

Livestock production within the context of the global nitrogen cycle – an overview of processes, impacts, and mitigation options related to sustainable agriculture and European Union policies

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Summary

The global nitrogen cycle has been significantly disrupted due to anthropogenic activities. The growing demand for food and energy contributes to the increased production of reactive nitrogen through chemical synthesis (the Haber-Bosch process). Negative consequences of intensified agricultural production include the impact of nitrogen compounds on the natural environment and human health. Due to the cascading and cumulative effects of reactive nitrogen compounds, it is essential to understand the processes of nitrogen transformation processes during agricultural production and their influence on the global nitrogen cycle. Agricultural production is inseparably linked with the surrounding ecosystem. While intensification of agricultural production improves profitability, it also leads to greater generation of by-products (manure, slurry) and greenhouse gas emissions. Modern agriculture faces new challenges, including the protection of the natural environment, climate change mitigation, and adaptation to changing environmental and climatic conditions. The agricultural sector, due to international agreements and national legal regulations, is obligated to take action to reduce the excessive and uncontrolled dispersion of biogenic compounds into soil and water. Nutritional strategies applied in livestock production are one of the key elements of environmental protection measures, due to their immediate applicability, positive effects on economic efficiency, and real potential to reduce the dispersion of reactive nitrogen compounds into the environment.

The aim of this paper is to present the key aspects linking livestock production with the nitrogen cycle. Rational nitrogen management requires an understanding of the processes nitrogen compounds undergo in the biosphere to effectively manage and mitigate their negative environmental impacts, and to enhance effective collaboration between the scientific community, veterinarians, animal scientists, and agricultural producers.

Keywords: global nitrogen cycle, reactive nitrogen compounds, livestock production, greenhouse gas emissions

The environment and natural resources are essential for the growth of key sectors of the economy, such as agriculture and the food sector (<https://www.consilium.europa.eu/pl/policies/biodiversity>). Agricultural practices, environmental factors, and climatic conditions are interconnected through various feedback loops. The main environmental challenges faced by agriculture include the management of land use, disruptions in the natural flow of macronutrients, climate change impacts, and the availability of water resources.

Global development forecasts suggest a persistent rise in both population numbers and economic activi-

ties (1, 10). This represents a significant challenge in terms of food, ecological, and economic security. Scientific research has shown that human activities leading to greenhouse gas (GHG) emissions and a declining capacity of the Earth to absorb them are the primary drivers of climate change. Climate change affects agriculture both directly, by altering climatic factors that determine crop yields (such as temperature, rainfall distribution, and soil moisture), and indirectly, by influencing the abundance and diversity of pathogens and pests (33). Its consequences extend beyond rising air temperatures to modifications in hydrologi-

cal cycles, the increased frequency, and intensity of extreme weather events. The risks of new diseases and shifts in the abundance and diversity of flora and fauna are also growing (27). Climate change may reduce productivity across various agricultural branches, thus limiting both the quantity and quality of food and feed produced. Many scientists warn that the planet's ability to regenerate, often referred to as planetary boundaries, may soon be surpassed. The ongoing exploitation of natural resources creates the need for integrated measures to balance GHG emissions (climate neutrality) by strengthening ecosystem capacity to absorb these gases (2, 56).

For many years, international efforts have been made to mitigate climate change. The idea of sustainable development, which emerged in the 1980s, has been incorporated into agricultural strategies. Through the Common Agricultural Policy (CAP) and national policies and guidelines, agriculture is expected to follow the environmental protection standards set by the European Union (EU). The European Green Deal, the Farm to Fork Strategy, and the EU Biodiversity Strategy for 2030 are interrelated and mutually supportive initiatives. They are accompanied by policy changes aimed at fostering sustainable agricultural practices and food production within EU member nations (90). This is accomplished through adaptation strategies, which respond to evolving environmental and climatic conditions, as well as mitigation efforts that focus on lowering greenhouse gas emissions. Agriculture is one of the few economic sectors with significant potential not only to reduce GHG emissions but also to sequester carbon dioxide (CO₂) (31, 82).

