Scientific and technical bulletin of Livestock farming Institute of NAAS of Ukraine, 2026, Is. 138
***ISSN* 3083-7987 print**

DOI 10.32900/3083-7987-2026-138-102-116
UDC 636:631.862:551.588.74

GREENHOUSE GAS EMISSIONS AND RENEWABLE ENERGY POTENTIAL FROM BY-PRODUCTS UNDER VARYING MILK PRODUCTION INTENSITIES (REVIEW)

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Received: August 27, 2026
Revised: September 03, 2026
Published: October 30, 2026
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Dairy farming is a significant component of agricultural production; at the same time, it is a sector that places a substantial burden on the climate system due to the generation of greenhouse gases. The primary sources of emissions in dairy operations include enteric fermentation, manure storage and utilization systems, feed production and harvesting, energy consumption, and transport processes. The extent of the climate impact depends significantly on the intensity of milk production, cow productivity, herd size, dietary composition, feed efficiency, and the technologies used to manage organic by-products. Conversely, manure and other organic residues can be viewed as raw materials for renewable energy production.

This paper synthesizes current scientific data regarding the relationship between the intensity of milk production, greenhouse gas generation, and the energy potential of by-products from dairy farming. It analyzes absolute and specific emission levels of CH_4, N_2O, and CO_2-equivalents, as well as animal productivity, the volumes of organic by-products generated, and the potential for their use in energy production.

It is established that increasing the productivity of dairy cows through efficient feed utilization and the optimization of technological processes can help reduce specific greenhouse gas emissions per unit of milk produced. At the same time, intensive production systems generate larger absolute volumes of manure and other organic by-products, creating potential for biogas production. Anaerobic digestion of manure enables the reduction of uncontrolled methane emissions, the generation of electricity and heat, or biomethane, and the production of digestate. The greatest environmental and energy benefits can be achieved through an integrated approach that combines increased animal productivity, efficient feed utilization, improved manure management systems, and the incorporation of organic by-products into biogas production.

Keywords: dairy farming, greenhouse gases, production intensity, biogas, biomethane, renewable energy, life cycle analysis.

ISSN 3083-7987 print

ВИКИДИ ПАРНИКОВИХ ГАЗІВ ТА ПОТЕНЦІАЛ ВІДНОВЛЮВАЛЬНОЇ ЕНЕРГІЇ З ПОБІЧНОЇ ПРОДУКЦІЇ ЗА РІЗНОЇ ІНТЕНСИВНОСТІ ВИРОБНИЦТВА МОЛОКА (ОГЛЯДОВА)

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Дата надходження до редакції: 27.08.2026 р.
Дата прийняття до друку після рецензування: 03.09.2026 р.
Дата публікації: 30.10.2026 р.
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Молочне скотарство є важливою складовою аграрного виробництва та водночас одним із секторів, що формує суттєве навантаження на кліматичну систему внаслідок утворення парникових газів. Основними джерелами викидів у молочних господарствах є ентеричне бродіння, системи зберігання та використання гною, виробництво і заготівля кормів, споживанняенергії та транспортні процеси. Рівень кліматичного впливу істотно залежить від інтенсивності виробництва молока, продуктивності корів, чисельності поголів'я, структури раціонів, ефективності використання кормів і технології поводження з органічною побічною продукцією. Водночас гній та інші органічні залишки можуть розглядатися як сировина для виробництва відновлюваної енергії.

У роботі узагальнено сучасні наукові дані щодо взаємозв'язку між інтенсивністю виробництва молока, утворенням парникових газів та енергетичним потенціалом побічної продукції молочного скотарства. Проаналізовано абсолютні та питомі показники викидів CH_4, N_2O і CO_2-еквіваленту, продуктивність тварин, обсяги органічної побічної продукції та можливості її енергетичного використання.

Установлено, що підвищення продуктивності молочних корів за ефективного використання кормів та оптимізації технологічних процесів може сприяти зменшенню питомих викидів парникових газів на одиницю виробленого молока. Інтенсивні системи виробництва водночас характеризуються більшими абсолютними обсягами гною та інших органічних побічних продуктів, що створює потенціал для виробництва біогазу. Анаеробне зброджування гною дає змогу зменшувати неконтрольовані викиди метану, виробляти електричну і теплову енергію або біометан та отримувати дигестат. Найбільший екологічний та енергетичний ефект може бути отриманий за комплексного підходу, що поєднує підвищення продуктивності тварин, раціональне використання кормів, удосконалення систем управління гноєм та залучення органічної побічної продукції до виробництва біогазу.

