Assessing greenhouse gas and ammonia emissions: A comparison of three egg production systems in Québec, Canada

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ABSTRACT

In Quebec, the phase-out of the conventional cage (CC) system for egg production, is expected to be completed by 2036, with a transition to alternative systems such as enriched colonies (ECs) and cage-free (CF) housing. This study aimed to assess Greenhouse gas (GHG), and ammoniac (NH_3) emissions associated with those systems. The investigation involved one visit per farm to 30 commercial laying hen facilities in Southern Québec, Canada. The findings revealed that the CF system exhibited the highest numerical average of CO_2 emissions (3207 ± 2423 mg h^{-1} hen^{-1}), followed by CCs (2835 ± 877 mg h^{-1} hen^{-1}) and ECs (2597 ± 949 mg h^{-1} hen^{-1}). Furthermore, the EC system had the lowest average CH_4 emissions (0.93 ± 0.54 mg h^{-1} hen^{-1}), while CC (1.07 ± 0.41 mg h^{-1} hen^{-1}) and CF (1.27 ± 1.11 mg h^{-1} hen^{-1}) facilities had higher values. Emissions of N_2O were similar across all three systems (0.04 to 0.05 ± 0.05 mg h^{-1} hen^{-1}). The study revealed significant differences in NH_3 emissions among CC (2.0 ± 1.0 mg h^{-1} hen^{-1}), EC (2.5 ± 2.0 mg h^{-1} hen^{-1}), and CF egg production systems (11.2 ± 15.9 mg h^{-1} hen^{-1}).

RÉSUMÉ

Au Québec, l'élimination progressive des cages conventionnelles (CC) pour la production d'œufs, devrait être achevée d'ici 2036, avec une transition vers systèmes alternatifs tels que les logement enrichies (CE) ou les volières (V). Cette étude a fait les comparaisons des émissions de Gaz à effet du serre (GES) et d'ammoniac (NH_3) entre systèmes. Pour l'étude, 30 installations commerciales de poules pondeuses dans le sud du Québec ont été visites. Les systèmes V présentaient les émissions moyennes de CO_2 les plus élevées (3207 ± 2423 mg h^{-1} hen^{-1}), suivis par les CC (2835 ± 877 mg h^{-1} hen^{-1}) et EC (2597 ± 949 mg h^{-1} hen^{-1}). Les systèmes EC ont présenté les émissions moyennes de CH_4 les plus faibles (0,93 ± 0,54 mg h^{-1} hen^{-1}), tandis que les CC (1,07 ± 0,41 mg h^{-1} hen^{-1}) et V (1,27 ± 1,11 mg h^{-1} hen^{-1}) ont affiché des valeurs plus élevées. Les émissions de N_2O étaient similaires dans les trois systèmes (0,04-0,05 ± 0,05 mg h^{-1} hen^{-1}). L'étude a révélé des différences significatives dans les émissions de NH_3 entre les systèmes (CC=2,0 ± 1,0 mg h^{-1} hen^{-1}, EC=2,5 ± 2,0 mg h^{-1} hen^{-1}, et en volières (11,2 ± 15,9 mg h^{-1} hen^{-1}).

KEYWORDS

Laying hens; Air quality; Conventional cage; Enriched colony; Cage-free housing; Carbon Dioxide, Methane; Nitrous Oxide.

MOTS CLÉS

Poules pondeuses ; qualité de l'air ; cage conventionnelle ; cage enrichie ; volière; Dioxyde de carbone ; méthane ; oxyde nitreux.

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Table 1. Summary of hen housing conditions and manure management system.

N°	Date dd-mm-aa	System	N° hens	Average hen weight (kg)	Age (weeks)	Temperature (°C)		Relative humidity (%)		Ventilation rate ($m^3 h^{-1} hen^{-1}$)	Manure management system
						Indoor	Outdoor	Indoor	Outdoor		
1	25-02-20	CC	20,000	1.6	64	20.93	7.70	49	48	1.04	Pit storage
2	10-03-20	EC	22,800	1.8	56	20.09	4.47	55	72	0.76	Manure belt drying system
3	31-07-20	CF	16,000	1.5	45	25.85	27.00	66	53	5.32	Manure drying on bedded floors
4	26-09-20	CF	15,000	1.7	55	25.46	25.00	59	49	0.80	Manure drying on bedded floors
5	27-10-20	EC	14,000	1.4	50	21.27	-0.40	63	71	0.56	Pit storage
6	03-11-20	CF	18,000	1.9	50	22.07	0.80	67	46	1.08	Manure conveyor and scraper system
7	17-11-20	EC	13,919	1.9	60	23.95	-0.70	55	57	0.53	Pit storage
8	24-11-20	CF	19,500	1.8	69	18.54	-2.30	56	46	0.98	Manure belt drying system
9	08-12-20	CC	35,000	1.6	46	23.09	-2.00	57	58	0.78	Manure belt drying system
10	15-12-20	EC	17,000	1.8	57	22.24	-11.20	64	44	0.11	Manure belt drying system
11	05-01-21	EC	48,000	1.7	55	25.85	-2.40	66	61	0.58	Manure belt drying system
12	07-01-21	EC	14,484	1.7	65	22.62	1.00	57	46	0.61	Manure belt drying system
13	27-01-21	EC	19,997	1.8	57	23.73	0.64	54	44	0.63	Manure belt drying system
14	29-01-21	EC	9000	1.7	45	21.24	-6.70	57	37	0.86	Manure belt drying system
15	09-02-21	EC	92,000	1.7	50	22.96	-12.00	54	47	0.70	Manure belt drying system
16	02-03-21	CF	22,978	1.7	60	21.12	-6.24	66	34	0.97	Manure conveyor and scraper system
17	13-03-21	EC	12,000	1.8	55	20.51	-5.62	42	51	0.82	Manure belt drying system
18	16-03-21	CF	17,675	1.7	57	21.69	-1.80	52	34	0.16	Manure belt drying system
19	16-04-21	CF	12,935	1.7	55	24.21	5.80	56	74	0.52	Manure belt drying system
20	02-12-21	CF	33,417	1.6	43	23.16	5.75	71	71	2.07	Manure conveyor and scraper system
21	23-11-21	CF	13,694	1.6	58	21.08	-3.48	52	52	0.71	Manure conveyor and scraper system
22	07-12-21	CF	21,065	1.6	57	22.20	-3.09	58	44	0.46	Manure belt drying system
23	18-01-22	CC	16,510	1.7	51	17.14	-14.80	59	32	0.77	Manure belt drying system
24	01-02-22	CC	25,040	1.9	57	20.79	-11.43	62	47	0.45	Manure belt drying system
25	22-02-22	CC	44,028	1.8	68	22.01	-7.44	51	52	0.23	Manure belt drying system
26	02-03-22	CC	25,009	1.7	67	21.84	-5.76	57	50	0.55	Manure belt drying system
27	29-07-22	EC	22,500	1.8	73	26.9	25.6	52	53	3.33	Manure belt drying system
28	01-08-22	EC	10,518	1.8	64	26.69	28.5	63	56	11.45	Manure belt drying system
29	02-09-22	EC	33,600	1.7	59	23.46	30.01	51	38	2.32	Manure belt drying system
30	12-09-22	EC	9221	1.7	37	26.62	26.45	58	54	4.51	Manure belt drying system

