Seasonal dynamics and climatic influences of greenhouse gases (CO$_2$, CH$_4$) and ammonia (NH$_3$) concentrations on loose housing cattle shed

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ABSTRACT

Measurement of gas concentrations is crucial for the calculation of emissions from livestock buildings. The study aimed to examine how the concentrations of greenhouse gases (CO$_2$, CH$_4$) and ammonia (NH$_3$) vary seasonally and influenced by climatic conditions in loose housing cattle sheds in India. Two dairy cow sheds with different layouts, floor types, and cleaning practices were selected for measurements during the summer, rainy, and winter seasons. The concentrations of CO$_2$, CH$_4$, and NH$_3$ exhibited significant variations, ranging from 405 to 717 ppm for CO$_2$, 0.01 to 16.12 ppm for CH$_4$, and 0.00 to 1.90 ppm for NH$_3$. The winter season showed higher levels of CO$_2$ and CH$_4$, while NH$_3$ concentrations were higher during the summer season. Notable differences were observed in CO$_2$ and CH$_4$ levels between sheds during feeding, as well as in CO$_2$ levels during cleaning activities. The study revealed a weak correlation between greenhouse gases, ammonia, and climatic conditions in the cattle sheds, except for a moderate positive correlation between CO$_2$ and relative humidity during winter which means other factors such as housing design, facilities and practices play a significant role.

Keywords: Ammonia, Cattle, Climatic conditions, Methane, Seasons

Globally, the livestock sector is responsible for around 65% and 18% of anthropogenic NH$_3$ and greenhouse gas (GHG) emissions (Steinfeld et al. 2006). In 2018, enteric fermentation and manure management were responsible for 46% of CO$_2$ emissions, 78% of CH$_4$ emissions, and 6% of NO$_x$ emissions in agriculture (FAO 2020). Greenhouse gases and ammonia have significant impact as they also contribute to climate change and ecosystem damage. The factors linked to gas concentration in livestock houses are feed type, flooring, bedding, the climatic factors (temperature, relative humidity and air velocity), the time of day, species, farm structure design, ventilation and manure removal system (Baldini et al. 2016).

Carbon dioxide is produced by animal respiration, the breakdown of urea in urine, and during storage of manure while CH$_4$ is primarily produced by enteric fermentation and a small portion by manure. Ammonia is almost entirely produced by animal excreta, which includes dung and urine (Samer 2016). The relationship between a housing solution and its associated floor type, as well as the manure collection, removal and storage system affect NH$_3$ and greenhouse gas emissions (Wu et al. 2012, D’Urso et al. 2021). Seasonally, the concentration of CO$_2$ and CH$_4$ was higher in winter compared to summer while NH$_3$ concentration was higher in summer compared to winter.

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Experimental location and sheds: The study was carried out at Guru Angad Dev Veterinary and Animal Sciences University (GADVASU), Directorate of Livestock Farms in Ludhiana, Punjab (30.9°N 75.85°E). It involved a three-season experiment during 2022-2023: summer (April-June), monsoon (July-August), and winter (December-January).

Cattle sheds descriptions: Two loose houses, designated as C1 and C2, were selected for the study, oriented in an east-west direction and their dimensions is given Supplementary Fig. 1. C1 had a gable roof with ridge ventilation, while C2 had a shed type (single sloped) roof. C1 had a length of 60.9 m and a width of 48.5 meters, divided into two rows with three pens in each row. The shed’s height from the floor to the eaves was 4.5 m, increasing to 9.14 m at the center ridge. It had completely open sides and was...
enclosed by two rows of steel fencing around its perimeter. Each pen within C1 had a covered area measuring 20.3 meters by 15.53 meters. The shed floor consisted of a solid surface in the central alley, feeding trough, and standing area, while the resting and open areas were covered with sand. C1 housed approximately 15-20 cows per pen and featured a feedline sprinkler cooling system, panel fans in both the standing and resting areas, and scrappers for manure removal from the standing area. Feeding of the cows took place three times a day, including a combination of concentrate, total mixed ration (TMR), and dry/green fodder. In the summer, the scrappers operated twice a day, while in winter, they ran once a day for manure removal.