Greenhouse gas emissions from agriculture in Poland

In Poland in 2023, the total anthropogenic greenhouse gas emissions, expressed in CO₂ equivalent, amounted to 348 Mt CO_{2eq}. The dominant contributors to national emissions were carbon dioxide (81.4%), methane (11.5%), and nitrous oxide (5.9%). According to the report by the National Centre for Emissions Management (KOBiZE), in 2023, greenhouse gas emissions from the agricultural sector in Poland represented 9.8% of the nation's overall human-induced emissions (<https://www.kobize.pl/pl/fileCategory/id/16/krajowa-inwentaryzacja-emisji>). The energy sector remains the largest source of CO₂ emissions (92.9%). In contrast, agriculture contributes only 0.4% of CO₂ emissions, mainly due to crop intensification, which is largely offset by the ability of cultivated biomass to sequester carbon. The low CO₂ emission value in the „Agriculture” category results from reporting conventions that separate GHG emissions by sources and types. Actual CO₂ emissions from agriculture are higher when considering the entire food system, including emissions from deforestation, peatland drainage, land-use change (LULUCF), fossil

fuel combustion in agricultural machinery (energy sector), and fertilizer production (industry). It is worth noting that the classic Haber-Bosch process, due to its energy consumption, may be responsible for up to 2% of global CO₂ emissions (72). In that same year, methane emissions from agriculture made up 40.7% of the country's total emissions. The primary sources of agricultural methane were enteric fermentation in livestock (36.5%) and manure management (4.07%). The total emissions of nitrous oxide (N₂O) across the nation in 2023 reached 20.72 million tons CO₂, with the agriculture sector contributing to 80.8%. Nitrous oxide significantly contributes to the greenhouse effect because it remains in the atmosphere for a long time (about 120 years) and has a global warming potential of 265 times that of CO₂ over a 100-year period. In Poland, most agricultural N₂O emissions came from: the fertilization of farmland (68.8%) and livestock waste (12%), particularly from cattle and pigs.

Nitrogen emissions and EU strategies for mitigation

Agriculture is considered the primary source of excessive nitrogen emissions into the environment, both from crop and livestock production. Under the framework of the European Green Deal, the European Commission has introduced measures aimed at reducing nitrogen losses by limiting its dispersion into the atmosphere, soil, and water. The integrated EU approach to reducing reactive nitrogen forms (RNF) within the food system focuses on three key areas: (1) improving Nitrogen Use Efficiency (NUE) (monitoring nitrogen sources and usage, reducing nitrogen fertilizer inputs, minimizing field losses, reducing emissions from livestock housing and manure management); (2) reducing nitrogen losses across the food system (lowering demand through reduced food waste, increasing the use of by-products and waste from the food industry, retail, and consumption, improving waste processing and management); (3) modifying human diets (reducing animal protein and energy intake, enabling a 50% reduction in agricultural nitrogen demand within the EU).

At present, livestock production is the least efficient sector in terms of nitrogen use within the food system. Therefore, the most significant potential for reducing nitrogen loss lies in: optimizing animal husbandry, improving feeding strategies, and developing sustainable manure management practices (3, 32, 38, 82).

Agriculture has a significant impact on the amount and diversity of reactive nitrogen species emitted into the environment. Animal husbandry is an important branch of agricultural production and is closely linked to crop production. Data collected in Poland from 2004 to 2022 shows that RNF emissions were linked to the type of nitrogen fertilizers applied, whether mineral or natural (32, 82). Integrated actions undertaken at both European and global levels are intended to counteract

the negative effects of nitrogen on nature. In Poland, reducing RNF emissions may be one of the most difficult to achieve due to the significant number of small and medium-sized farms (13, 38). To grasp the intent and extent of these initiatives, it is essential to understand how agroecosystems influence the global nitrogen cycle's balance. To compile a comprehensive and well-structured literature selection for the review, the following criteria were adopted: databases (PubMed, Scopus, Google Scholar), keywords (global nitrogen cycle, reactive nitrogen compounds, animal production, greenhouse gas emissions), logical operators (“and”, „or”), and publication type (peer-reviewed articles).

The nitrogen cycle

Nitrogen is a key biogenic element essential for sustaining life. Alongside carbon, oxygen, and hydrogen, it constitutes the foundational components of proteins, nucleic acids, glycosaminoglycans, complex lipids, and nucleotides, which are key to processes such as photosynthesis, cellular respiration, and lipid metabolism. Nitrogen is also a component of porphyrins, chlorophyll, cytochromes, various secondary metabolites (e.g., alkaloids, glucosinolates, cyanogenic glycosides), and excretory products (e.g., urea, uric acid).