INTRODUCTION

Emerging livestock production paradigms are increasingly integrating contemporary animal welfare considerations. For instance, novel housing systems prioritize affording animals the freedom of movement, a paramount aspect of living conditions as perceived by the public (Schuppli et al., 2014). Recognizing the importance of animal welfare in production, factors such as the provision of resting places and opportunities for exercise significantly impact animals' physical health and behavior (Campbell et al., 2019; Ciarelli et al., 2023). Recently, the Canadian egg production system has faced criticism due to its failure to provide adequate surface area, a crucial factor for hen welfare (Lay et al., 2011; Fulton, 2019; Schuck-Paim et al., 2021), in conventional, cramped wire cages (CCs; 432-484 cm^2/hen). Consequently, the CC system for rearing laying hens was prohibited on January 1, 2015 (Larivière, 2016), with a complete transition to alternative systems slated for completion by 2036 (CNSAE, 2017). Since then, there has been a gradual shift towards alternative systems such as enriched colonies (ECs) and cage-free (CF) environments, which better adhere to contemporary standards for animal well-being. The EC system provides hens with more space (750 cm^2/hen) and environmental stimulation (perches, scratching area, dust bath, and dedicated laying zone). In the CF systems, the minimum area is 930 cm^2/hen, which allows for the hens to find themselves in an environment more in keeping with their nature, where they can express various natural behaviors specific to their species, such as flying, dustbathing, and laying eggs in private (Leyendecker et al., 2005; Mollenhorst et al., 2005; FPOQ, 2012).

However, the move towards more compassionate practices in the industry reveals a significant increase in the environmental impact due to a higher surface per bird and exercise, which induces greater feed consumption and manure excretion (Shields & Greger, 2013). In fact, EC and CF housing systems are often associated with notable increases in emissions of greenhouse gases (GHGs) and ammonia (NH_3) (Shepherd et al, 2015;Bist et al., 2023). Assessing the environmental impact of this change is crucial, particularly given Canada's overarching environmental issues. Nationally, the poultry sector contributes respectively 37%, 5 %, and 57% of total carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions from agriculture (Camirand & Gingras, 2011). Ammonia emissions from poultry accounted for 6.2% of total livestock emissions (Carew, 2010).

LIST of SYMBOLS

CC		conventional cage
EC		enriched colonies
CF		cage-free
GHG		greenhouse gases
CO_2		carbon dioxide
CH_4		methane
N_2O		nitrous oxide
NH_3		ammonia
VR	$m^3_{air}\ h^{-1}$	ventilation rate

In the realm of animal livestock, the majority of CO_2 emissions stem from animal respiration (Pedersen et al., 2008). While laying hens produce negligible CH_4 emissions through enteric fermentation, the absence of oxygen in stored manure produces CH_4 emissions (Fabbri et al., 2007a). Nitrous oxide is generated during nitrification and denitrification processes under low oxygen conditions (Fabbri et al., 2007a; Ngwabie et al., 2018). Emissions of NH_3 in laying hen houses primarily originate from manure, with the concentration of NH_3 within buildings largely influenced by various factors, including husbandry systems (such as cages, litter, or alternative systems), house capacity, density (whether in cages or on unit floor area), and feed composition such as protein content (Kilic & Yaslioglu, 2014).

Measuring emissions from various egg production systems is crucial for promoting sustainability and responsibility, balancing animal welfare, environmental stewardship, and human health concerns. Several studies have explored the complexities of GHG and NH_3 emissions within diverse egg production systems. Shepherd et al. (2015) observed air emissions from three commercial egg production systems simultaneously at the house level. The study showed that NH_3 emissions from EC (2.25 mg hen^{-1} h^{-1}) were significantly lower compared to those from CC (3.42 mg hen^{-1} h^{-1}) and CF (4.67 mg hen^{-1} h^{-1}). Liu et al. (2020) monitored the emissions rate from three laying hen houses: CC, aviary, which is similar to CF system, and natural mating colony cage, which is similar to EC system. They reported higher NH_3 emissions in the Natural Mating (27.16 mg h^{-1} hen^{-1}) system than in conventional systems (3.43 mg h^{-1} hen^{-1}) or aviary (3.23 mg h^{-1} hen^{-1}). Zhao et al. (2015) noted similar gaseous concentrations between systems (CC, EC, CF) and highlighted NH_3 concentrations in the CF system significantly higher than those in the CC or EC system and occasionally exceeded 25 ppm under ambient temperature above 7.2°C. By comprehensively examining emissions, targeting mitigation strategies and policy development can minimize environmental impact and promote sustainable practices.