The C2 shed had a length of 45.74 meters and a width of 21.18 meters. It had two sides enclosed, facing the east and west directions, with a brick boundary surrounding the open area of the shed. The roof height on both sides was 3.0 meters, and the covered area measured 45.74 meters by 6.54 meters. The floor in both the covered and open areas was made of brick paving, and there was a cemented feeding trough. Within the shed, there were approximately 15-20 cows accommodated within a length of 27.5 meters, with the remaining length utilized for feed storage, equipment, and milking of the animals. To ensure proper ventilation, wall-mounted table fans were installed. Cleaning of the shed took place once a day using water flushing and a broom. The cows were fed three times a day, following a regular feeding schedule. The both sheds had consistent cattle density of 15-20 animals.

Greenhouse gases (CO$_2$, CH$_4$) and ammonia (NH$_3$) measurements: The greenhouse gases (CO$_2$, CH$_4$) and ammonia (NH$_3$) concentration were continuously measured by air quality monitoring station (AQMS) of Environment & Engineering Solutions in India. The AQMS utilized sensor technologies which includes non-dispersive infrared (NDIR) sensors for CO$_2$ and CH$_4$ detection, and electrochemical sensors for NH$_3$ detection, all measured in parts per million (ppm). The sensors have an accuracy of ±0.1 ppm and detection range of 400-5000 ppm for CO$_2$, and 0-100 ppm for both CH$_4$ and NH$_3$. The sensor suite includes additional components such as a glass fiber thimble for efficient air filtration, and a rotometer to regulate airflow. The sensor suite is equipped with inlet and outlet ports at the bottom to facilitate controlled intake and release of the sampled air. Air samples were collected using an air pump with a flow rate of 5 litres/min at regular 15 min intervals. Continuous measurements are conducted in cattle sheds for 24 h with data recorded every 15 min with AQMS equipment as positioned marked in Supplementary Fig. 1. This monitoring was carried out for approximately one week per month in both sheds, covering different seasons. Data is acquired using a data logger and NEXTCOMM software, then organized into excel sheets for analysis.

Microclimatic conditions: Temperature and relative humidity (RH) inside the sheds were monitored using temperature and RH sensors fixed in Supreme International (New, Delhi) equipment for continuously 24 h. Additionally, air velocity was measured using a portable thermo-anemometer (METRAVI AV-04, India) three times a day (morning, afternoon, and evening) on a weekly basis per shed per month.

Statistical analysis: The data collected during the experimental period was organized in Microsoft Excel and subjected to statistical analysis using SPSS version 26.0 (SPSS Inc., IBM, Armonk, NY, USA). To assess significant differences (P<0.05) between variables, one and two way ANOVA analysis and Tukey’s test for post-hoc analysis were applied, considering different sheds and seasons. Additionally, the relationship between climatic variables (temperature, relative humidity, and air velocity) and greenhouse gas concentrations and ammonia within different sheds was examined using the Pearson correlation coefficient. All figures had been generated using GraphPad prism 8.

**RESULTS AND DISCUSSION**

Greenhouse gases (CO$_2$, CH$_4$) and ammonia (NH$_3$) concentration: Table 1 and Supplementary Fig. 2 depicts the concentrations of greenhouse gases, specifically CO$_2$ and CH$_4$, as well as ammonia (NH$_3$) concentrations in cattle sheds on a monthly basis. The concentration ranges in the cattle sheds exhibit notable variations from 405 to 717 ppm for CO$_2$, 0.01 to 16.12 ppm for CH$_4$, and 0.00 to 1.90 ppm for NH$_3$. During the summer season, the average concentrations of CO$_2$, CH$_4$, and NH$_3$ exhibit a range of 405-717 ppm, 0.01-12.88 ppm, and 0.00-1.90 ppm, respectively while 406-651, 0.08-7.84 and 0.00-1.90 ppm in rainy season. Similarly, the winter season exhibits notable variations in overall concentrations of CO$_2$ and NH$_3$.

