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# Quantifying and Mitigating Greenhouse Gas Emissions in Egg-Laying Hen Farming: A Path Towards Carbon Neutrality

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**ABSTRACT**

This study presents a comprehensive framework for assessing and mitigating greenhouse gas (GHG) emissions in commercial egg-laying hen farming in Uttaradit Province, with the aim of achieving carbon neutrality within the poultry sector. Employing a detailed life cycle assessment (LCA) over a 450-day production period, this research identifies key sources of emissions, with feed consumption identified as the largest contributor, followed by water use and energy demands. To address these emissions, the study explores several innovative strategies: transitioning to solar photovoltaic systems for lighting and water pumping, shifting from diesel to biodiesel for fuel, and optimizing feed compositions. Additionally, advanced manure management practices are proposed to reduce methane and nitrous oxide emissions. Collectively, these interventions could significantly diminish the emissions associated with hen farming operations, thereby advancing environmental sustainability. This work not only provides actionable insights for poultry farms seeking to lower their emissions but also offers a scalable and adaptable model with broader implications for sustainable practices across the agricultural sector. The findings underscore the importance of renewable energy integration, feed optimization, and efficient waste management in mitigating the environmental impact of agriculture, thereby informing both policy and practice in the pursuit of carbon-neutral food production.

## 1. Introduction

Global warming, driven by the accumulation of greenhouse gases (GHGs) in the atmosphere, poses a significant environmental challenge in contemporary society. GHGs, including carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$), are responsible for trapping heat within the Earth's atmosphere. This phenomenon results in rising global temperatures, the melting of polar ice caps, and an increase in the frequency of extreme weather events. The combustion of fossil fuels, deforestation, and agricultural practices are key contributors to the escalation of $CO_2$ levels [1]. Climate change is strongly correlated with a range of severe consequences, including exacerbated air pollution, increased health risks, and the potential for 6 to 9 million premature deaths annually by 2060 [2]. The greenhouse effect, resulting from the retention of infrared radiation by GHGs, is inducing significant alterations in climate patterns, such as an increase in the frequency of heatwaves and rising sea levels [3]. Although the urgency of addressing global warming is widely acknowledged, the intricate interplay of social, economic, and political factors presents challenges to the implementation of effective solutions [4]. The agricultural sector is responsible for approximately 24% of global GHG emissions, significantly contributing to climate change. Livestock production, particularly poultry farming, plays a substantial role in GHG emissions due to $CH_4$ released during manure management and the energy requirements for feed production. Although the GHG impact of poultry farming is generally lower than that of ruminant livestock, the livestock sector contributes about 14.5% of total anthropogenic GHG emissions, with poultry accounting for a smaller, yet steadily increasing, share [5]. While poultry production has lower GHG emissions per unit of product compared to ruminants, emissions from the poultry sector have been rising, highlighting the urgent need for sustainable practices to mitigate its environmental impact.

Laying hens for egg production constitute a fundamental component of the global food system, providing a critical source of protein for millions, particularly as the global population is anticipated to reach 9.7 billion by 2050. The poultry sector, and egg production specifically, will play an essential role in meeting the increasing demand for affordable and accessible protein sources necessary to sustain global food security [6]. Furthermore, the poultry industry contributes significantly to food security by supplying essential nutrients and promoting economic growth on a global scale. The egg-laying phase represents a substantial contributor to GHG emissions, with research indicating that feed production serves as a primary determinant of the carbon footprint associated with this phase [7]. GHG emissions from layer farms can reach as high as 5.612 $kgCO_2eq$/kg of eggs produced, underscoring the critical importance of this phase in the life cycle assessment (LCA) of egg production [8]. Strategies aimed at mitigating GHG emissions within the poultry sector encompass enhancements in feed efficiency, optimization of manure management practices to curtail emissions, and the integration of renewable energy technologies. For example, the anaerobic digestion of manure can convert waste into biogas, thereby reducing $CH_4$ emissions and overall energy consumption by as much as 85% [9]. Furthermore, the adoption of renewable energy sources, such as wind and solar power, presents significant potential for the reduction of carbon footprints, with wind turbines estimated to diminish carbon dioxide emissions by approximately 17,155 $kgCO_2eq$/annually, and hybrid photovoltaic-geothermal systems achieving reductions of 8.3 $tCO_2eq$ [10]. Although the initial financial investment required for the implementation of renewable energy technologies may be considerable, the long-term savings in energy costs and emission reductions generally yield a payback period ranging from 3 to 8 years [11]. Smaller-scale farms may face financial barriers to adopting sustainable systems. Achieving long-term environmental sustainability in the poultry sector requires continuous innovation and the adoption of sustainable practices. Comprehensive LCAs are crucial for quantifying emissions, evaluating emerging technologies like alternative feeds, advanced manure treatment, and renewable energy, and identifying strategies to reduce the industry's ecological footprint [12]. The study conducted by Reijnders [13] provides a comprehensive assessment of emissions from resource extraction to waste disposal (cradle-to-grave), offering a broad perspective on environmental impacts. Although this approach is data-intensive, it is invaluable for understanding full life cycle emissions and identifying opportunities for system-wide optimization. In contrast, studies by Grassauer et al. [14] and Maciel et al. [15] focus on emissions up to the production phase (cradle-to-gate), which are particularly useful for analyzing major contributors to greenhouse gas (GHG) emissions, such as feed production and management practices. This narrower focus facilitates targeted upstream strategies while balancing data requirements. Guillaume et al. [16] further narrow their assessments to the production phase (gate-to-gate), effectively identifying specific on-site operational improvements. However, this limited scope may overlook both upstream and downstream impacts. Recognizing the need for a pragmatic approach, this study adopts a gate-to-gate framework that concentrates on operational enhancements. This focus enables a detailed analysis of on-site activities within egg-laying hen farming, facilitating specific recommendations aimed at improving practices such as optimizing feed utilization and incorporating renewable energy solutions. This methodological approach aligns with the study's objective of providing implementable strategies to mitigate GHG emissions, with an emphasis on advancements in feed efficiency and energy utilization.