Ключові слова: *молочне скотарство, парникові гази, інтенсивність виробництва, біогаз, біометан, відновлювальна енергія, аналіз життєвого циклу*

Introduction. Agriculture plays a significant role in global climate change, accounting for approximately 20–25% of global anthropogenic greenhouse gas (GHG) emissions. A substantial share of these emissions originates from livestock farming –

specifically dairy farming – which is one of the most resource-intensive yet socially vital sectors of the agricultural economy. According to the Food and Agriculture Organization of the United Nations (FAO), milk production is increasing annually in response to rising demand from the population, particularly in developing countries (FAO, 2023).

Dairy farming is characterized by a complex structure of greenhouse gas emissions. The primary component is methane (CH_4), which is generated through enteric fermentation in the rumen of ruminant animals, as well as during the storage and handling of manure. Nitrous oxide (N_2O) is produced mainly through the management of organic fertilizers and feed production, while carbon dioxide (CO_2) is associated with energy consumption, transportation, and the production of mineral fertilizers. The overall climate impact of dairy production depends not only on the size of the livestock herd but also on the intensity of production, animal productivity, dietary composition, and waste management technologies (Bava et al., 2014; Poore et al., 2018; IPCC, 2022).

The intensity of milk production is a key factor determining specific greenhouse gas emissions per unit of product. Extensive systems, which rely primarily on pasture-based management and a low level of technological input, typically generate lower total emissions; however, they are characterized by higher specific emissions per kilogram of milk due to lower cow productivity. In contrast, intensive systems exhibit higher absolute emissions but significantly lower specific emission rates, thanks to high milk yields, optimized feeding, and the mechanization of production processes (Capper & Bauman, 2013; Zehetmeier et al., 2012; Stolarski et al., 2025).

Alongside the challenge of reducing emissions, there is growing interest in utilizing by-products from dairy farming as a source of renewable energy. Manure, slurry, and feed residues serve as valuable feedstock for anaerobic digestion, yielding biogas or biomethane. The application of biogas technologies not only helps mitigate uncontrolled methane emissions during manure storage but also displaces fossil fuels, thereby enhancing the energy autonomy of agricultural holdings (Gerber et al., 2013b; Scarlat et al., 2018).

Contemporary scientific research increasingly examines dairy farming through a systems approach, integrating the analysis of greenhouse gas emissions, productivity, and the energy potential of by-products. Life Cycle Assessment (LCA) has emerged as a primary tool for comparing diverse production systems and evaluating their climate impact within a global context. This approach makes it possible to identify critical points where emissions are generated and to evaluate the effectiveness of integrated strategies for reducing the carbon footprint of dairy production (Flysjö et al., 2012; Henriksson et al., 2011; Prusty et al., 2014; Baldini et al., 2017).

The purpose of this research is to provide a systematic review of open-access international scientific studies focused on assessing greenhouse gas emissions and the potential for renewable energy production from dairy farming by-products under varying production intensities. The main tasks of this work are:

- analyzing the structure and sources of greenhouse gas emissions in dairy farming;
- comparing extensive, semi-intensive, and intensive milk production systems;
- assessing the potential for the bioenergetic utilization of by-products;
- summarizing integrated approaches to reducing emissions and improving energy efficiency.

Materials and methods. The informational and methodological basis of this study comprises scientific publications and methodological documents from the Intergovernmental Panel on Climate Change (IPCC), the Food and Agriculture Organization of the United Nations (FAO), and the International Organization for

Standardization (ISO). The study is based on a systematic and comparative analysis of scientific publications – primarily from the 2020–2025 period – sourced largely from the international scientometric databases Scopus and Web of Science. Methodologies employed include the synthesis and systematization of scientific information, comparative analysis of indicators across extensive, semi-intensive, and intensive milk production systems, life cycle assessment, and the application of IPCC calculation approaches for estimating CH_4 and N_2O emissions (subsequently converted into CO_2 equivalents). Biogas production potential was assessed based on the quantity of organic by-products, their dry matter and volatile solids content, and specific methane yield (IPCC, 2021, 2022; FAO, 2023; ISO 14040:2006).