The emission of GHG and NH_3 poses significant health risks to laying hens and poultry farm workers. Elevated levels of CO_2 (above 5000 ppm) can induce respiratory distress in both hens and workers by displacing oxygen in the air (Webster & Fletcher, 2001; Mohammed et al., 2021). Emissions of CH_4, while less directly harmful, contribute to poor air quality and may exacerbate respiratory issues over time (Mohammed et al., 2021). The N_2O induces heat stress and physiological changes in birds (Mohammad Al-Kerwi et al., 2022). Emissions of NH_3 severely threaten both hens and workers, causing respiratory irritation (Kilic & Yaslioglu, 2014; Zhao et al., 2015; Bist et al., 2023). Prolonged exposure to these gases can result in adverse effects on workers' respiratory health (Viegas et al., 2013). Production losses and compromised egg quality (Mohammad Al-Kerwi et al., 2022) represent overall economic losses for the industry.

Table 2. Animal characteristics and environmental parameters of sampled farms.

Parameter	CC			EC			CF		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Outdoor temperature (°C)	-14.8	-5.6	7.7	-12.0	5.6	30.0	-6.2	4.7	27.1
Indoor temperature (°C)	17.1	21.0	23.1	20.1	23.4	26.9	18.5	22.5	25.9
Indoor relative humidity (%)	49.1	56.1	61.6	42.3	57.3	66.3	51.7	61.6	71.1
Outdoor relative humidity (%)	32.3	48.2	58.0	37.3	52.1	72.0	33.8	50.2	74.0
Age of hens (weeks)	46.0	59.0	68.0	37.0	56.0	73.0	43.0	55.0	69.0
Hen population	16510.0	27598.0	44028.0	9000.0	24217.0	92000.0	12935.0	19026.0	33417.0

The present study aimed to evaluate GHG and NH_3 emissions originating from CCs and two alternative egg production systems (EC and CF) and identify the sources of emission variations across the systems (e.g., the manure management system) within the framework of Canada's agricultural sector under commercial conditions.

MATERIALS AND METHODS

Experimental setup and design

Thirty commercial farms equipped with mechanical ventilation systems located in the southern region of the province of Québec (Eastern Canada) were selected for this study. The selection criteria included the farms' production system, laying hens' quantity, geographical dispersion, and the producers' willingness to participate. The laying hens in the chosen barns were, on average, 57 ± 8 weeks old, reared in one of the three production systems: CCs (6 barns), ECs (14 barns), and CF systems (10 barns). The farms presented different manure management systems. Twenty-one had manure belt drying systems, which used conveyor belts to transport manure from the barn. Four farms utilized manure conveyor and scraper systems, where the manure is conveyed away from livestock housing areas using conveyor belts or chains equipped with scrapers. These scrapers remove the manure from the floor and transport it to a storage facility. Two farms employed manure drying on bedded floors, allowing manure to dry naturally on bedded floors. The remaining three farms used pit storage systems to collect and store manure in underground pits or tanks. Table 1 outlines the specifications of the farms.

Data collection

This study was conducted from 2020 to 2022 and involved a single visit to each farm. During these visits, measurements were taken twice daily: once in the morning (between 9 and 11 a.m.) and once in the afternoon (between 1 and 3 p.m.). The duration of each measurement session varied based on the number of operating fans. Data collected included gas concentrations, air velocity, temperature, and humidity at multiple points. For consistency and reliability, measurements were taken at the ventilation fans, the center of the facility, the air intake, and outside the barn. The data from the morning and afternoon sessions were averaged for statistical analysis.

Concentrations of GHGs and NH_3 were determined using an infrared gas analyzer (FTIR model DX4040, resolution 8 cm^{-1}, range CO_2 0 -3%, range CH_4 0-100, range N_2O 0-200, range NH_3 0-100, Gasmet, Vantaa, Finland). The infrared gas analyzer was calibrated before analysis with nitrogen gas at a flow level of 2 L min^{-1} for 4 min (3 min for calibration and 1 min for measurement validation). Airspeed, humidity, and temperature were measured using a telescopic multifunction thermo-hygrometer-anemometer (VT210 + SFC300 probe, air velocity accuracy ± 3% of reading ± 0.1 m/s, temperature accuracy 3% of reading ± 0.25°C, KIMO, Chevry-Cossigny, France).

It is important to note that using an average data point measurement for gas concentration and emission may not fully represent each system's emissions all over the year. However, this method offers valuable insights into emissions during measurement. Nonetheless, it serves as a helpful indicator of gas concentrations at a specific moment and location. It offers valuable data for understanding emission dynamics across egg production systems and providing insight into emissions at the measurement time.

Ventilation rate and gas emissions

The airspeed from each fan was meticulously measured across the fan area for one minute, and the values were then averaged. Using the known cross-sectional area of the fan, the airflow rate from each fan was calculated using the following equation:

$$q_f = v * A * \Omega \quad (1)$$

where q_f is the airflow rate of each fan f (m^3_{air} h^{-1}), v is the average air velocity (m h^{-1}), A is the fan cross-sectional area (m^2), and Ω is the duty cycle expressed in percentage (%) of the time during which fan f was active (Rosa et al., 2019). Ventilation rate (VR; m^3_{air} h^{-1}) is then calculated through the sum of the flow rates of all measured fans:

$$VR = \sum_{f=1}^{n} q_n \quad (2)$$

The emissions for all gases measured were calculated based on the following equation:

$$E_g = VR * \Delta C_{gaz} * \frac{M_{gas}}{M_{air}} * \frac{P_{atm} - P_v}{287 * T} \quad (3)$$

where E_g is the gaseous emissions (mg h^{-1}), ΔC_{gaz} is the difference in concentration (ppm_v) of the gas at the outlet and inlet of the room; T is the temperature (K), P_{atm} and P_v are respectively the atmospheric pressure at sea level and the vapor pressure in air (Pa), and M is the molar mass of the gases or air. The M values are 44.0 g mol^{-1} (CO_2), 16.0 g mol^{-1} (CH_4), 44.0 g mol^{-1} (N_2O), 17.03 g mol^{-1} (NH_3), and 28.97 g mol^{-1} (air).