The overall nitrogen stock on our planet is thought to be around 1.6×10^{17} tons. The primary sources of this nitrogen are the atmosphere (approximately 3.86×10^{15} tons), the lithosphere (around 1.64×10^{15} tons), and the biosphere (close to 2.8×10^{11} tons). Nitrogen occurs in various oxidation states and chemical forms (Tab. 1). Only about 2% of nitrogen present in the geosphere can be directly assimilated or converted into reactive forms available to living organisms. Within this fraction, nitrogen exists as: i) gaseous forms: atmospheric nitrogen (N_2), nitrogen oxides (NO_x), including nitrous oxide (N_2O), nitric oxide (NO), nitrogen dioxide (NO_2), and ammonia (NH_3); ii) organic compounds: amino acids, proteins, nucleic acids, urea, vitamins, chlorophyll, and others; iii) soil nitrogen: present as organic compounds and mineral nitrogen – ammonium ($N-NH_4^+$) and nitrate ($N-NO_3^-$) (65).

Tab. 1. Major nitrogen forms in the nitrogen cycle

Name	Molecular form	Oxidation state	Chemical process			
Organic nitrogen	R-NH ₃	-3	Oxidation	↓	Reduction	↑
Ammonia	NH ₂	-3				
Ammonium ion	NH ₂ ⁺	-3				
Molecular nitrogen	N ₂	0				
Nitrous oxide	N ₂ O	+1				
Nitric oxide	NO	+2				
Nitrites	NO ₂ ⁻	+3				
Nitrogen dioxide	NO ₂	+4				
Nitrates	NO ₃ ⁻	+5				

Nitrogen compounds in the geosphere are divided into inert and reactive forms (54). Molecular nitrogen (N_2), the main component of the atmosphere (78.084%), is not directly assimilable by plants or animals due to the stability of its triple covalent bond (16). Reactive nitrogen forms (RNF) encompass all biologically, photochemically, and radiatively active nitrogen species in the atmosphere and biosphere. These sources comprise reduced inorganic forms (like NH_3 and NH_4^+), oxidized inorganic forms (such as NO_x , N_2O , and NO_3^-), as well as organic nitrogen substances (R-NH₃, including proteins, and non-protein nitrogen compounds). Under natural conditions, reactive nitrogen is generated through atmospheric lightning discharges, mineralization of organic matter, and biological nitrogen fixation (BNF), where atmospheric N_2 is converted into NH_3 by prokaryotes (12). From an evolutionary perspective, before the emergence of humans, RNF did not accumulate in ecosystems, as the processes of nitrogen activation and deactivation (e.g., denitrification) remained in balance. Today, due to industrialization, RNF accumulation occurs at local, regional, and global scales (16). The primary anthropogenic sources of RNF are: leguminous crops supporting the transformation of N_2 into organic nitrogen via biological nitrogen fixation, fossil fuel combustion, where both atmospheric and fossil nitrogen undergo oxidation to form NO_x , while the Haber-Bosch method transforms unreactive N_2 into NH_3 for use in fertilizers and various industrial applications (17, 18). As a result of human activity, RNF has accumulated significantly in ecosystems, with cascading and cumulative effects.

The nitrogen cascade

The nitrogen cascade, described by Galloway (17), is a sequential process in which reactive nitrogen forms are transferred and transformed across environmental compartments. The key moment is the formation of a reactive nitrogen compound. Once created, a reactive nitrogen compound can transform between reduced and oxidized inorganic forms depending on environmental conditions. Due to the limited efficiency of deactivation processes (e.g., denitrification), RNF may remain in their place of origin (air, soil, water) or be transported via air or water to other ecosystems. The reactive nitrogen forms can enter the nitrogen cycle at various stages depending on their chemical structure, leading to environmental effects both during their movement and when they settle in different ecosystems. Thus, the biogeochemical circulation pathways and the magnitude of RNF fluxes determine whether their effects in the biosphere are beneficial (e.g., stimulating plant growth) or harmful (e.g., acidification, eutrophication) (18).