The primary objectives of this research encompass the identification of significant emission sources, the quantification of their environmental impacts, and the proposal of targeted mitigation strategies to promote carbon neutrality within the poultry sector. To further reduce the environmental footprint, the study underscores the significance of optimized feed strategies and effective manure management practices, both of which have the potential to substantially diminish emissions. Moreover, the recommendations advocate for the adoption of energy-efficient technologies and the integration of renewable energy sources, such as solar power and biodiesel, to enhance the sustainability of farm operations. These strategies aim not only to help poultry farmers reduce operational costs and enhance environmental sustainability but also to position the egg-laying industry as a leader in global climate change mitigation efforts. By promoting practical, scalable solutions, the study aims to encourage broader industry adoption and support future research into sustainable practices within the poultry sector.

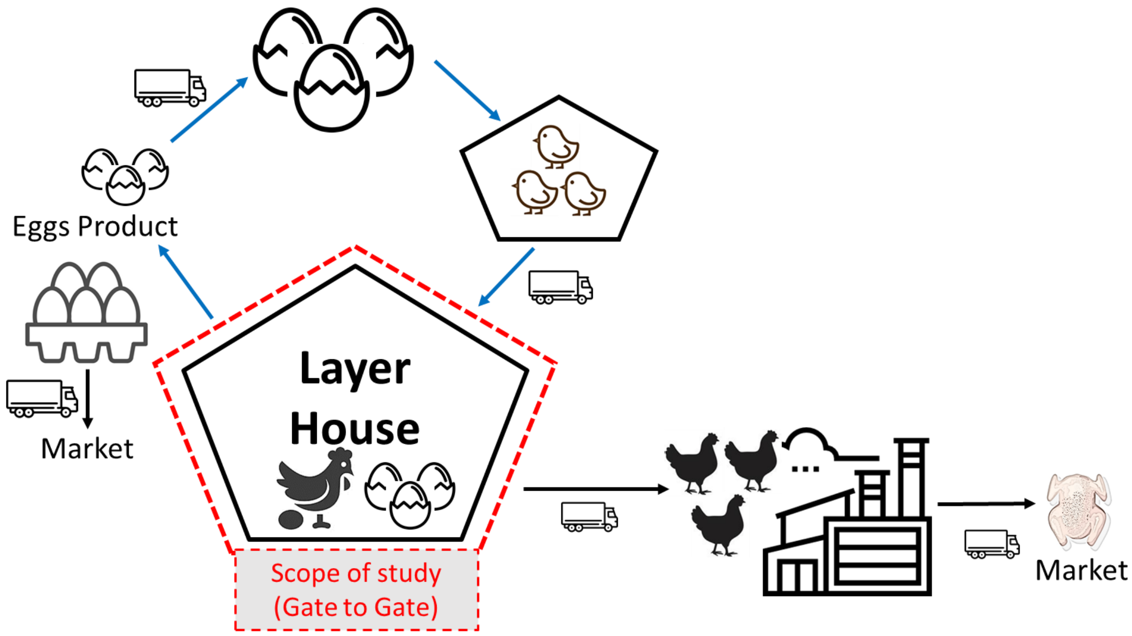


Fig. 1 Boundary and scope of this study.