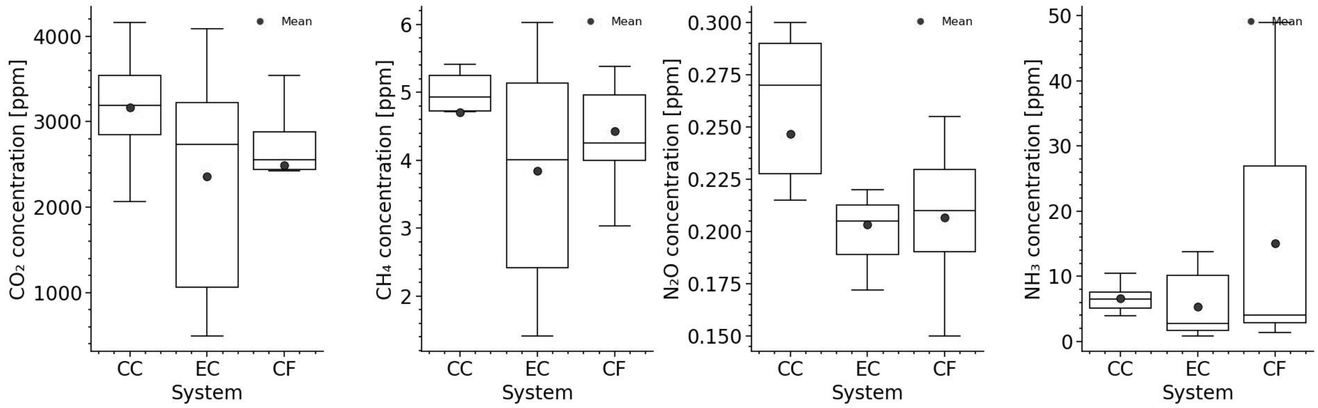

Fig. 1. Indoor concentrations of GHG and NH3 gases across different systems: conventional cages (CC), enriched colonies (EC), and cage-free system (CF). Each boxplot represents the distribution of concentrations for the gas, while the red dots indicate the average concentration for each system. * Statistically different (p < 0.05).

Statistical analyses

The statistical analysis was performed using Python libraries (Pedregosa et al., 2011), with the package models.stats.multitest.multiple tests. Similar studies have used these statistical setups to provide rigorous and objective analyses of differences in gas emissions in housing systems and environmental parameters (H. Li et al., 2012; Zhao et al., 2014). The method for adjusting the significance level of individual tests under multiple comparisons was the Bonferroni test approach, which uses a series of t-tests but corrects the significance level for multiple tests by dividing the significance levels by the number of tests being performed, reducing the chances of a Type I error occurring. Significance and tendencies were declared at $p < 0.05$ and $p < 0.10$, respectively, for the main effects.

Two correlations were performed. First, a Spearman correlation was performed between outdoor and indoor gas concentrations to determine whether there was any interference between internal and external concentrations. Correlation coefficients were strong (1 or -1), moderate (coefficients close to 0.5 or -0.5), or weak (coefficients close to 0). Then, a correlation analysis was performed to determine the association between six variables (number of hens, outdoor and indoor humidity relative, outdoor and indoor temperature, and VR) and gas concentrations and emissions. This last correlation analysis was initially conducted using all available data; however, no significant correlations were found. Therefore, separate correlation analyses were performed for the cold season, which included data from 25 farms, and the warm season, which included data from 5 farms. Due to the unequal distribution of farms between both seasons, subsequent analyses considered all results to ensure equitable representation across the dataset.

RESULTS

Environmental parameters

Table 2 presents the results of the environmental conditions and parameters evaluated for the sampled farms. Indoor temperatures were within the range established by the National Farm Animal Care Council (NFACC, 2017) for laying hens older than six weeks, i.e., between 10°C and 28°C. Concurrently, indoor relative humidity levels were within the optimal threshold of 55% to 65%.

Indoor and outdoor concentrations

No significant differences in GHG concentrations ($p > 0.05$) were observed between the housing systems (Fig. 1). The CO_2 levels were 3166 ± 721 ppm in the CC system, 2361 ± 1217 ppm in the EC system, and 2488 ± 1114 ppm in the CF system. The CH_4 concentrations were 4.70 ± 0.91 ppm for the CC system, 3.84 ± 1.51 ppm for the EC system, and 4.43 ± 1.30 ppm for the CF system. The N_2O levels were 0.25 ± 0.06 ppm in the CC system, 0.20 ± 0.03 ppm in the EC system, and 0.21 ± 0.03 ppm in the CF system. No significant differences ($p > 0.05$) were observed between the housing system groups for NH_3 concentration (Fig. 1). However, values were numerically higher in the CF system (15.1 ± 17.0 ppm) compared to the CC (6.66 ± 2.32 ppm) and EC (5.36 ± 5.01 ppm) systems.

The results of the variance analysis revealed no significant differences among housing systems concerning the CO_2 (p=0.30), CH_4 ($p = 0.14$), N_2O ($p = 0.17$), and NH_3 (p=0.30) outdoor concentrations (Fig. 2). For the three systems, the external CO_2 and CH_4 concentrations average were similar CC (CO_2 - 484 ± 128 ppm, CH_4 - 1.90 ± 0.32 ppm), EC (CO_2 - 429 ± 39.4 ppm, CH_4 - 2.01 ± 0.40 ppm), and CF (CO_2 - 467 ± 81.9 ppm, CH_4 - 2.24 ± 0.31 ppm). For N_2O, the CC system had the highest average concentration (0.28 ± 0.05 ppm), followed by the EC (0.23 ± 0.03 ppm) and CF (0.21 ± 0.05 ppm) systems. For NH_3, the CC system had the highest average concentration (1.54 ± 2.40 ppm), followed by the CF (1.02 ± 0.90 ppm) and EC (0.65 ± 0.30 ppm) systems.