<table>
<thead>
<tr>
<th>Shed</th>
<th>Gases</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>December</th>
<th>January</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>CO$_2$</td>
<td>456.1±40.65</td>
<td>428.8±34.58</td>
<td>431.3±34.79</td>
<td>416.6±14.25</td>
<td>441.4±36.73</td>
<td>508.3±74.17</td>
<td>490.2±53.57</td>
</tr>
<tr>
<td></td>
<td>NH$_3$</td>
<td>0.024±0.064</td>
<td>0.160±0.256</td>
<td>0.245±0.296</td>
<td>0.005±0.007</td>
<td>0.004±0.01</td>
<td>0.064±0.088</td>
<td>0.128±0.027</td>
</tr>
<tr>
<td>C2</td>
<td>CO$_2$</td>
<td>454.1±29.21</td>
<td>446.4±42.04</td>
<td>430.6±27.65</td>
<td>434.9±29.08</td>
<td>459.4±39.64</td>
<td>552.9±87.86</td>
<td>478.7±47.38</td>
</tr>
<tr>
<td></td>
<td>CH$_4$</td>
<td>5.260±3.408</td>
<td>3.636±0.367</td>
<td>0.454±0.422</td>
<td>3.533±2.416</td>
<td>3.988±2.546</td>
<td>4.280±3.603</td>
<td>4.357±3.413</td>
</tr>
<tr>
<td></td>
<td>NH$_3$</td>
<td>0.014±0.036</td>
<td>0.222±0.259</td>
<td>0.061±0.101</td>
<td>0.007±0.010</td>
<td>0.005±0.008</td>
<td>0.104±0.137</td>
<td>0.044±0.175</td>
</tr>
</tbody>
</table>
(409-879 ppm), CH\textsubscript{4} (0.49-16.12 ppm), and NH\textsubscript{3} (0.00-0.70 ppm) in the cattle sheds. During the winter season, carbon dioxide and methane concentrations were higher compared to other seasons, while ammonia concentrations were higher during the summer season.

To effectively reduce greenhouse gas and ammonia emissions, it is crucial to gain an understanding of the concentrations of these gases linked to various farms. This understanding becomes essential due to the wide range of variations among farms in terms of climatic conditions, building designs, feeding and cleaning methods, animal density, and manure storage systems. By comprehending the specific concentrations associated with different farm practices, it becomes possible to develop targeted mitigation strategies. Present findings were comparable with several previous studies such as D’Urso et al. (2021) (CO\textsubscript{2}: 500-800; CH\textsubscript{4}: 5-15), Divyalaxmi et al. (2017) (CH\textsubscript{4}: 0-0.03; NH\textsubscript{3}: 0.33-2.58), Joo et al. (2015) (CO\textsubscript{2}: 443-789) and Kaasik and Maasikmets (2013) (NH\textsubscript{3}: 0.24-2.38), and, regarding greenhouse gas concentrations. However, higher concentrations were observed compared to studies conducted by Ngwabie et al. (2014) (CO\textsubscript{2}: 566-1335; CH\textsubscript{4}: 20-107), Rong et al. (2014) (CO\textsubscript{2}: 463-2716; CH\textsubscript{4}: 2.1-219; NH\textsubscript{3}: 0.3-15.5), Wu et al. (2012) (CO\textsubscript{2}: 492-1066; CH\textsubscript{4}: 7.93-57.3; NH\textsubscript{3}: 0.5-8.62) and Ngwabie et al. (2011) (CO\textsubscript{2}: 960±210; CH\textsubscript{4}: 39±16.9), probably due to the higher stocking density of animals than their studies in addition to other differences. Furthermore, current results indicated that CO\textsubscript{2} and CH\textsubscript{4} concentrations were higher during winter compared to summer, while NH\textsubscript{3} concentration was higher in summer compared to winter. These seasonal variations align with the findings of Rong et al. (2014), Saha et al. (2014), and Kaasik and Maasikmets (2013). The higher concentrations of CO\textsubscript{2} and CH\textsubscript{4} observed during the winter season can be attributed to the presence of condensed and moist air, which hinders the easy escape of these gases from buildings compared to the summer and rainy seasons. Notably, certain studies have reported unexpectedly high average ammonia concentrations in December and January, although the specific cause for this phenomenon remains unknown. During colder months, the activity of microorganisms responsible for ammonia production is less optimal, resulting in lower ammonia emissions. However, the disparity in emissions of greenhouse gases and ammonia between summer and winter is less pronounced, as indicated by studies conducted by Mihina et al. (2012), Rong et al. (2014), Pu et al. (2021).