Research Results.

Greenhouse Gas Emissions in Dairy Farming.

Dairy farming constitutes a complex biotechnological system that generates greenhouse gas emissions varying in origin and intensity. According to assessments by intergovernmental and scientific organizations, the primary gases determining the sector's climate impact are methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) (IPCC, 2022). Their relative contribution varies significantly depending on animal housing technologies, feeding systems, and the management of by-products (Owen & Silver, 2017).

Methane is the dominant component of the carbon footprint in dairy production. It is generated primarily through enteric fermentation within the digestive systems of ruminants and, to a lesser extent, during the anaerobic decomposition of manure. According to FAO estimates, enteric fermentation can account for 45% to 55% of total emissions in dairy farming, making it a key target for climate-oriented management strategies (FAO, 2023).

Nitrous oxide is formed through the microbiological processes of nitrification and denitrification, which occur during manure storage and application, as well as during the cultivation of feed crops. Although the share of N_2O in total emissions by mass is relatively small, its global warming potential is nearly 300 times greater than that of CO_2, resulting in a significant impact even at low emission volumes (IPCC, 2021).

Carbon dioxide emissions in dairy farming are primarily linked to indirect processes, such as the use of fossil fuels for production mechanization, the transport of feed and milk, and the manufacturing of mineral fertilizers. In recent research, $CO_2$is increasingly analyzed within the context of the product's full life cycle, allowing for a more accurate assessment of the climate impact of various production systems (Flysjö et al., 2012). The intensity of milk production is a key determinant of specific greenhouse gas emissions. Scientific literature typically distinguishes between extensive, semi-intensive, and intensive dairy farming systems, which differ significantly in terms of productivity levels, resource consumption, and environmental impact. Extensive systemscommon in regions where pasture-based management predominatesare generally characterized by low cow productivity and limited use of concentrated feeds. Research indicates that while such systems may result in lower absolute emissions, specific emissions per kilogram of milk are often higher due to low milk yields and less efficient feed utilization (Zehetmeier et al., 2012; Smith et al., 2020). Conversely, intensive systems rely on high-yielding breeds, balanced rations, and a high level of technological infrastructure. Despite higher total emissions per farm, these systems exhibit significantly lower specific emission rates, driven by increased milk yield per animal. Capper and Bauman (2013) demonstrated that the intensification of dairy production in the United States has reduced greenhouse gas emissions per unit of product by more than 60% compared to the mid-20th century. Semi-intensive systems combine elements of pasture-

based and stall-based management and are often viewed as a compromise between environmental sustainability and economic efficiency. However, research results indicate that their climate profile depends significantly on local conditions, the structure of the feed base, and the level of manure management (Henriksson et al., 2011; Rotz et al., 2021).

Table 1 presents milk productivity and greenhouse gas emission intensity at different levels of milk production intensity.

According to Dida et al. (2024), in 120 pasture-based dairy farms in Australia, an increase in the level of concentrate feeding was associated with a decrease in calculated emission intensityfrom 0.85 to 0.63 kg CO_2-eq/kg FPCM (a reduction of approximately 26%) excluding emissions from the production of the concentrates themselves. When such emissions are taken into account, the corresponding values were 0.90 and 0.77 kg CO_2-eq/kg FPCM (a reduction of approximately 14%). Thus, the assessment of the environmental impact depends on the boundaries adopted for emissions accounting.

Table 1

Effect of the level of concentrate feed supplementation on the calculated greenhouse gas emission intensity in Australian pasture-based dairy farms (Dida et al., 2024)

Country	Feeding of concentrates, tonnes of dry matter/head/year	Level ofconcentratefeeding	Emission intensity excluding concentrate production, kg CO_2-eq/kg FPCM	Emission intensity associated with concentrate production, kg CO_2-eq./kg FPCM
Australia	≤ 1	low	0.85 ± 0.019	0.90 ± 0.071
Australia	1–2	moderate	0.72 ± 0.010	0.79 ± 0.065
Australia	2–3	high	0.68 ± 0.007	0.79 ± 0.049
Australia	≥ 3	veryhigh	0.63 ± 0.005	0.77 ± 0.039

Source: Dida et al. (2024), Tables 6 and 7. FPCM = fat- and protein-corrected milk; values are presented as means ± standard error. Farm groups are compared based on the volume of concentrates fed, rather than on independently defined productivity categories.