Greenhouse Gas and Ammonia Emissions

The statistical analysis revealed no significant differences ($p > 0.05$) in CO_2 emissions among the three systems (Fig. 3). However, the CF system exhibited the highest numerical average (3207 ± 2423 mg h^{-1} hen^{-1}), followed by CC (2835

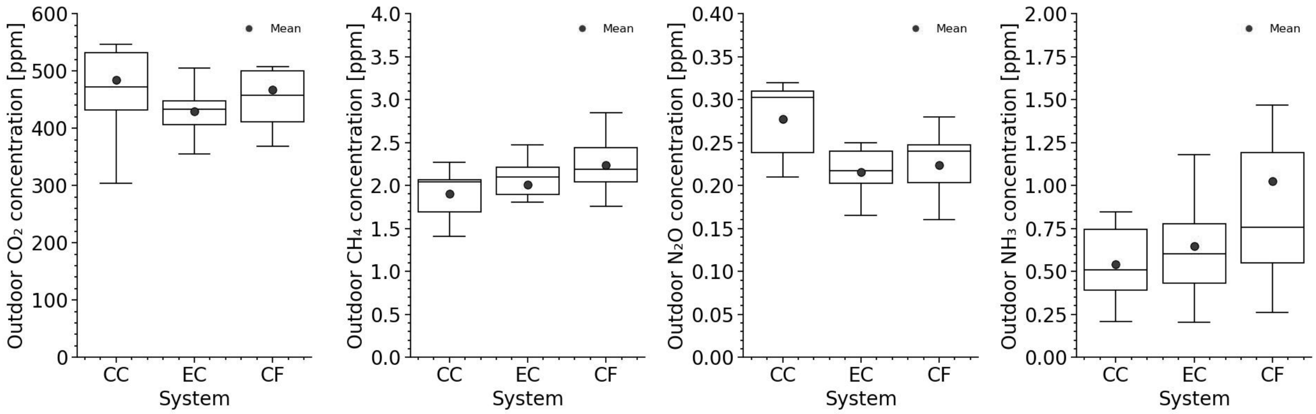

Fig. 2. Outdoor concentrations of GHG and NH_3 gases across different systems: conventional cages (CC), enriched colonies (EC), and cage-free system (CF). Each boxplot represents the distribution of concentrations for the gas, while the red dots indicate the average concentration for each system. *Statistically different ($p < 0.05$).

± 877 mg h^{-1} hen^{-1}) and EC (2597 ± 949 mg h^{-1} hen^{-1}) systems. Similarly, no significant differences ($p > 0.05$) were observed in CH_4 emissions among the CC, EC, and CF systems, indicating uniformity in methane production (Fig. 3). The EC system had the lowest average CH_4 emissions (0.93 ± 0.51 mg h^{-1} hen^{-1}), while CC (1.07 ± 0.40 mg h^{-1} hen^{-1}) and CF (1.27 ± 1.11 mg h^{-1} hen^{-1}) showed higher values. Analysis revealed no significant differences ($p > 0.05$) in N_2O emissions among the CC (0.04 ± 0.05 mg h^{-1} hen^{-1}), EC (0.05 ± 0.05 mg h^{-1} hen^{-1}), and CF (0.05 ± 0.07 mg h^{-1} hen^{-1}) systems (Fig. 3).

Regarding NH_3 emissions, there is a significant difference ($p = 0.04$) among the mean emissions of the CC and EC systems with the CF system (Fig. 3). The CF system showed considerably more emissions on average (11.2 ± 15.9 mg h^{-1} hen^{-1}) than the CC (1.98 ± 1.00 mg h^{-1} hen^{-1}) and EC (2.46 ± 2.00 mg h^{-1} hen^{-1}) systems.

Emissions by type of manure management

Table 3 presents the emission of GHG and NH_3 gases from the four types of manure management systems. the Manure Conveyor and Scraper System emits higher CO_2, CH_4, and NH_3 than alternatives like the Manure Belt Drying System and Pit Storage. However, N_2O emissions are relatively consistent across all systems, with slightly lower emissions observed in the Manure Belt Drying and Conveyor Systems.

Correlation Analysis

Indoor and outdoor gas concentration Figure 4 presents the results from the Spearman correlation analysis between indoor and outdoor GHG and NH_3 concentrations. The results reveal significant correlations between CO_2 and CH_4 concentrations inside the farm ($r = 0.83$, $P < 0.05$), as well as between indoor and outdoor N_2O concentrations ($r = 0.84$, $P < 0.05$). Other correlations are weak ($r < 0.65$).

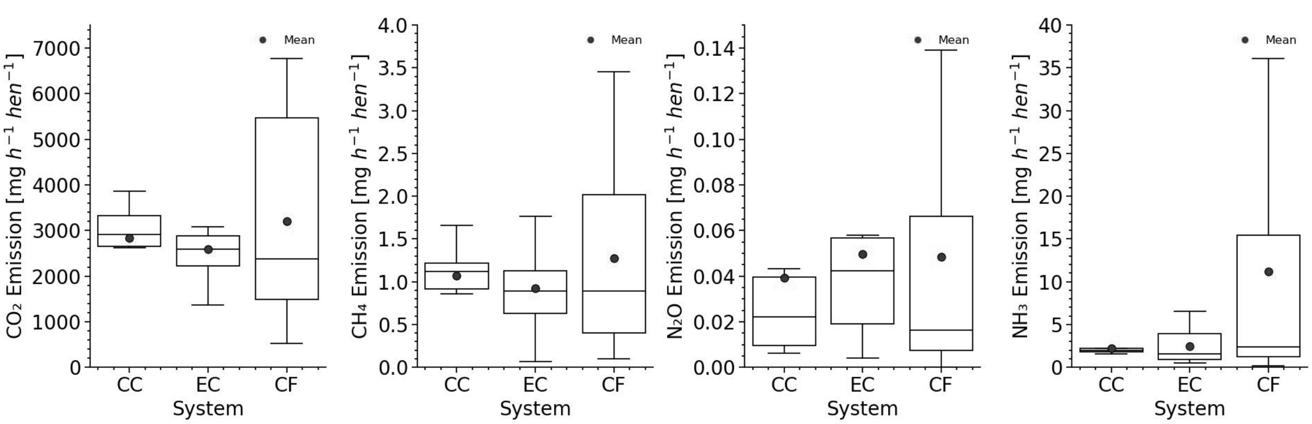

Fig. 3. Greenhouse gases and NH_3 barn emissions across different systems: conventional cages (CC), enriched colonies (EC), and cage-free (CF). Each boxplot represents the distribution of gas emissions, while the red dots indicate the average concentration for each system. *Statistically different ($p < 0.05$).