**2. Methodology**

The evaluation of GHG emissions from laying hens, following the principles of LCA, was carried out using a systematic research methodology consisting of four distinct steps [17].

*2.1 Goals and scope of study*

This study evaluated the GHG emissions associated with egg-laying hen farming at a commercial layer farm situated in Wang Kapee Subdistrict, Mueang District, Uttaradit Province, Thailand. The assessment specifically focused on the egg-laying phase of the hens' lifecycle, encompassing the period from their introduction to the farm until their removal for sale (Fig. 1). The farm, which has a capacity of 9,800 hens, utilized a closed-house system. The study concentrated on on-farm activities, including feeding, cleaning, and energy consumption, over a 450-day period. The primary objective of the study is to quantify emissions from on-farm activities during this specific lifecycle stage, thereby enabling a focused analysis of on-site processes.

*2.2 Life Cycle Inventory Analysis (LCI)*

The life cycle inventory analysis was performed in accordance with the ISO 14040-44 standards, complying with the established methodologies and employing the formats and recommendations prescribed by these standards [18]

In this study, the poultry facility was designed as a closed, single-unit structure. The environmental control system comprises the following components:

- the ventilation system features a 5-blade fan powered by a 14 hp diesel tractor engine. Two primary units and two backups operate 24 hours a day, controlled automatically based on humidity and temperature. Filters are cleaned biweekly for optimal air circulation. Diesel fuel consumption data were collected using fuel receipts in conjunction with measuring the amount of fuel refilled during each instance.

- the electrical system powers two lighting setups: 60 yellow bulbs (3W each) for 19 hours/day and 36 white bulbs (5W each) for 2 hours/day during feeding and egg collection. A 1,500W pump operates 15–18 hours/day for groundwater cooling and floor cleaning, while a 650W system runs 3 hours/day for pumping tap water for drinking and vitamin mixing. Electricity consumption was determined using the facility's electric meter readings in combination with electricity bill records.

- Chicken manure is manually collected every 2–3 weeks, dried, and sold for fertilizer production. The weight of chicken manure was recorded by weighing it after collection, prior to bagging and storage for sale.

- The chickens are fed a pelletized complete feed for laying hens, requiring 38 bags (1,140 kg) daily.

- Groundwater used for cooling and cleaning was measured per usage based on the water storage tank levels, similarly to tap water used for chicken consumption.

This structure and system are designed to maintain optimal conditions for poultry health and productivity. Key inputs include feed, water, and energy, which are essential for daily operations. Feed consumption produces GHG emissions; water is vital for drinking and sanitation; and energy is required for lighting, heating, and ventilation. The primary outputs consist of eggs and manure. This analysis emphasizes resource-intensive areas and sources of emissions, facilitating the identification of opportunities for improvement aimed at mitigating the environmental impact of egg production (Fig. 2).

This study adopts a streamlined approach rather than a gate-to-gate scope, excluding antecedents like feed production, chicken transport, and the transport and sale of eggs during on poultry farms. Emissions are implicitly measured as daily emissions per chicken. Including these additional elements would enhance clarity and provide actionable insights for reducing emissions in egg production, thereby enabling more effective comparisons with other life cycle assessment studies in the agricultural sector.

*2.3 Life Cycle Impact Assessment (LCIA)*

In life cycle impact assessment, selecting an appropriate impact assessment methodology is crucial for accurately characterizing environmental impacts. For GHG emissions, the Intergovernmental Panel on Climate Change (IPCC) methodology is widely used to calculate global warming potential (GWP), expressing emissions as $CO_2$-equivalents over a specified timeframe—100 years in this study. This approach provides a standardized metric by weighting emissions from diverse sources based on their impact, making it particularly effective for assessing and mitigating climate-related impacts in agricultural settings, such as direct energy use, feed, and manure management. The GHG emissions assessment in this study is based on the IPCC methodology, following the principles of LCA and calculation methods detailed in equation (1) [19]. This approach ensures an accurate quantification of total GHG emissions generated by the laying hen operation, offering a clear estimation of GHG emissions over the egg-laying period.

$$GHG_{emission} = \sum(A_i \text{ X } EF_i) \tag{1}$$

Where '$GHG_{emission}$' denotes the total quantity of GHG emitted from the activity, quantified in kilograms of carbon dioxide equivalent ($kgCO_2eq$). 'A' represents the activity data (Unit) that contributes to GHG emissions, measured in specific units (e.g., energy consumption, feed utilization). 'EF' designates the emission factor, which indicates the GHG emission coefficient, expressed in $kgCO_2eq$ per unit of the activity.