Thus, the impact of production intensity on greenhouse gas emissions is non-linear and requires assessment within the context of specific production systems, using standardized analytical methods.

Life Cycle Assessment (LCA) has emerged as the leading methodological approach for studying greenhouse gas emissions in dairy farming. Its key advantage lies in the ability to comprehensively evaluate the environmental impact of milk production, accounting for all stages – from feed cultivation to the transport of finished products. In LCA, particular attention is paid to the selection of a functional unit, most commonly defined as 1 kg of energy-corrected milk (ECM). This allows for accurate comparisons between different production systems, regardless of animal productivity levels (Flysjö et al., 2012).

Research indicates that incorporating the bioenergy use of manure into the LCA system boundaries can significantly alter assessment results. The use of anaerobic digestion can reduce the overall carbon footprint of dairy production by mitigating uncontrolled methane emissions and displacing fossil-based energy sources (Scarlat et al., 2018). Despite its widespread application, Life Cycle Assessment (LCA) has several limitations, most notably, the high sensitivity of its results to the quality of input data and

the assumptions made. This underscores the need to harmonize methodologies and utilize open-access databases to improve the reproducibility of results on a global scale.

By-products from dairy farming, such as manure, slurry, and feed residues, represent a significant yet frequently overlooked source of renewable energy. Current estimates suggest that only a fraction of this bioresource is utilized effectively; a substantial portion remains a source of uncontrolled methane and nitrous oxide emissions into the atmosphere (Mazurkiewicz, 2023; Oyedun et al., 2025). As demands for the decarbonization of the agricultural sector intensify, the energy recovery from these by-products is increasingly viewed as a key instrument for the sustainable development of dairy production (Ledgard et al., 2020; Malliaroudaki et al., 2022; Ni et al., 2025).

Cattle manure is characterized by a high organic matter content and a consistent generation rate throughout the year, making it a suitable feedstock for biogas production via anaerobic digestion. Unlike energy crops, the use of manure does not compete with food production and requires no additional land resources – a significant advantage from the perspective of environmental sustainability (Scarlat et al., 2018). Research indicates that the biogas potential of dairy manure depends heavily on animal housing conditions, dietary rations, and dry matter content. On average, 1 tonne of cattle manure can yield between 20 and 30 m³ of biogas, of which 55–65% is methane. Furthermore, the efficiency of converting biomass into energy increases when manure is co-fermented with other organic substrates, such as maize silage or food waste (Varol & Ugurlu, 2017; Masih-Das & Tao, 2018).

The intensity of dairy production directly influences not only greenhouse gas emission levels but also the potential for renewable energy generation. Intensive systems characterized by high livestock density and indoor housing create favorable conditions for the centralized collection of manure and its subsequent processing in biogas plants. This significantly reduces logistics costs and enhances the economic viability of bioenergy projects. Conversely, extensive systems often face limited access to biogas technologies due to the dispersed nature of livestock rearing and the seasonal generation of manure. Nevertheless, such systems can demonstrate superior environmental performance by combining pasture-based management with small-scale, localized bioenergy solutions tailored to the needs of individual farms or cooperatives (Henriksson et al., 2011; Van Middelaar et al., 2014).

Semi-intensive systems occupy an intermediate position and are frequently regarded as the most promising in terms of integrating bioenergy technologies on a regional scale. It is precisely in such systems that the optimization of the ratio between milk production volumes, emission levels, and energy yield from by-products is possible (Kristensen et al., 2011; Abbas et al., 2026).

Table 2 compares three model levels of dairy productivity used by Zehetmeier et al. (2012) with the estimated methane potential from manure, based on Miranda et al. (2016). These data originate from different studies and do not constitute a single, unified experiment. The specific emission values under economic allocation are confirmed as follows: 1.06 and 0.89 kg CO_2-eq./kg of milk, corresponding to productivity levels of 6,000 and 10,000 kg/cow/year, respectively. Other numerical values that could not be verified against the available text of the original sources are omitted from the table.

