

2.2. Animal welfare concerns

Intensive livestock farming ('factory farming') is designed to maximize production efficiency while minimizing costs. This involves keeping a large number of animals in confined spaces, often in restrictive cages or overcrowded barns (*Anomaly*, 2014), limiting natural behaviors such as foraging and social interactions, and leading to discomfort among animals. Selective breeding for rapid growth and high yield can have severe health issues, such as skeletal disorders in poultry and lameness in cattle (*Hartcher and Lum*, 2019). The transportation of livestock from farms to slaughterhouses is a critical phase that significantly impacts animal welfare. Long journeys, overcrowded conditions, and improper handling can cause severe stress, injuries, and fatalities among transported animals. Rough handling by workers and the use of electric prods can cause pain and fear among animals (*Ljungberg et al*., 2007; *Lambooij*, 2024). Re-establishing short meat supply chains, by promoting investment in local slaughterhouses, can reduce the need for long-distance transport minimizing the stress experienced by livestock (*Kneafsey et al*., 2013).

2.3. Public health risks

Foodborne hazards are significant concern in industrial meat production, with public health risks from low-level farm biosecurity, poor heard health management, improper handling and unhygienic processing at slaughter, and cross-contamination during further stages along meat supply chain (deboning, meat-processing, distribution, retail). Pathogens such as *Salmonella*, *Campylobacter*, Shiga

toxin-producing *E. coli* (STEC), and *Listeria monocytogenes* are commonly associated with meat products and can lead to severe foodborne illnesses (*Lianou et al.*, 2017), in particular in vulnerable populations including children, the elderly, pregnant women, and immunocompromised individuals (YOPI). Chemical residues from pesticides, hormones, dioxins, and heavy metals in meat products raise additional health concerns (*Onyeaka et al*., 2024). The overuse/misuse of antibiotics in animal farming is another pressing public health risk, as it contributes to the emergence of antimicrobial-resistant (AMR) bacteria and reduced therapy response in livestock and people. To mitigate these risks, policymakers and industry stakeholders must enforce stricter regulations on antibiotic use in livestock production and promote alternative disease prevention strategies (*Nastasijević et al*., 2023).

2.4. Food safety control

Conventional culturing methods, enzyme-linked immunosorbent assay (ELISA), and polymerase chain reaction (PCR) are widely used for detecting foodborne pathogens in the meat chain to meet the regulatory food safety requirements, but they are often time-consuming, labor-intensive, and require specific laboratory facilities. This emphasizes the need for the cheap and point-of-care devices, e.g., biosensors offering rapid, accurate (sensitive and specific), and on-site food safety diagnostics to reduce contamination risks (*Nastasijević et al*., 2025).

2.5. Economic inequality

Industrial meat production often outcompetes small and medium enterprises (SMEs), creating monopolization and reducing diversity in meat production. Large corporations produce meat at lower costs, benefiting from vertical integration, controlling multiple stages of the supply chain, from feed production to meat processing and retail (feed-to-retail continuum), also having the financial strength to fulfil the livestock environmental regulations (*Jiang et al*., 2023). In attempts to find the best way to organize meat production between large-versus small-scale production systems or long-versus short meat supply chain, it would be wise to adopt the attitude that coexistence of both ways can be effective and expected in the long run (*Schulze et al*., 2006).

3. Sustainable transformation strategies

To overcome mentioned barriers and drive a sustainable transformation of the meat production chain to lessen the environmental footprint, a multilayer approach is needed as presented below.

3.1. Advancing sustainable farming practices

Agro-ecological approaches, regenerative agriculture techniques, and valorization of animal by-products can reduce reliance on chemical inputs, improving animal welfare standards, promoting alternative protein sources, and enhancing the circular economy. An agroecological approach involves practices, such as pasture-based and rotational grazing systems, to reduce environmental impact (*Marchegiani et al*., 2025). Regenerative agriculture supports soil health, reducing chemical inputs and enhancing biodiversity (*Borsari*, 2020). Valorization of animal by-products from slaughter can be done by incorporating high-protein and micronutrient-rich materials into food products, such as Ready-to-use Supplementary Food (RUSF) and Ready-to-use Therapeutic Food (RUTF) (*Fetriyuna et al*., 2023).