Reactive nitrogen compounds – environmental interactions

The consequences of human impacts on the global nitrogen cycle include both benefits (intensified food

production) and losses associated with the adverse effects of reactive nitrogen forms on human health, biodiversity loss, and climate change (60). The influence of every chemically active nitrogen molecule in the environment (ecosystem) persists during its transfer until it is immobilized through assimilation into an organic form (R-NH₃) or transformed into a chemically inert form (N₂). The cascading character of these impacts lies in their ability to trigger various downstream effects as nitrogen contained in RNF moves through environmental reservoirs. For example, before being reconverted to N₂, the same atom of reactive nitrogen may successively increase tropospheric ozone (O₃) concentrations, PM_{2.5} particle concentrations, precipitation acidity, soil acidity, surface-water acidity, hypoxia in coastal waters, the greenhouse effect, and influence forest productivity (18, 89).

Nitrogen compounds released through human activities influence climate change not only in a direct way (for example, by reducing the ozone in the stratosphere) but also indirectly (such as by changing the way CO₂ is stored in land and water environments) (58). Nitrogen oxides (NO and NO₂) interact with sulfur oxides (SO_x) to create acid rain (74). The chemical reaction of NO_x from car emissions contributes to the creation of smog. Direct contact and NH₃ absorption damage the protective wax layer on plant surfaces, increasing drought sensitivity and vulnerability to fungal infections and pests (68, 79). In humans and animals, RNF exposure increases the incidence of respiratory and cardiovascular diseases. Nitrate toxicity (NO₃⁻) stems from its role in inducing methemoglobinemia and, as precursors of nitrosamines, in causing mutagenic, carcinogenic, and teratogenic effects (1, 7, 61).

Globally, agriculture is the primary source of NH₃, N₂O, and NO₃⁻ emissions, while industry and transport are the main sources of NO_x emissions (64, 81). In Europe, about 6.7 million tons of nitrogen are emitted annually into the atmosphere as NO_x, much of which after transformation, returns to the soil as nitric acid. In Poland, the yearly nitrogen deposition, including both wet and dry forms, is between 15 and 20 kg/ha, which contributes to the issues of nitrogen pollution and the acidification of soil and water (1, 12, 22, 58).

The production of livestock is a major contributor to NH₃ emissions, primarily caused by the breakdown of uric acid in poultry waste and urea in urine through the action of enzymes like uricase and urease. In Europe, a large portion of NH₃ emissions comes from cattle, accounting for 51%, followed by pigs at 15%, and poultry at 13%. The levels of emissions are influenced by the type and quantity of manure alongside the methods and timing of its application (24, 64, 85).

In aquatic ecosystems, nitrogen is mainly present in oxidized forms (NO₃⁻). Nitrate is the most mobile form of soil nitrogen, contaminating groundwater and aquifers under favorable conditions. Significant sources of nitrogen pollution in aquatic ecosystems

include livestock effluents and fertilizer runoff (66). The absorption of nitrogen from fertilizers by plants ranges between 30% and 70%, which is contingent upon the type of crop, agricultural practices, and the kind of fertilizer used (49). High single doses of soluble mineral fertilizers lead to the accumulation of mobile nitrogen forms in the soil and their leaching into water. This leads to eutrophication, which results in algal blooms, oxygen depletion, the decay of organic matter, and biodiversity loss in aquatic ecosystems. Additional effects include diminished aesthetic, recreational, and economic values of water bodies. Livestock effluents contain nitrogen concentrations of ~1350 mg N/L, significantly exceeding the total nitrogen content in municipal sewage (~50 mg N/L) (49). Concentrated animal production produces significant amounts of animal manure containing organic nitrogen (R-NH₃). Both protein-based nitrogen and non-protein nitrogen compounds undergo ammonification and/or nitrification. Poor storage practices allow nitrate leaching into soil and groundwater (44, 79).

Nitrogen deposition is the third most significant factor – after land-use change and climate change – affecting global biodiversity and the productivity of forests and grasslands (62). When nitrogen inputs exceed 5-10 kg N/ha/year, nitrophilous species dominate, displacing oligotrophic species. Eutrophication consequently reduces the diversity of plant species, which in turn has impacts on the diversity of insects and animals (44, 79).