The emission factors are obtained from the Thailand Greenhouse Gas Management Organization (TGO) and the SimaPro software. Furthermore, 'i' denotes the various activities that contribute to GHG emissions. The assessment results are expressed in $kgCO_2eq$/day and $kgCO_2eq$/hen, calculated from the weighted average of daily resource consumption.

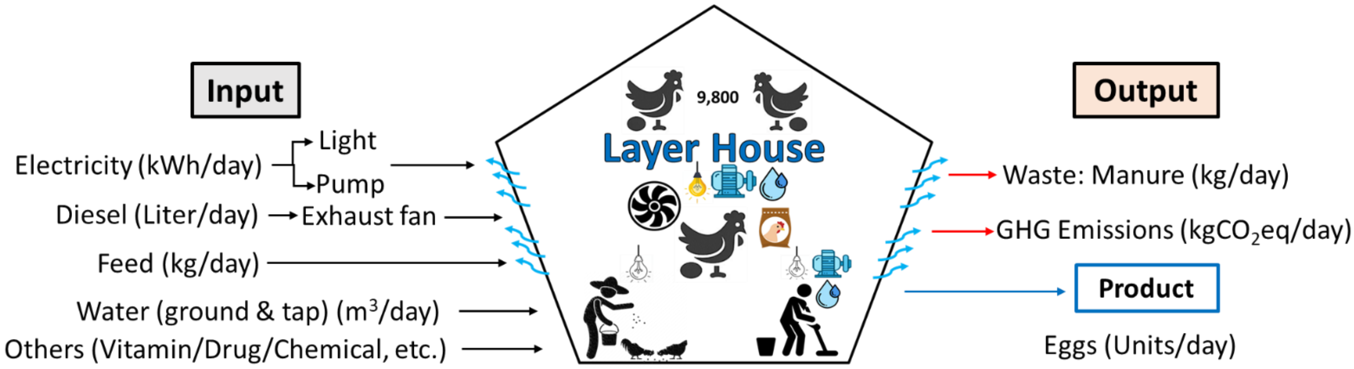


Fig. 2 The life cycle inventory of egg-laying hen farming.

*2.4 Interpretation and Recommendations*

The final stage of the GHG emission assessment involves interpreting the findings and formulating strategies to reduce emissions. This entails pinpointing the primary sources of GHG emissions within the egg-laying hen production system, such as energy consumption, feed, and manure management. Subsequently, tailored recommendations are provided to poultry farmers for adopting practices that minimize their emissions, including optimizing feed efficiency, improving manure management, and transitioning to renewable energy sources. These measures are designed to align with global initiatives aimed at reducing the agricultural sector's carbon footprint and mitigating climate change.

**3. Results and Discussions**

*3.1 Assessment of GHG Emissions in Egg-Laying Hen Farming*

This section evaluates the GHG emissions associated with various processes within a laying hen farm, with a focus on key factors such as feed resource utilization, water consumption, and energy expenditures. Table 1 offers a detailed breakdown of resource use and emissions across each category, providing a comprehensive overview of these contributions.

Fig. 3 shows that feed consumption is the primary contributor to GHG emissions, representing nearly 94% of the total emissions, or approximately 807.46 kg $CO_2$-eq/day. These results are consistent with findings by Usubharatana and Phungrassami [20], who reported that chicken feed contributes 45–55% of total GHG emissions. Similarly, Guillaume et al. [16] emphasized that feed composition is a critical factor influencing GHG emissions in egg production. This underscores the significant environmental impact of feed production and transportation, suggesting that enhancing feed efficiency or sourcing more sustainable feed could lead to substantial reductions in overall emissions.

Cleaning activities that utilize groundwater account for roughly 3% (27.63 $kgCO_2eq$/day) of total emissions, making it the second-largest source. Given the high-water usage, implementing water-saving measures or recycling systems could lower both water consumption and GHG emissions.

Manure management is responsible for just under 1% (8.53 $kgCO_2eq$/day) of daily emissions. While this figure is relatively low, optimizing manure handling—such as repurposing it as fertilizer—could further minimize emissions and add value to waste management efforts.