This effect is primarily explained by the distribution of so-called "maintenance" emissions over a larger volume of output. Each cow requires a certain amount of energy and nutrients to sustain vital functions, regardless of the volume of milk produced. Keeping an animal entails CH_4 emissions from enteric fermentation, CH_4 and N_2O emissions during manure storage and application, as well as indirect emissions from feed production and the use of energy and other resources. With higher productivity, these

emissions are distributed over a larger quantity of milk, resulting in a lower value for kg CO_2-eq./kg of milk (Zehetmeier et al., 2012; Capper & Bauman, 2013; Manono, 2026).

Table 2

Comparison of greenhouse gas emissions and the estimated bioenergy potential of manure at different levels of milk productivity (based on Zehetmeier et al., 2012; Miranda et al., 2016)

Indicator	Low intensity	Medium intensity	High intensity	Source
Milk yield, kg/cow/year	6 000	8 000	10 000	Zehetmeier et al., 2012
GHG, kg CO_2-eq/kg milk	—	—	—	Not confirmed based on the available text of Zehetmeier et al., 2012
GHG based on economic allocation, kg CO_2-eq/kg milk	1.06	—	0.89	Zehetmeier et al., 2012 (extreme values)
CH_4 yield from manure, m³ CH_4/kg VS	0.190–0.230	0.190–0.230	0.190–0.230	Miranda et al, 2016
Energy potential of manure, kWh/kg VS	1.89–2.29	1.89–2.29	1.89–2.29	Calculated based on Miranda et al., 2016

Note: GHG — greenhouse gases; CO2-eq — CO2-equivalent; VS — volatile solids. The methane yield and energy potential figures characterize the properties of the substrate and are not direct results from the study by Zehetmeier et al. (2012). Intermediate specific GHG values should be cross-checked against the full text of the original source. The symbol "—" indicates that the numerical value is not confirmed in the available text of the original source; it does not represent a zero value. The row excluding economic allocation has been removed from the quantitative comparison pending full verification.

A comparison of three productivity levels (6,000, 8,000, and 10,000 kg/cow/year) in Zehetmeier et al. (2012) demonstrates that emission estimates depend on system boundaries and the method used to account for the co-production of beef. With economic allocation, specific emissions are shown to decrease from 1.06 to 0.89 kg CO_2-eq/kg of milk between the lowest and highest productivity levels. The intermediate value requires verification against the full text of the article.

Increasing milk yield does not necessarily imply a reduction in the total emissions of the entire production system. The outcome may vary depending on whether the reduction in beef production from the dairy herd is compensated for by other sources. The data regarding the methane potential of manure in Table 2 represent a separate, generalized estimate per unit of volatile solids (VS), rather than a measurement specific to each milk yield level.

A meta-analysis by Miranda et al. (2016), covering 115 publications and 2,181 experimental cases, demonstrated that CH_4 yield from dairy cattle manure depends on the anaerobic digestion technology employed. Mean values were 0.230 ± 0.016 m³ CH_4/kg VS for batch reactors, 0.190 ± 0.016 m³ CH_4/kg VS for CSTRs, and 0.204 ± 0.032 m³ CH_4/kg VS for semi-continuous systems.

Using the range of 0.190–0.230 m³ CH4/kg VS for a generalized estimate and given an energy equivalent for methane of approximately 9.97 kWh/m³, the theoretical energy potential is roughly: 0.190 × 9.97 = 1.89 kWh/kg VS and 0.230 × 9.97 = 2.29 kWh/kg VS. Thus, 1 kg of volatile solids (VS) in manure potentially corresponds to approximately 1.89–2.29 kWh of chemical energy in the form of methane. This figure should not be equated with actual electricity generation, as technical losses occur during the conversion of biogas into electrical and thermal energy. At the same time, the identical value of 0.190–0.230 m³ CH4/kg VS across the three productivity levels shown in the table does not imply that low-, medium-, and high-yielding cows possess the same total bioenergetic potential in their manure. Miranda et al. determined that CH4 yield depends primarily on substrate characteristics and reactor technology, rather than on the productivity of the cows. The total potential CH_4 yield is determined by the mass of manure, dry matter content, the proportion of volatile solids (VS), the diet, feed digestibility, the number of animals, and the efficiency of manure collection.