Crop production – impacts on the nitrogen cycle

Soil is one of the fundamental factors of production in agriculture. Land covers only 29% of the planet's surface. Agriculture occupies more than 35% of the planet's land area, with approximately half of the farmland resulting from changes in land use, such as the transformation of wetlands, peat bogs, and forests (57). Agricultural land is being lost to urbanization and infrastructure development, as well as to wind and water erosion, salinization of irrigated soils, and the conversion of pastures into semi-deserts and deserts. Agricultural practices – particularly disruptions in macronutrient cycling – can lead to excessive land exploitation and soil degradation (erosion, nutrient depletion, and desertification), ultimately reducing productivity. Lower agricultural yields create a demand for more land, which ultimately harms natural habitats and adds to climate change.

Fertilizer application is a significant concern regarding soil health. The elevated nutrient demands of modern cultivars point to the need for rational nutrient management. In high-intensity farming practices, the use of mineral fertilizers is a critical agricultural technique that affects production results (including yield and the nutritional quality of the primary crop) and farm financials (11). Fertilizer application rates need

to correspond to the needs of the crops and the specific conditions of the field. In Polish family farms, nitrogen application exceeds that of other macronutrients (phosphorus and potassium). An imbalanced nutrient supply reduces nitrogen use efficiency and increases environmental risks associated with the dispersal of reactive nitrogen forms. Organic fertilizers contain most of the nutrients essential for proper plant growth and development. The volume of organic fertilizer types (manure, slurry, and liquid manure) are primarily driven by herd structure, stocking density, and housing system. The substantial use of mineral fertilizers in crop production results, among other factors, from decreases in the number of farms and livestock, which increases demand for industrial agricultural inputs (34).

Nitrogen regulates proper plant development by influencing the growth of both below-ground and above-ground organs. By affecting the duration of the growing season, it impacts the utilization of other nutrients (such as potassium and phosphorus) and thus alters the technological properties and nutritional quality of the harvest (leading to higher protein, chlorophyll, vitamins, and digestibility). A lack of nitrogen hampers growth, resulting in poor tillering, thinner and shorter stems, and a lower leaf-to-stem ratio. Excess readily available nitrogen during the growing season leads to uneven, stunted development, increased frost susceptibility, and higher disease and pest pressure. In plant cells, it also increases the proportion of non-protein nitrogen (like nitrates), resulting in a decrease in the nutritional quality of the harvested yields (28).

Nitrogen is virtually absent from soil minerals. In the upper soil layers, nitrogen primarily exists in organic forms (accounting for over 90% of total nitrogen) and in mineral forms (approximately 6%). Organic nitrogen is not directly available to plants; it is a mixture of chemical substances constituting soil microbial biomass, plant residues, organic fertilizers added to soil,

and humic materials. The water-soluble mineral forms are primarily ammonium (NH_4^+) and nitrate (NO_3^-). Inorganic nitrogen is produced through the breakdown of organic nitrogen (R-NH_2) or is introduced through synthetic fertilizers (45, 67). In soil, transformations continuously convert nitrogen into mineral forms available to plants and, conversely, convert mineral nitrogen into gaseous forms (N_2 , N_2O , NH_3) that are released into the atmosphere. Most changes in soil nitrogen are facilitated by microorganisms such as bacteria, archaea, and fungi, which are essential to the nitrogen cycle. The pool of plant-available mineral nitrogen in soil reflects primarily the balance between mineralization and immobilization processes (Tab. 2). Under natural conditions, biological nitrogen fixation (BNF, also known as diazotrophy) is one of the most effective ways to introduce plant-available nitrogen into soils. It is estimated that globally, microorganisms fix about 100 to 265 million tons of atmospheric N_2 each year, with roughly 150 million tons coming from soil-dwelling microorganisms (83, 84).