Diesel-powered ventilation systems contribute 0.75% (6.41 $kgCO_2eq$/day) of emissions. Transitioning to electric or renewable-powered fans could slightly lower emissions and enhance air quality within the facility. Electricity-related emissions make up only about 0.51% (4.33 $kgCO_2eq$/day) of the overall emissions. Although minor, optimizing lighting and pumping systems or utilizing renewable energy sources can still contribute to overall environmental improvements.

Drinking water usage for chicken's accounts for 0.45% (3.84 $kgCO_2eq$/day) of daily emissions. While necessary, slight adjustments in water usage efficiency could yield modest reductions in emissions. General groundwater usage constitutes 0.22% (1.85 $kgCO_2eq$/day) of total emissions. Reducing or optimizing groundwater usage could have a small positive effect on emissions.

The total GHG emissions are calculated at 860.05 $kgCO_2eq$/day, with daily emissions estimated at approximately 39.49 $kgCO_2eq$/hen. Notably, our findings reveal higher per-hen emissions compared to those reported by Kassab and Fouda [21], who estimated emissions at 30.165 $kgCO_2eq$/hen in a closed-system farm. This discrepancy may stem from differences in system boundaries, farm management practices, or regional factors, underscoring the importance of standardized assessment methodologies in life cycle assessment within poultry farming.

The assessment of energy consumption for lighting, ventilation, and pumping systems in poultry housing indicates a substantial dependence on conventional energy sources, particularly fossil fuels, which are major contributors to GHG emissions [4]. Although electricity is not the primary source of emissions in poultry farming, there is significant potential for reductions through the implementation of energy-efficient systems or the integration of renewable energy technologies [9-11].

Additionally, the use of diesel-powered Ventilation fans in barn operations highlights a critical area for emissions mitigation. This analysis identifies feed consumption and water used for cleaning as the primary contributors to GHG emissions. Modifying feed sources, optimizing water use, and transitioning to renewable energy for electricity and diesel generation could substantially reduce the environmental impact of poultry facilities

Table 1 Daily resource consumption and associated GHG Emissions.

| Process/Sources | Resources | Amount | Unit/Day | GHG ($kgCO_2eq$/day) |
|---|---|---|---|---|
| Warm light bulb | Electricity | 3.42 | kWh | 2.05 |
| White light bulb | Electricity | 0.36 | kWh | 0.22 |
| Pump (Drinking water) | Electricity | 1.95 | kWh | 1.17 |
| Cooling water pump | Electricity | 1.50 | kWh | 0.90 |
| | Ground water | 3.42 | $m^3$ | 1.85 |
| Clean (floor + cage) | Ground water | 51.07 | $m^3$ | 27.63 |
| Ventilation fan | Diesel | 10.00 | Liter | 6.41 |
| Chicken | Tap water | 6.68 | $m^3$ | 3.84 |
| Feed | Food | 1,140 | kg | 807.46 |
| Waste | Chicken manure | 77.78 | kg | 8.53 |
| | | | **Total** | **860.05** |

*3.2 Mitigation Strategies for GHG Emissions Reduction*

**Scenario 1:** Strategies for reducing GHG emissions from poultry feed. Reducing GHG emissions from poultry feed is critical for enhancing sustainability in poultry production. Various strategies have been identified to mitigate emissions associated with feed production and utilization, focusing on improving feed composition and management practices. Conventional poultry feed systems typically generate higher GHG emissions due to intensive agricultural practices and the reliance on synthetic fertilizers, which contribute to nitrogen losses and $CH_4$ emissions [22].

Research indicates that organic poultry production systems can reduce GHG emissions by promoting ecological processes and reducing synthetic inputs [23-24]. Integrating specific feed additives, such as seaweed or Moringa oleifera, has been shown to further mitigate GHG emissions in both organic and conventional systems [25]. Additionally, incorporating alternative ingredients, such as cassava root, can substantially decrease emissions [20]. The use of fermented agricultural byproducts also enhances feed digestibility and reduces nitrogen excretion, thereby lowering $N_2O$ emissions [26]. Increasing the protein content of soybean meal from 44% to 50% can reduce lifecycle emissions by up to 4.5% in poultry diets, while also enhancing feed value [27]. Implementing precision feeding techniques allows for tailored nutrient delivery to individual birds, optimizing feed efficiency and minimizing waste [28]. While organic feed may contribute to lower emissions, it can be less economically viable, resulting in trade-offs between sustainability and cost-effectiveness in poultry production.