**Diurnal variations:** Fig. 1 illustrates the changes in greenhouse gas (CO\textsubscript{2}, NH\textsubscript{3}) and ammonia (NH\textsubscript{3}) concentrations throughout the day across different seasons in cattle sheds. Notably, carbon dioxide (CO\textsubscript{2}) concentrations showed significant variations, both between seasons and during different time intervals. CO\textsubscript{2} levels exhibited a consistent variation from 08:00 to 16:00 h. In C1 shed, a similar pattern was observed for CO\textsubscript{2} in both summer and rainy seasons, with higher peaks during night time compared to daytime. In C2 shed, higher CO\textsubscript{2} emissions were observed at night during summer and in afternoon during the rainy seasons. In winter, CO\textsubscript{2} concentrations decreased after 8:00 AM, increased after 16:00 h, and remained higher during the night in both sheds. On the other hand, methane and ammonia did not show a clear pattern of increase or decrease throughout the day.

**Greenhouse gases (CO\textsubscript{2}, CH\textsubscript{4}) and ammonia (NH\textsubscript{3}) concentration during feeding and cleaning time:** Table 2 provides data on gases concentration during feeding and cleaning activities in cattle sheds throughout the day. Significant differences were observed in CO\textsubscript{2} and CH\textsubscript{4} levels between sheds during feeding, as well as in CO\textsubscript{2} concentrations were higher during feeding and cleaning times.

<table>
<thead>
<tr>
<th>Shed</th>
<th>Feeding time</th>
<th>Cleaning time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO\textsubscript{2}</td>
<td>CH\textsubscript{4}</td>
</tr>
<tr>
<td>C1</td>
<td>429.8±17.72\textsuperscript{a}</td>
<td>2.567±1.779\textsuperscript{b}</td>
</tr>
<tr>
<td>C2</td>
<td>444.1±28.87\textsuperscript{a}</td>
<td>3.385±1.818\textsuperscript{b}</td>
</tr>
<tr>
<td>P-value</td>
<td>0.031</td>
<td>0.051</td>
</tr>
</tbody>
</table>

Fig. 1 Diurnal variations of GHG and NH\textsubscript{3} in C1 and C2 sheds.

Table 2. GHG and NH\textsubscript{3} concentration during feeding and cleaning times.
EFFECT OF GREENHOUSE GASES AND AMMONIA ON CATTLE SHED

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levels during cleaning hours. The concentration of CO$_2$ and CH$_4$ was notably higher in C2 shed compared to C1 shed. This difference could be attributed to the lower height of the C2 shed, which may affect air circulation and ventilation, leading to higher greenhouse gas concentrations. A study by D’Urso et al. (2021) revealed that higher NH$_3$ emissions occur during cleaning activities due to the mixing of urine and faeces, while CO$_2$ and CH$_4$ emissions were higher during animal activity, followed by the cleaning process. Similar to present findings, Divyalaxmi et al. (2017) and Joo et al. (2015) reported lower concentrations and peaks of CO$_2$ and CH$_4$ during day-time. However, contrasting results were observed in studies conducted by D’Urso et al. (2021), Saha et al. (2014), and Wu et al. (2012), where greenhouse gases and ammonia exhibited peaks during daytime. This disparity can be attributed to the higher temperatures and increased animal activity that typically occur during daylight hours. Conversely, Pu et al. (2021) found no significant variations in greenhouse gas and ammonia emissions throughout the day.