Livestock production – impacts on the nitrogen cycle

The continuing growth of the global population is accompanied by efforts to ensure food security. In livestock production systems, strategies focus on scaling up, intensification, specialization, and regional concentration (47). Animal husbandry is crucial for maintaining a stable food supply and constitutes an important social and economic component of the global economy (23, 52, 63). It is anticipated that productivity in developed nations will keep increasing in the future. In contrast, in developing regions, the number of animals, including both large and small ruminants, is expected to increase significantly (37, 76). Despite undeniable benefits, livestock production also presents environmental challenges. The livestock

Tab. 2. Main pathways of nitrogen transformations in the nitrogen cycle

Process	Explanation
Ammonification**	Conversion of nitrogen into organic compounds into ammonia (in water, present as ammonium ion). In the case of proteins, the process begins with proteolysis (hydrolytic breakdown of proteins into amino acids), followed by ammonification (decomposition of amino acids into ammonia) Pathway: Protein → Amino acids → NH_3 (NH_4^+)*
Nitrification**	Oxidation of ammonium ions into nitrites, and subsequently into nitrates Pathway: $\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^-$ *
Denitrification	Strict (anaerobic conditions): multi-step reduction of nitrates to molecular nitrogen Pathway: $\text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2$ Partial (facultative anaerobic conditions): reduction of nitrates to nitrites or ammonia Pathway: $\text{NO}_3^- \rightarrow \text{NO}_2^-$ or NH_3
Biological nitrogen fixation (BNF, diazotrophy)***	Reduction of atmospheric molecular nitrogen into ammonia Equation: $\text{N}_2 + 8\text{H}^+ + 8\text{e}^- + 16\text{ATP} \rightarrow 2\text{NH}_3^* + \text{H}_2 + 16\text{ADP} + 16\text{Pi}$
Immobilization/Assimilation of nitrogen	Conversion of inorganic nitrogen forms into organic compounds via microbial or plant assimilation Pathway: NH_3 (NH_4^+), $\text{NO}_3^- \rightarrow \text{R-NH}_2$

Explanations: * – Assimilable nitrogen forms for plants; ** – Mineralization of organic nitrogen compounds – biochemical transformation of complex organic matter into simple mineral forms available to plants; *** – Mineralization of organic nitrogen compounds – biochemical transformation of complex organic matter into simple mineral forms available to plants

industry accounts for around 14.5% of human-induced greenhouse gas emissions worldwide, contributing to climate change through methane (CH_4) released from digestive processes, nitrous oxide (N_2O) from managing manure, and carbon dioxide (CO_2) resulting from changes in land use and the production of animal feed. The growing global demand for foods from animals necessitates the creation of sustainable approaches that can reduce greenhouse gas emissions while maintaining food production levels (21, 39, 41, 51).

In livestock feeding, diets often contain more protein than required for animals' metabolic needs. Reasons include errors in ration formulation (estimating animal requirements, protein content of feedstuffs), strategies to minimize the risk of reduced productivity in case of protein deficiency. Such rations result in the excretion of undigested protein or nitrogen from unused amino groups (in the form of urea and uric acid) in manure. The biogenic nitrogen content of manure depends on the species, production group, feeding strategies, feeding methods, and type and amount of bedding. Organic fertilizers can effectively supply plant nutrients (e.g., in slurry, 40-70% of nitrogen is in ammonium form, ~6% in nitrate form). However, if stored poorly, applied excessively for soil capacity, or administered in amounts greater than what crops need, they can significantly contribute to greenhouse gas emissions in agriculture (50, 73, 76).

The rise in population and greater wealth have driven urban expansion, infrastructure growth, and heightened demand for energy and food. The livestock sector uses ~70% of global agricultural land (40). Rising demand for animal-source foods heightens the risk of converting natural habitats (forests, wetlands, peatlands, and natural grasslands) into farmland. Land-use change contributes to biodiversity loss and increases GHG emissions (10, 20). Therefore, integrated actions are needed to improve land-use efficiency in livestock production, and animal productivity (87). Promoted solutions include increasing crop yields, improving feeding efficiency in animal production, and rational use of nutrients across the entire food chain (farm-to-fork strategy). Moreover, the use of by-products from agri-food processing and feed materials from lands with low opportunity costs for crop production is recommended (9, 19, 20).