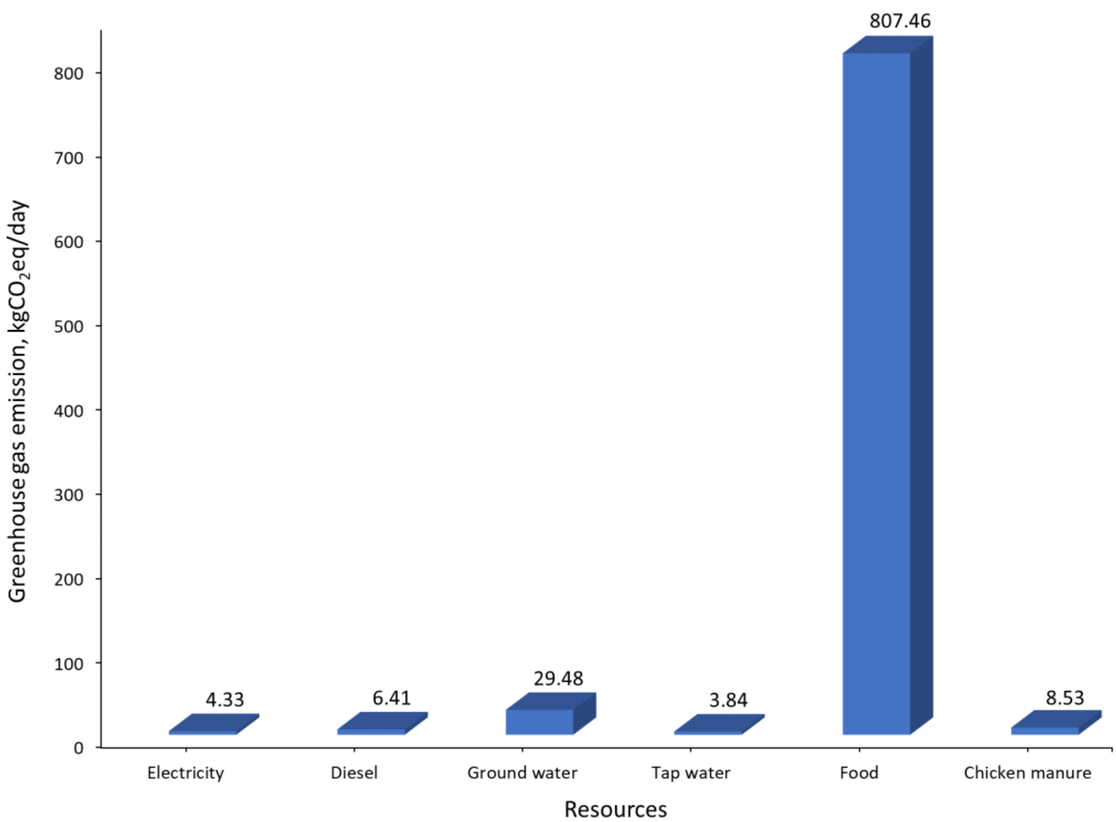


Fig. 3 Daily GHG emissions by source in egg-laying hen farming.

**Scenario 2:** Mitigating GHG emissions from poultry manure. Reducing GHG emissions from poultry manure is essential for mitigating environmental impacts. Multiple strategies have been identified across various stages of manure management, including composting techniques, the use of additives, and specific management practices. These approaches not only improve compost quality but also significantly reduce $CH_4$ and $N_2O$ emissions.

For instance, removing manure two to three times per week can effectively decrease GHG emissions during the housing stage, while acidification can lower ammonia ($NH_3$) emissions by 33%-93% and $CH_4$ emissions by 67%-87% [29]. Incorporating 20% mature compost into poultry manure can further reduce $NH_3$ emissions by up to 56.12% and $CH_4$ emissions by 62.24% [30]. The addition of materials like zeolite and superphosphate during composting can cut GHG emissions by up to 39.3%, mainly through the reduction of $CH_4$ emissions [31]. Combining poultry manure with cow manure or other organic waste can also improve compost quality and reduce GHG emissions, with specific combinations showing substantial reductions in $NH_3$ emissions [32]. While these strategies are promising, their effectiveness can vary based on local conditions and specific practices, underscoring the need for customized approaches tailored to different contexts.