Table 3. Emission rates of GHG and NH_3 gases from different types of manure management systems.

Type of manure management	CO_2 mg h^{-1} hen^{-1}	NH_3 mg h^{-1} hen^{-1}	CH_4 mg h^{-1} hen^{-1}	N_2O mg h^{-1} hen^{-1}
Manure Belt Drying System	2562.0	2.3	1.0	0.04
Manure conveyor and scraper system	5545.0	24.7	2.3	0.05
Manure Drying on Bedded Floors	971.0	1.5	0.2	0.10
Pit storage	2498.0	2.5	0.7	0.06

Concentrations, Emissions, and Key Variables Tables 4 and 5 present the correlation coefficient matrices generated using the Spearman method for the cold and warm seasons, respectively. They illustrate the relationships between the six environmental variables (Number of hens, outdoor and indoor temperature and relative humidity, and Ventilation rate), gas concentrations, and emissions ($p < 0.05$). Additionally, the correlation between VR and emissions is illustrated in Fig. 5 due to its importance for emissions calculation. A positive correlation was observed between the four emissions across the cold and warm seasons.

DISCUSSION

This study delved into the emissions associated with various egg production systems across a representative sample of 30 farms in Québec, Canada. The systems under scrutiny were the conventional cage (CC), enriched colonies (EC), and cage-free (CF) environments. The hypothesis was that there would be substantial variations in emissions among these systems, reflecting potential differences in their environmental impact due to the differences in the space and disposition of each housing system.

Greenhouse gases

The cage-free systems presented higher CO_2 emissions. This could be attributable to the lower stocking densities, which increased hen activities such as flying, running, and dust bathing (Mollenhorst et al., 2005). Animal activity levels influence metabolic rates, with a higher metabolic rate resulting in increased CO_2 due to respiration (Pedersen et al., 2008). Additionally, CO_2 could also originate from the decomposition of manure in the litter on the floor of the CF (Ning et al., 2008; Hayes et al., 2013). There is notable variation in CO_2 emissions across the different systems. The barns with the conveyor and scraper system exhibit the highest CO_2 emissions, followed by the manure belt drying system. Conversely, manure drying on bedded floors has considerably lower CO_2 emissions, suggesting lower energy activity than other systems. When manure is left to rest in bedding (as in CF systems), especially in a warm and moist environment conducive to microbial activity, decomposition occurs more rapidly (Groot et al., 1996). As microorganisms decompose the organic matter, they consume oxygen and produce CO_2 as part of the respiratory process. The results presented here are comparable with

Table 4. Correlation Spearman coefficient matrix for the cold season of the six variables with gas concentrations and emissions.

Variables	Concentrations				Emissions			
	CO_2	CH_4	N_2O	NH_3	CO_2	CH_4	N_2O	NH_3
Number of hens	0.21	0.37	0.21	0.17	0.17	0.26	0.05	0.27
Outdoor temperature	-0.64	0.04	-0.57	-0.46	0.01	-0.15	-0.13	0.16
Indoor temperature	0.05	-0.02	-0.05	-0.07	-0.14	-0.17	-0.46	-0.15
Indoor relative humidity	0.30	0.52	0.47	0.26	0.32	0.48	-0.33	0.40
Outdoor relative humidity	-0.55	-0.02	-0.38	-0.34	-0.20	-0.11	-0.11	0.03
Ventilation rate	-0.27	0.11	-0.01	-0.30	0.82	0.71	0.51	0.51

Table 5. Correlation Spearman coefficient matrix for the warm season of the six variables with gas concentrations and emissions.

Variables	Concentrations				Emissions			
	CO_2	CH_4	N_2O	NH_3	CO_2	CH_4	N_2O	NH_3
Number of hens	0.09	0.03	0.43	0.20	-0.54	0.26	-0.37	-0.26
Outdoor temperature	-0.83	0.09	0.03	0.37	0.26	0.54	0.26	0.49
Indoor temperature	-0.09	-0.49	-0.77	-0.09	0.77	0.54	0.37	-0.09
Indoor relative humidity	-0.43	0.14	0.09	-0.89	0.20	-0.09	0.54	0.09
Outdoor relative humidity	-0.37	-0.37	-0.77	-0.09	0.94	0.43	0.54	0.20
Ventilation rate	-0.83	-0.03	-0.54	-0.26	0.83	0.54	0.83	0.49

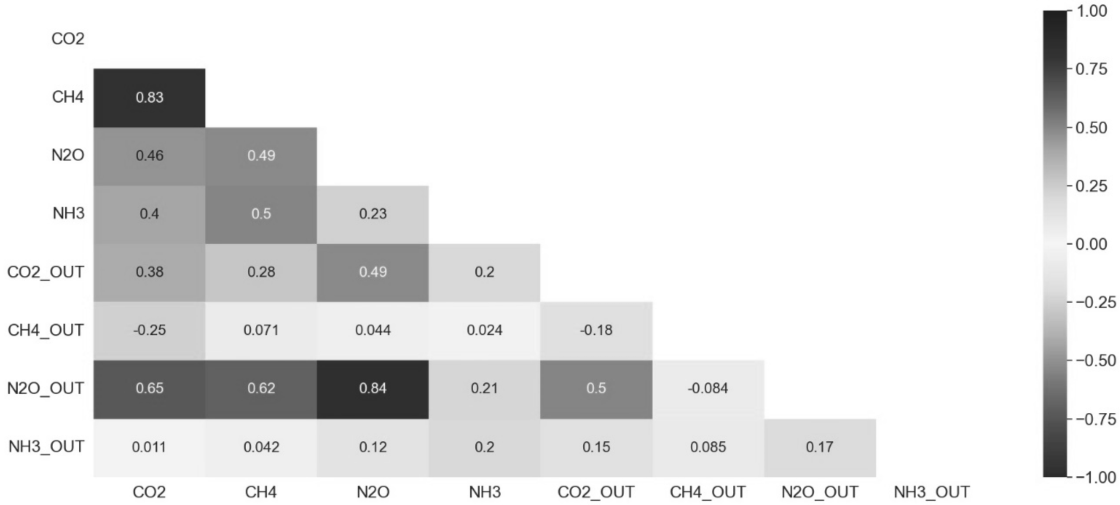

Fig. 4. The correlation matrix for the interaction between GHG and NH_3 gases considers indoor and outdoor gas concentrations.