Human dietary choices – impacts on the nitrogen cycle

Intensively managed agroecosystems, including concentrated livestock production, are major drivers of changes in the nitrogen cycle. Growing nutritional needs and dietary preferences not only increase health risks but also contribute to climate change and accelerated biodiversity loss (55). Approximately 70% of anthropogenic nitrogen is introduced into agroecosystems to increase food production. According to Smil (71),

around 40% of humanity depends on mineral fertilizers (via the Haber-Bosch process) for food availability. Animal agricultural systems produce protein-rich foods such as milk, eggs, and meat, primarily relying on protein sourced from crop agricultural systems. However, most nitrogen entering animal systems via feed is lost to the environment. The efficiency of converting protein into edible animal protein is low and species-dependent, averaging about 15% (80). The remaining nitrogen is lost mainly through manure and food waste. Losses and waste in the agri-food chain are estimated at 30-40%, due to multiple factors, including food quality issues (35, 70). Nitrogen in animal manure can be recycled into crop production as organic fertilizer. However, substantial amounts of reactive nitrogen forms are lost via conversion to gaseous forms (NH_3 , N_2O , NO , N_2) released to the atmosphere and leaching into surface water and groundwater as nitrates (NO_3^-). Mitigation strategies aimed at decreasing nutrient runoff from manure not only safeguard the ecosystem but also enhance the financial returns of livestock farming (15). Adopting a sustainable diet, with at least a 50% reduction in animal-based foods and a greater reliance on plant-based foods, is an essential element of environmental protection (36).

The unprecedented rise in global demand for dietary protein has intensified the search for alternative protein sources for both human and animal nutrition (6, 55, 77). In addition to having physical and economic availability of food, the quality of that food is a crucial element (46). The assessment of protein quality considers not just its nutritional benefits but also its flavour, the lack of harmful compounds, and its functional characteristics (29, 69, 86). Protein quality can be explained as its ability to promote growth, health, and overall wellness. Criteria most frequently used in evaluation include total protein content, amino acid profile, digestibility (accounting for amino acid absorption up to the ileum). Deficiencies in protein or essential amino acids (EAA) limit the nutritional and functional value of proteins (5, 43, 75).

In animal nutrition, the crude protein concept (used in feed formulation and legal regulation) requires a reliable method for estimating "protein content." This concept is ambiguous, as the term "protein" encompasses a range of substances seen collectively, yet differing in their chemical and analysis characteristics. Specifically, "protein" can denote certain, biochemically refined substances or highlight the primary purpose of "protein" in nutrition, where amino acids are the most crucial component.

There are various techniques for analyzing protein in feed items, classified into quantitative and qualitative methods. Determining protein content, depending on the analytical methods used (direct, indirect) and the parameters being assessed, can be challenging due to the heterogeneity of feed materials, especially those

of plant origin, in terms of composition, structure, and matrix. Therefore, the method selected should depend on the purpose of the analysis and the sample type (42, 75).

Indirect techniques, including the Dumas and Kjeldahl methods, are employed to measure the total nitrogen present in a sample. The protein content is then derived using a conversion factor that relates nitrogen to protein. A common factor of 6.25, created in the 19th century, presumes an average nitrogen level of 16% in proteins. Nevertheless, relying on this general factor could result in errors of 15 to 20% when estimating the precise protein content. More accurate conversion factors that take into account variations in amino acid profiles and nitrogen content are suggested. Indirect methods also fail to distinguish between protein nitrogen and non-protein nitrogen (NPN), such as nucleic acids, amines, urea, ammonia, nitrates, nitrites, phospholipids, and nitrogenous glycosides (43). The share of non-protein nitrogen may vary significantly depending on species, growth conditions, fertilization, and processing. This carries both nutritional and financial consequences, especially concerning plant-based protein sources.

Contemporary feed evaluation systems increasingly emphasize precise requirements for essential amino acids (EAA), and non-specific requirements for endogenous amino acids. Therefore, a more precise evaluation of protein's nutritional worth can be achieved by analyzing nitrogen and amino acid concentrations (4, 30). Inadequate EAA supply increases protein turnover, which, in the long term, reduces animal performance, impairs physiological functions (including immunity, hormonal, and enzymatic activity), and increases nitrogen emissions through manure. A critical stage of feed formulation is selecting ingredients in amounts and proportions that meet the complete EAA requirements). Determining the essential amino acid content or the amino acid composition of animal feed is crucial for assessing protein quality and for grasping the impact of storage and processing (14, 53). Amino acid profiling is a direct method, and unlike others, it is not affected by interfering substances or extraction techniques. This makes it especially important for low-protein diets in high-yield livestock (42, 59).