Increasing productivity can reduce greenhouse gas (GHG) emissions per kilogram of milk, while anaerobic digestion offers a means to manage the methane potential of manure by converting a portion of the organic matter into useful energy. Therefore, evaluating the efficiency of intensive dairy production based solely on cow productivity is insufficient. A comprehensive assessment should incorporate several parameters: kg CO_2-eq per kg of milk, absolute CH_4 and N_2O emissions, the quantity of manure generated, VS content, potential CH4 yield, and the energy potential of the manure.

The application of biogas technologies in dairy farming is viewed not only as a method for producing renewable energy but also as an effective mechanism for reducing greenhouse gas emissions. Anaerobic digestion of manure mitigates methane emissions during the storage of organic waste while simultaneously enabling the production of heat and electricity, or biomethane for use in transport (Scarlat et al., 2018).

According to LCA studies, integrating biogas plants into dairy farms can reduce the total carbon footprint of milk production by 10–30%, depending on the scale of production and the efficiency of energy utilization from the biogas (Peters et al., 2010; Villarroel-Schneider et al., 2022; Rotz et al., 2025). An additional benefit is the production of digestate, which can be used as an organic fertilizer with improved agrochemical properties and a lower potential for N_2O emissions compared to untreated manure.

Figure 1, based on literature data (Miranda et al., 2016; U.S. EPA, 2021), presents a schematic model of a dairy farm with bioenergy utilization of by-products, combining milk production, manure management, and renewable energy generation.

Despite significant potential, the implementation of bioenergy technologies in dairy farming faces several limitations. Key challenges include high initial investment costs, the need for skilled technical personnel, and the dependence of economic viability on government support and tariff policies ((Dankevych et al., 2022; Dadi et al., 2025). At the same time, global trends toward decarbonization and the development of a circular economy are creating favorable conditions for the further adoption of biogas technologies. Recent research places particular emphasis on combining bioenergy solutions with improvements in animal feeding efficiency and breeding; this approach yields a synergistic effect, simultaneously reducing emissions and enhancing productivity in the dairy sector.