CO_2 emissions presented in the existing literature (Shepherd et al., 2015). This latter study indicated that CO_2 emissions for CC were 2846 mg hen^{-1} h^{-1} but lower than EC (3100 mg hen^{-1} h^{-1}) and CF (3083 mg hen^{-1} h^{-1}). In addition, a negative association was observed between the ambient temperature and CO_2 concentration. This could be attributed to higher VR at the farms on warmer days as CO_2 concentration decreases with increased outdoor temperature. This is in line with the findings of (Paura et al., 2022), who also found a negative non-linear correlation between CO_2 concentration and outdoor temperature in assessing CO_2 levels in a commercial layer farm. The VR exhibits a positive correlation in both seasons with CO_2 emissions, indicating that higher VR effectively removed indoor air pollutants. Adequate ventilation removes gases emitted by hens and their manure from the indoor environment (Snell et al., 2003; Liu et al., 2016; Park et al., 2018). Nevertheless, relative humidity positively correlated with CO_2 emissions during the warm season. This may be because relative humidity affects the air's capacity to retain certain gases, including CO_2 (Kim et al., 2020). Conversely, lower outside temperatures in the cold season inhibit microbial activity, reducing the impact of relative humidity on CO_2 emissions.

The laying hens produce negligible CH_4 emissions in egg production systems through enteric fermentation. Therefore, CH_4 emissions are from the absence of oxygen in stored manure. In this study, the housing systems did not

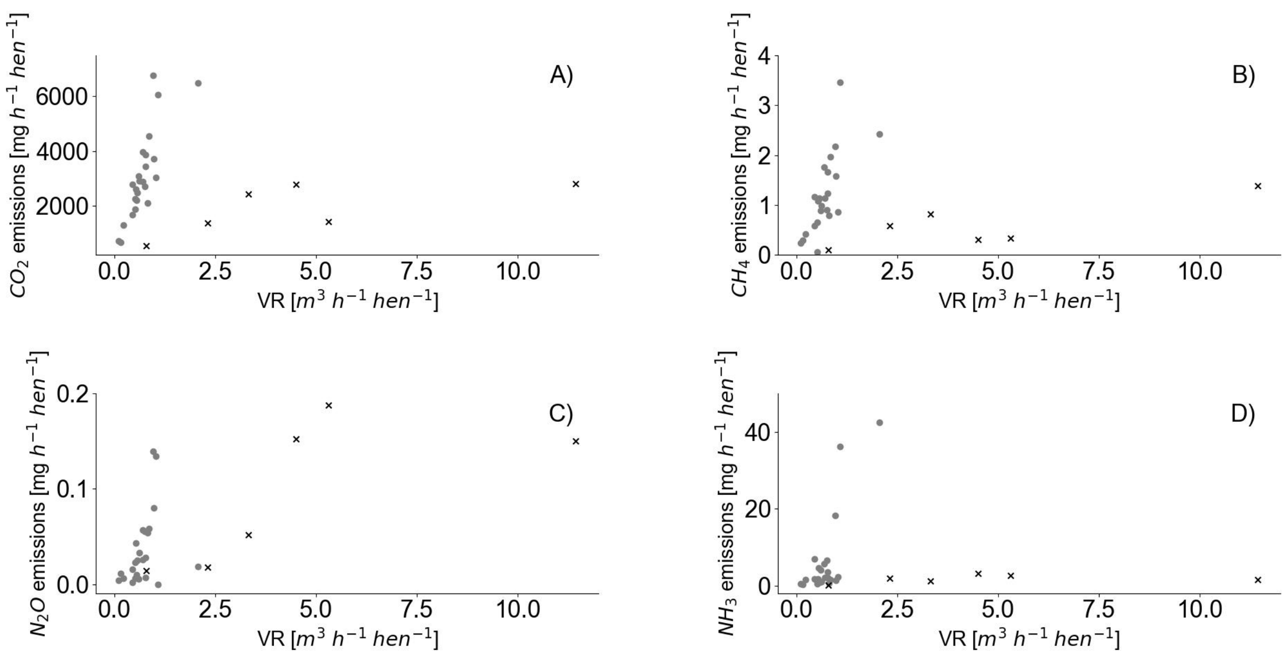

Fig. 5. Regression analysis of VR with recorded emissions of CO_2 (A), CH_4 (B), N_2O (C), and NH_3 (D) under cold (●) and warm (×) season.

substantially impact CH_4, as no statistically significant differences were observed. However, the CC system exhibited higher CH_4 concentrations, but the CF system showed the highest emissions of CH_4 because of the VR. The high correlation between VR and CH4 emissions could corroborate this. On the other hand, the higher emission rate in CF may be due to the space configuration of this system, in which the CF system provides hens with the most freedom of movement, allowing them to roam freely within a barn or enclosure (Mollenhorst et al., 2005). The increased floor space and litter availability in CF systems may lead to differences in manure management practices and microbial activity, ultimately impacting CH_4 emissions (Fournel et al., 2012; Nannoni et al., 2022). Shepherd et al. (2015) reported higher CH_4 emissions across all three systems, ranging from 2.92 to 3.33 mg hen^{-1} h^{-1}. One potential contributing factor to this difference could be the variation in average temperature between the two studies. In our study, the average temperature was lower than that reported by Shepherd et al. (2015). Lower temperatures can inhibit microbial metabolism and reduce the rate of organic matter decomposition, potentially leading to lower CH_4 production (Cheng et al., 2022). This is supported by the positive correlation found between temperature and CH_4 emissions for the warm season.