Food matrices consist of a diverse assortment of nutrients that exhibit variations in macro-, meso-, and microstructure, which influence their biological, mechanical, and stability characteristics (8). For food system applications, it is necessary to understand proteins' functional properties, such as viscosity, gelling, fat-binding, water-holding, emulsification, solubility. Functional properties are affected by both internal elements (such as protein arrangement, amino acid order, distribution of charges, as well as their hydrophobic and hydrophilic nature), and external elements (like pH, moisture levels, temperatures, enzymes, chemical additives, and mechanical processing). Alterations in

physicochemical attributes affect how proteins function during storage, processing, preparation, and consumption. A deep understanding of these processes and the development of effective modification methods are crucial for expanding the use of plant-based proteins in both human and animal nutrition, as well as in the food industry (48, 78).

Discussions on the potential consequences of climate change suggest that agriculture is facing increasing climate-related risks. On the one hand, the agricultural sector significantly contributes to adverse environmental and climatic impacts; on the other hand, it holds the potential and tools to mitigate their extent and intensity.

Among the numerous processes that shape the circulation of biogenic elements, the nitrogen cycle holds a unique position. Nitrogen determines the quantity and quality of food and feed produced for humans and animals. Nevertheless, most nitrogen present in the environment exists in forms that are not readily accessible for plants and animals. Since the mid-20th century, agriculture has relied heavily on chemical fertilizers. Excessive and unbalanced use, especially of synthetic fertilizers, negatively affect soil biodiversity and microbial activity. However, soil microorganisms play a fundamental role in maintaining trophic balance in the biosphere, particularly through processes such as diazotrophy. Livestock production remains, and will continue to be, an important sector of agriculture. Population growth, globalization of the market economy and rising consumerism increase demand for food. In debates on food security, much attention is devoted to meeting the demand for dietary protein. In the context of healthy human nutrition, factors beyond just protein content, including the amino acid profile, bioavailability, potential allergenicity, and physicochemical properties, are significant as they affect their functional applications in the food sector. Animal-derived proteins are highly nutritious, which simplifies the process of creating diets. In addition to providing high-quality nutrients, livestock farming also supplies multi-component organic fertilizers, which stimulate plant growth, improve soil quality, and enhance biodiversity. However, the ongoing trend of concentrating and intensifying livestock production poses an increased risk to the environment. Rational animal feeding, proper storage, processing and application of manure, and human diets with a higher share of plant-based foods are the priority actions currently underway.

From an implementation standpoint, the proposed measures differ significantly in both their potential for reduction and the challenges to their broad adoption. In a practical hierarchy, interventions that directly improve nitrogen use efficiency on farms – such as more precise fertilisation, reducing the total protein content in feed rations while balancing exogenous amino acids, and enhancing the storage, processing, and application of natural fertilisers – should be prioritised, as they

can relatively quickly decrease nitrogen surpluses and NH_3 and N_2O emissions, often also providing benefits in production through better feed and fertiliser use (26, 38, 60, 73, 88). The second category involves more structural changes, like increased integration of crop and livestock production or investments in low-emission animal husbandry systems and infrastructure for natural fertiliser management. While these may offer greater long-term gains, they require higher capital investment, access to expert advice, and organisational adjustments – factors that can be especially challenging for small and medium-sized farms (24, 37, 82, 90). Therefore, the actual extent of reduction depends not only on technical feasibility but also on the effective design of agricultural policy tools, including CAP eco-schemes, agri-environmental-climate measures, investment support, and knowledge transfer programmes. At the food system level, dietary shifts – reducing animal product consumption and increasing the share of alternative protein sources – can significantly lessen nitrogen pressures. However, social acceptance depends on price, taste, convenience, cultural norms, perceived nutritional value, and the availability of acceptable alternatives; hence, sustainable change requires consumer education, product innovation, and public policies that make such choices more accessible and socially acceptable, rather than relying solely on individual responsibility (3, 6, 20, 36, 38). Collaboration across various disciplines among researchers, veterinarians, animal scientists, farmers, and community involvement – such as public demand for sustainable farming practices – is vital for realising sustainable agriculture and achieving climate neutrality.

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