**Scenario 3:** Transition to Biodiesel Fuel, proposes a shift from conventional diesel fuel to biodiesel as the principal energy source. Biodiesel is a renewable and biodegradable fuel derived from organic materials, such as vegetable oils and animal fats, through a process known as transesterification. This process yields fatty acid methyl esters (FAME), which can be utilized in diesel engines either in their pure form (B100) or blended with petroleum diesel (e.g., B20) [33]. Unlike diesel, which is a fossil fuel, biodiesel presents significant environmental advantages, with life cycle assessments indicating a potential reduction in $CO_2$ emissions of up to 78% [34]. Although diesel exhibits slightly higher energy efficiency due to its greater energy content, the renewable properties and cleaner combustion of biodiesel render it a more sustainable alternative. Diesel engines can operate on biodiesel with minimal modifications; however, the performance of older engines may be adversely affected by higher blends of biodiesel.

Replacing conventional diesel with biodiesel in farm operations could reduce emissions by 1.39 $kgCO_2eq$/day. This transition could result in a cumulative reduction of 624.78 $kgCO_2eq$ over the 450-day production cycle. This reduction highlights the environmental benefits of biodiesel, a renewable fuel that exhibits lower lifecycle emissions in comparison to diesel. While the daily decrease in $CO_2$-equivalents is noteworthy, achieving long-term emission objectives requires assessing the scalability of biodiesel production, enhancing its energy efficiency, and addressing challenges such as engine compatibility. Only by addressing these aspects can the full environmental advantages of biodiesel be realized without sacrificing operational efficiency.

**Scenario 4:** Adoption of Solar Energy Systems, solar cells, also known as photovoltaic (PV) systems, represent an exemplary renewable energy solution for the illumination and water pumping requirements in egg-producing poultry farms [35].

These systems efficiently convert sunlight into electrical energy by utilizing semiconductor materials, predominantly silicon, as illustrated in Fig. 4(a)-(b). Multiple solar cells are interconnected to create solar panels. In addition to the panels, these systems include an inverter that converts the direct current (DC) generated by the panels into alternating current (AC), which is suitable for household or commercial applications. Furthermore, they incorporate a mounting mechanism designed to optimize solar exposure and may integrate optional battery storage for surplus energy [10,36]. By harnessing solar power, these systems offer significant environmental and economic benefits. They reduce reliance on fossil fuels, mitigate GHG emissions, and can result in cost savings through decreased energy bills or energy credits [37].

Research has demonstrated that the implementation of solar cell for water pumping systems and electricity can significantly reduce GHG emissions across various applications [38]. Solar cell produces 0.0000 $kgCO_2eq$ during both electricity generation and consumption [39]. Implementing solar photovoltaic (PV) systems for lighting and water pumping could potentially eliminate 2.07 $kgCO_2eq$/day of emissions associated with conventional electricity use. Over the 450-day production cycle, this could result in a total reduction of 929.34 $kgCO_2eq$. While the initial investment in solar PV systems can be substantial, previous economic analyses suggest a payback period of 2.86 to 6.22 years [40], indicating long-term economic viability alongside environmental benefits.

### *3.3 Comprehensive Approach to Carbon Neutrality*

While our proposed strategies demonstrate promise, achieving carbon neutrality in egg-laying hen farming necessitates a more comprehensive approach. Additional considerations include:

1) Given that feed consumption constitutes the primary source of emissions, optimizing feed formulations and improving feed conversion efficiency through the use of sustainable feed ingredients, such as cassava or fermented byproducts, and incorporating protein-rich meals has the potential to significantly reduce emissions [41].

2) The application of advanced manure management techniques aimed at minimizing $CH_4$ and $N_2O$ emissions is of critical importance [42]. Techniques such as frequent manure removal, composting with additives like zeolite, and co-composting with other organic waste can enhance compost quality and substantially reduce emissions.

3) Transitioning to renewable energy sources, such as solar power for lighting and water pumps, can replace fossil fuel-based electricity and mitigate GHG emissions. The document highlights the potential of solar photovoltaic systems to significantly decrease emissions and reduce energy costs in the long run, thereby enhancing overall energy efficiency within agricultural operations, which can substantially contribute to the reduction of GHG emissions.

4) Shifting from diesel to biodiesel for farm machinery and equipment can reduce GHG emissions capitalizing on biodiesel's renewable and biodegradable nature. Biodiesel can often be utilized in existing engines with minimal modifications, rendering it a practical solution for diminishing fuel-related emissions.