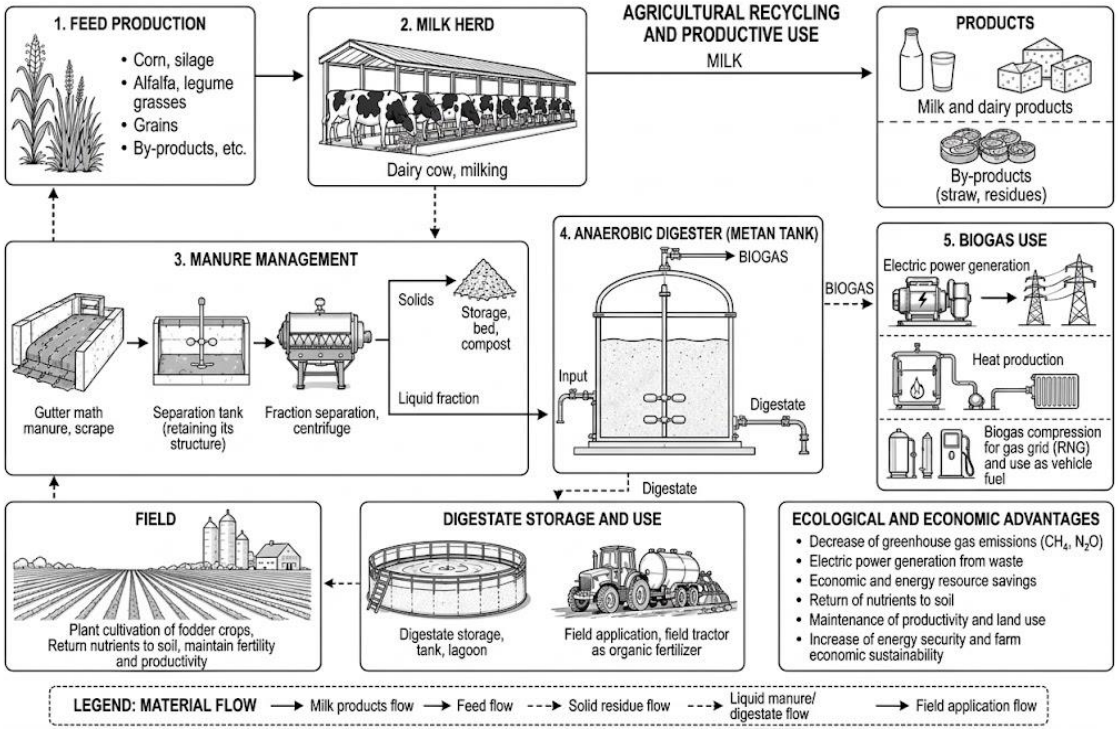

Fig. 1. **Integrated model of a dairy farm utilizing by-products for bioenergy**

Discussion. A comprehensive review of international research indicates that greenhouse gas emission levels in dairy farming are closely linked to production intensity, the composition of the feed base, and methods for managing by-products. A comparative analysis of extensive, semi-intensive, and intensive systems reveals that no single system can be definitively classified as the most environmentally optimal without considering local conditions and integrated management strategies (Rotz et al., 2020).

Intensive milk production systems exhibit the lowest specific greenhouse gas emissions per unit of product, a finding consistent with research by Capper and Bauman (2013) and Henriksson et al. (2011). High animal productivity, optimized diets, and efficient resource utilization make it possible to reduce the carbon footprint per kilogram of milk, even though absolute emission volumes per farm may be higher. At the same time, such systems require significant energy inputs and may pose additional environmental risks associated with the concentration of manure.

Extensive systemscommon in many regions with well-developed pasture-based livestock farmingare characterized by a lower anthropogenic burden; however, they often result in higher specific emissions due to lower milk yields. This underscores the importance of shifting from an assessment based solely on absolute emissions to a full life-cycle analysis, which allows for an objective comparison of different production models (Flysjö et al., 2012).

Recent research has focused specifically on integrating bioenergy technologies into dairy production. The use of anaerobic digestion for manure is considered an effective tool for simultaneously reducing methane emissions and enhancing the energy self-sufficiency of farms. According to Adam et al. (2025) and Hao et al. (2025), incorporating biogas plants into manure management systems can significantly lower the overall carbon footprint of dairy production, particularly within intensive and semi-intensive systems.

In a modeling study, Zehetmeier et al. (2012) analyzed three productivity levels: 6,000, 8,000, and 10,000 kg of milk per cow per year. Using economic allocation, specific

emissions attributed to milk decreased from 1.06 to 0.89 kg CO_2-eq/kg of milk between the extreme productivity levels. At the same time, the authors emphasize that the results depend on system boundaries, the accounting for co-produced beef, and model assumptions. Unverified intermediate numerical estimates are not used in this review.

However, these results do not imply that maximizing productivity automatically ensures the lowest total GHG emissions. Zehetmeier et al. demonstrated that the conclusion depends significantly on the boundaries of the system under study. If the total volume of milk at the system level remained constantand the reduction in beef production from the dairy herd was not compensated forthen increasing productivity reduced total GHG emissions. Conversely, when both milk and beef production were kept constant, increasing productivity from 6,000 to 8,000 kg resulted in virtually no change in total emissions, while at 10,000 kg, emissions were approximately 8% higher. The reason lies in the close interlinkage between dairy and beef production. As productivity increases, fewer dairy cows are required to produce a given quantity of milk. Consequently, there is a simultaneous reduction in the number of culled cows and calves that enter the beef production chain. If a beef deficit is compensated for by specialized beef cattle farming, some of the climate advantage gained from increased dairy productivity may be lost. In the study, using economic allocation, emissions attributed to milk decreased from 1.06 to 0.89 kg CO_2-eq/kg, whereas emissions attributed to beef increased.

The figure of 0.89 kg CO_2-eq/kg of milkachieved at a yield of 10,000 kg per cow per year using economic allocationdoes not prove that maximum-intensity production is unconditionally superior. It should be interpreted only within the context of the specific scenario and the method used to allocate emissions between milk and beef (Zehetmeier et al., 2012).