3.2. Enhancing food safety testing

As food safety testing can be time-consuming and expensive (costs for collection of samples, shipment to the accredited laboratory and labor), the development of alternative methods that are cheaper and can be applied on-site is needed, such as biosensors. Biosensors are devices which offer real-time monitoring to detect foodborne hazards at selected critical points along the meat chain (farm-retail continuum) by recognizing a target 'biomarker' characteristic for a particular pathogen or chemical contaminant via an immobilized sensing element called a 'bioreceptor' (monoclonal antibody, RNA, DNA, aptamer, glycan, lectin, enzyme, tissue, whole cell). By integrating biosensors into the meat safety assurance system, early and rapid (response 20-60 min) quantitative detection of foodborne pathogens, toxins, and food spoilage markers becomes possible, reducing reliance on time-consuming traditional methods, e.g., 5-7 days for culturing for *Salmonella* and *Listeria*, respectively, or 24 h for ELISA and PCR. Biosensors transform the meat chain by enabling proactive risk mitigation, enhancing food safety management and compliance with food safety regulations, reducing food waste through early

intervention, and increasing consumer confidence in meat products (*Nastasijević et al*., 2025).

3.3. Investment in alternative proteins

Re-using the proteins from animal by-products leads to reducing the environmental and ethical issues and promoting the circular economy (*Mylan et al*., 2023). Food supplements from proteins sourced from animal by-products present a sustainable means of utilizing nutrient-rich materials that would otherwise be wasted, offering high-quality protein sources for human and animal nutrition. This presents a foreseeable future in transformation of the meat chain (*Fetriyuna et al*., 2023). Further, 'hybrid products' (blending plant-based proteins with meat) can act as a transitional solution for reducing meat consumption without drastic dietary changes (*Profeta et al.*, 2021). Governments and private investors should accelerate funding for lab-grown (cultured) meat technologies to enhance scalability and affordability (*Mancini and Antonioli*, 2022).

3.4. Policy and regulatory support

Effective policy support is essential for driving sustainability in the meat chain. The governments should find ways to simplify complex compliance requirements, such as certification processes for organic and sustainable meat production, to encourage small-scale farmers while providing the platform for ensuring food safety (*Home et al.,* 2017). Subsidies should be revised by redirecting financial support from conventional industrial livestock farming more to sustainable and alternative protein production systems (RUSF, RUTF). This helps the meat sector to transform itself more efficiently and maintain its position in a global market (*Sutton et al*., 2024).

4. Consumer awareness and behavioral change

Educational campaigns should actively promote the benefits of sustainable meat production (*Ramsing et al*., 2021). Consumers should be encouraged to adopt flexitarian diets (more frequent consumption of hybrid or plant-based products) advocating moderate use of good quality meat and meat product programs (*Dagevos*, 2021). Since consumers tend to be resistant to fundamental changes in their diet, a rapid transition is not foreseen (*Siegrist et al*., 2024). Pricing and labeling strategies and affordable prices for sustainable meat products should guide consumer choices (*Amman et al*., 2023). Overcoming industry resistance rooted in emotional ties to conventional practices requires coordinated support from governments and stakeholders through technology, incentives, and education (*Hübel and Schaltegger*, 2022).

5. Conclusion

Transforming the meat production chain is both a pressing necessity and a complex, multifaceted challenge requiring multi-sectorial efforts across environmental, economic, ethical, and public health dimensions. Addressing animal welfare concerns, public health risks, innovations in food safety testing, valorization of animal waste proteins, adjustment of regulatory framework, addressing economic inequalities, and changing consumer behavior are crucial for this transformation, which will support a more ethical, resilient, and sustainable meat chain to ensure food security and public health protection for future generations.

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