No significant differences were noticed for indoor or outdoor N_2O concentrations and emissions. Most of the literature found that the levels of N_2O were lower than the detection levels (Fabbri et al., 2007; Shepherd et al., 2015; Naylor et al., 2016). However, correlations with other variables were identified. A negative correlation was found between indoor temperature and concentration, while a negative correlation was observed between VR and emissions. For instance, as Fournel et al. (2012) mentioned, higher temperatures can accelerate organic compounds' decomposition rate while reducing nitrogenous substrates' stability. This could lead to a decrease in N_2O production, as these processes may limit the availability of precursors for N_2O generation. Additionally, dietary factors, such as protein intake, can influence the production of N_2O in indoor environments. Diets rich in protein can contribute to increased nitrogenous substrates (Kim, 2015), potentially leading to higher N_2O emissions. Furthermore, the VR demonstrates a positive correlation in both seasons with N_2O emissions, suggesting that increased VR efficiently eliminates indoor air pollutants. Sufficient ventilation dismisses gases emitted by poultry and their waste from the indoor atmosphere. (Snell et al., 2003; Liu et al., 2016; Park et al., 2018).

Ammonia gas

The CF housing system exhibited the highest NH3 concentration, with overall two times more than CC and EC concentrations (15.1 ppm vs 6.66 ppm and 5.36 ppm, respectively). Three farms exhibited NH_3 concentrations exceeding the permitted health levels of 25 ppm (Gouvernement du Québec, 2023). The VR in the CF rooms was 1.31 m^3 h^{-1}, higher than the 0.64 m^3 h^{-1} observed in the CC system (measured only during cold conditions), but lower than the 1.98 m^3 h^{-1} in the EC system. Notably, the average VR for the CF system was 76.3% lower than that of the EC system. This lower ventilation rate likely contributed to the higher NH_3 concentrations observed in CF. In larger buildings, such as those found on the three farms with NH_3 concentrations exceeding 25 ppm, lower VR may prevent contaminants from flowing and accumulating, particularly when the airflow cannot dilute and expel them adequately. However, these lower rates are likely due to temperature-controlled ventilation systems, which reduce airflow to conserve heat in low-density environments. While effective for maintaining temperature, these systems may unintentionally exacerbate air quality issues by limiting the removal of contaminants such as NH_3. High concentrations of ammonia are counterproductive to hens and humans. They can harm sensitive tissues, such as the eyes in hens(Miles et al., 2006), irritate the respiratory tract of chickens (Liu et al., 2020) and humans (Soltanzadeh et al., 2023), and lead to decreased growth rates and reduced egg production (Li et al., 2020).

Similarly, NH_3 emissions were significantly higher in the CF system than in the CC and EC systems. NH_3 production in bedding primarily stems from protein deamination, which results from microbial decomposition of nitrogenous compounds found in feces and urine *(Mohiuddin & Khattar, 2024)*. Specifically, bacteria decompose urea and other nitrogen-containing compounds in excreta, releasing NH_3 (Romillac, 2019). This process is closely linked to the protein intake of the birds, as higher protein diets result in increased nitrogen excretion and subsequent NH_3 production in the bedding material *(Mohiuddin & Khattar, 2024)*. Therefore, the significant difference in NH_3 emissions among the systems can be attributed to several factors. The CF system's increased space and floor litter may promote higher microbial activity and NH_3 production. More litter provides a larger substrate for microbial decomposition, leading to elevated NH_3 emissions (Swelum et al., 2021). Likewise, in the CF system, where hens have more freedom of movement and access to litter, moisture levels may be higher (due to stocking density, season, humidity, ventilation, kind and management of drinkers, and consistency and amount of fecal material), creating favorable conditions for microbial activity and NH_3 production (Fabbri et al., 2007; Ni et al., 2017; Shepherd et al., 2015).

Ammonia emissions exhibit considerable variation among manure management systems. The barns with the manure drying on bedded floors exhibit the highest NH_3 emissions, likely due to increased exposure of manure to the atmosphere during drying processes. Differences in manure management practices between the systems can affect litter moisture content and removal frequency. The accumulation of manure in confined spaces, coupled with the constant movement of hens, accelerates the decomposition process, releasing more NH_3 into the air (Fournel et al., 2012). In addition, farms employing conveyorized manure drying systems experience a broad range of relative humidity levels, potentially impacting NH_3 concentrations, as fluctuations in relative humidity can significantly influence the rate of NH_3 release from the manure (Huijsmans et al., 2001). Shepherd et al. (2015) found similar results. They reported higher NH_3 emission rates in the CF system compared to CC and EC systems. However, it is noteworthy that the magnitude of CF emissions in their study was lower (4.7 mg hen^{-1} h^{-1}) than observed in our study. Differences in environmental conditions, particularly temperature, humidity, VR, and geographical location, could significantly contribute to the observed variations in NH_3 emission magnitudes between the studies.

CONCLUSIONS

The primary impact observed was on ammonia emissions, with cage-free systems exhibiting significantly higher levels than conventional cage and enriched colonies systems. Additionally, while there were differences in carbon dioxide emissions among the systems, the variation was not as pronounced as with ammonia. Cage-free systems showed the highest average carbon dioxide emissions. Moreover, EC systems demonstrated the lowest average methane emissions. However, emissions of nitrous oxide were similar across all three systems.

Further research is necessary to comprehend the long-term effects of emissions on air quality, worker health, and animal health and welfare and explore potential mitigation strategies for minimizing environmental impact while sustaining efficient egg production. Additionally, these results highlight the importance of investigating ventilation rates to optimize ventilation systems for effective emission monitoring, thereby ensuring better air quality and environmental sustainability in egg production. From an industry perspective, these findings emphasize the need for careful consideration when transitioning between housing systems. While alternative systems may offer benefits such as improved animal welfare and consumer perception, they also bring challenges related to environmental emissions. Understanding the environmental implications of different production systems is crucial for informing sustainable practices and meeting regulatory standards. Moreover, exploring mitigation strategies that balance environmental concerns with the efficient production of high-quality eggs is essential. By addressing these issues, the egg production industry can work towards reducing its environmental footprint while maintaining profitability and meeting consumer demand for ethically produced eggs.

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