As productivity increases, feed intake, diet composition, organic matter excretion, and manure characteristics all change. Therefore, evaluating production intensity based solely on the CO_2-eq/kg of milk does not fully characterize the environmental efficiency of the system. Manure serves two fundamentally different functions. Under traditional storage methods, it acts as a source of greenhouse gases (GHGs), primarily CH_4 and N_2O. At the same time, the organic matter in manure serves as a feedstock for anaerobic digestion; the methane, which might otherwise be released into the atmosphere, can be captured within biogas and utilized as an energy resource (Reisinger et al, 2021; Miranda et al., 2016).

Therefore, when comparing systems with productivity levels of 6,000, 8,000, and 10,000 kg of milk per cow per year, it is appropriate to analyze not only GHG emissions per kilogram of milk but also the volatile solids (VS) content of the manure, the potential CH_4 yield, the energy potential, and the potential for emission reductions through anaerobic digestion. This approach allows for a shift from the traditional view of "livestock waste" to the concept of a by-product that functions as a renewable bioenergy resource. In operations with high livestock density, a key advantage of intensive dairy farmsbeyond higher milk volumeis the ability to centrally collect large quantities of manure. This creates the necessary technological conditions for operating an anaerobic digester and utilizing biogas to generate electricity and heat. Furthermore, the resulting digestate can be returned to the agricultural system as a source of nutrients (Zehetmeier et al., 2012; Miranda et al., 2016). Consequently, for an integrated system, it is appropriate to consider a closed-loop technological cycle:

feed → dairy herd → milk + manure → anaerobic digestion → biogas + digestate → energy + field fertilization → feed production.

The synthesis by Zehetmeier et al. (2012) confirms the necessity of accounting for system boundaries and by-products when assessing the carbon footprint of milk. For

productivity levels of 6,000 and 10,000 kg per cow per year, and applying economic allocation, the values are 1.06 and 0.89 kg CO_2-eq per kg of milk, respectively. The potential methane yield from manureexamined separately by Miranda et al. (2016) reflects substrate properties and anaerobic digestion conditions; it does not establish a direct correlation with milk yield.

Moreover, intensification should not be evaluated solely based on specific greenhouse gas (GHG) emissions per unit of milk. It is essential to consider total system emissions, the interlinkage between dairy and meat production, the feed base, manure generation and management, and the potential for anaerobic digestion. A comprehensive combination of high productivity, efficient manure management, and biogas production can simultaneously enhance resource efficiency and reduce the climate impact of dairy farming (Weiske et al., 2006; Ye, M., & Li, Y.-Y., 2023; Rahic et al., 2025).

Furthermore, the economic viability of bioenergy solutions depends significantly on the scale of production, access to investment, and government support. This underscores the need for an integrated approach that combines the technological, economic, and environmental dimensions of sustainable dairy farming.

Conclusions:

1. A review of international open-access scientific research indicates that dairy farming is a key source of greenhouse gas (GHG) emissions in the agricultural sector, with emission levels depending significantly on production intensity and the technologies employed. The primary components of the carbon footprint in dairy production are methane, nitrous oxide, and carbon dioxide; methanegenerated through enteric fermentation and manure storageplays the dominant role.

2. A comparative analysis of various production systems reveals that intensive systems yield the lowest specific GHG emissions per unit of milk. Conversely, extensive systems exhibit higher specific emission rates but may offer advantages regarding the preservation of natural ecosystems. Semi-intensive systems represent a promising compromise, capable of balancing productivity with environmental sustainability, provided that by-products are managed effectively.

3. Utilizing by-products from dairy farming for renewable energy production, specifically through the anaerobic digestion of manure, offers significant potential for reducing GHG emissions and enhancing the energy efficiency of the sector. Integrating biogas technologies into production systems helps minimize methane losses, displace fossil fuels, and foster the development of a circular economy.

4. The obtained results confirm the validity of applying a systems approach and life cycle analysis to assess the climate impact of dairy farming. Future research should focus on quantifying regional variations in bioenergy potential and developing integrated strategies for emission reduction in dairy production, while taking economic and social factors into account.

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