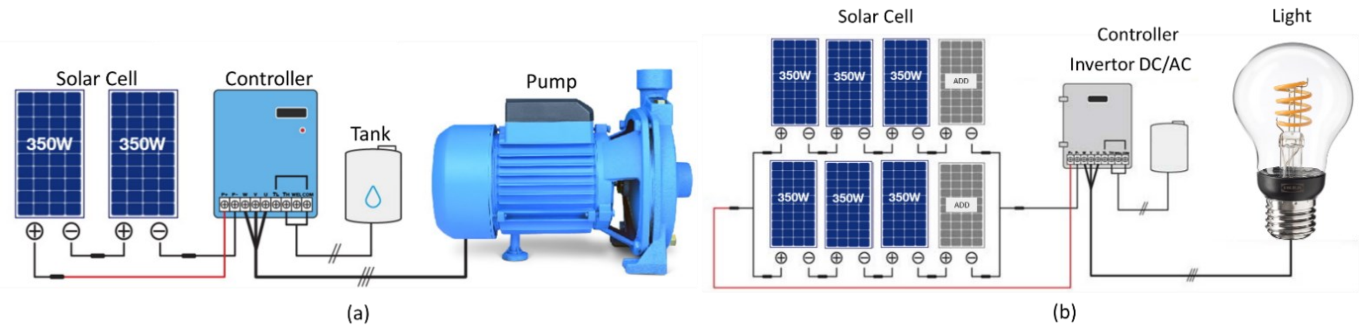


Fig. 4 Schematic of solar cell systems for (a) Water pumping and (b) Lighting.

5) The exploration of carbon sequestration opportunities, both on-farm and off-farm, holds significant potential for offsetting residual greenhouse gas emissions. On-farm practices may include techniques such as agroforestry, reduced tillage, and cover cropping, which can enhance soil organic carbon stocks by increasing carbon retention in soil organic matter. Implementing these carbon sequestration practices, supported by monitoring and verification systems, can effectively offset residual emissions while providing additional environmental benefits, such as biodiversity conservation, improved soil fertility, and enhanced water quality.

This study's focus on a single farm restricts the generalizability of its findings. Future research should incorporate a diverse range of farm sizes and geographical locations, conduct a comprehensive life cycle assessment that encompasses both upstream and downstream processes, and perform sensitivity analyses to address variations in farm management practices and technologies. Additionally, evaluating the economic feasibility and scalability of the proposed mitigation strategies across different types of farms would enhance the understanding of their impacts.

In conclusion, while our study offers valuable insights into GHG emissions in egg-laying hen farming and potential mitigation strategies, achieving carbon neutrality in the poultry sector necessitates ongoing research, innovation, and a commitment to sustainable practices throughout the supply chain. Continuous assessment of environmental impacts is critical for adapting to evolving agricultural practices and improving sustainability.

**4. Conclusion**

This study presents an integrated framework for achieving carbon neutrality in egg-laying hen farming by systematically assessing GHG emissions and proposing targeted mitigation strategies. Our analysis reveals that feed consumption, water usage, and electricity are the largest contributors to emissions, underscoring the importance of a multi-faceted approach to emission reduction. Implementing energy-efficient systems and transitioning to renewable energy sources, such as solar power for lighting and water pumping, demonstrate considerable potential for lowering electricity-related emissions. Additionally, shifting from diesel to biodiesel for fuel can significantly reduce the carbon footprint associated with fuel consumption, contributing to a more sustainable agricultural operation.

To reduce feed-related emissions, the study highlights optimizing feed formulations and exploring alternative ingredients, while advanced manure management techniques—such as composting with specific additives—provide effective ways to cut $CH_4$ and $N_2O$ emissions. These measures align with global sustainability objectives, providing a practical roadmap toward carbon neutrality for poultry farming, which holds implications for the broader agricultural sector. However, we recognize that initial financial investments and operational adjustments may challenge smaller-scale farms; thus, policy support and incentives will be critical for the widespread adoption of these practices.

The key findings demonstrate that targeted strategies in feed efficiency, renewable energy integration, and manure management can have a substantial impact on reducing emissions in poultry farming. These insights offer a scalable model that, if widely implemented, could play a crucial role in decarbonizing the poultry industry and serve as a benchmark for sustainability in agriculture. To further strengthen this approach, future research should expand the scope to include a full supply chain analysis, examining emissions beyond on-farm activities to encompass feed production, processing, and transportation. Additionally, assessing the economic feasibility of the proposed mitigation strategies across diverse farm scales would enhance our understanding of their practical applicability. By addressing these broader aspects, ongoing research can help advance the poultry sector's transition toward net-zero emissions, supporting policy development and sustainable practices throughout the agricultural supply chain. It is also recommended that collaboration between industry stakeholders, policymakers, and researchers be prioritized to ensure that the strategies are effectively adopted and implemented on a global scale. Future efforts should focus on aligning these strategies with regional policies and regulations to facilitate their practical application.

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