**Microclimatic conditions:** The microclimatic conditions within cattle sheds between seasons and months is given in Supplementary Table 1 and Supplementary Fig. 3. In cattle sheds, the maximum and minimum temperatures during the summer and rainy seasons were recorded within the ranges of 33.80-41.52°C and 26.05-28.73°C, respectively. In the winter season, the maximum temperatures ranged from 18.61-23.76°C, while the minimum temperatures ranged from 9.36-13.88°C in cattle sheds. In summer and rainy seasons, average air velocity ranged from 0.0-4.3 m/s, while in winter it ranged from 0.0-1.22 m/s in cattle sheds.

**Relationship of climatic conditions with greenhouse gases (CO$_2$, CH$_4$) and ammonia (NH$_3$):** The correlation coefficients between CO$_2$, CH$_4$, NH$_3$ and climatic conditions (temperature, relative humidity and air velocity) between cattle sheds is given in Table 3. There was a strong and significant negative correlation between CO$_2$ and air temperature. On the other hand, CO$_2$ shows a moderate positive relationship with relative humidity and weak negative correlation with air velocity. The methane shows moderate significant negative correlation with air velocity in C1 shed. NH$_3$ shows a poor positive correlation with both temperature and air velocity and poor negative correlation with relative humidity.

The correlation coefficients between greenhouse gases (CO$_2$, CH$_4$) and ammonia (NH$_3$) with climatic conditions are presented in Table 4 and Fig. 3. The greenhouse gases and ammonia were weakly correlated with climatic conditions except moderate positive correlation between RH and CO$_2$ during winter season.

Ammonia concentration was positively correlated with temperature in studies by Ngwabie et al. (2011), Wu et al. (2012), Kaasik and Maasikmets (2013), Rong et al. (2014), Saha et al. (2014), Pu et al. (2021), and while negatively with relative humidity as per Pu et al. (2021). The emission of NH$_3$ is influenced by temperature through two distinct mechanisms: the formation of NH$_3^-$ in the aqueous phase and the release of NH$_3$. An increase in temperature within the range of 10°C to 40°C stimulates urease activity, leading to a significant production of NH$_3^-$.

Conversely, at temperatures below 10°C, urease activity slows down, resulting in reduced NH$_3$ emissions (Rong et al. 2014). Higher relative humidity (RH) can increase the dissolution of NH$_3$ in moist air, as NH$_3$ has a tendency to adsorb in water. This can result in lower measured concentrations of gaseous NH$_3$, as a larger portion of it remains in the

### Table 3 Correlation coefficients between climatic variables and GHG and NH$_3$ in cattle sheds

<table>
<thead>
<tr>
<th>Shed</th>
<th>Parameter</th>
<th>CO$_2$</th>
<th>CH$_4$</th>
<th>NH$_3$</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Temperature(°C)</td>
<td>-0.598</td>
<td>-0.311</td>
<td>0.073</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity (%)</td>
<td>0.382</td>
<td>0.150</td>
<td>-0.154</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Air Velocity(m/s)</td>
<td>-0.298*</td>
<td>-0.407*</td>
<td>0.100</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C2</td>
<td>Temperature(°C)</td>
<td>-0.519</td>
<td>-0.237</td>
<td>0.041</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity (%)</td>
<td>0.307</td>
<td>0.226</td>
<td>-0.206</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Air Velocity(m/s)</td>
<td>-0.220*</td>
<td>-0.078</td>
<td>-0.103</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

*Indicates significant difference for particular row.

### Table 4 Season-wise correlation coefficients between climatic variables and GHG and NH$_3$ in cattle sheds

<table>
<thead>
<tr>
<th>Season</th>
<th>Variable</th>
<th>CO$_2$</th>
<th>CH$_4$</th>
<th>NH$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>Temperature(°C)</td>
<td>-0.230**</td>
<td>-0.120**</td>
<td>0.120**</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity (%)</td>
<td>0.094**</td>
<td>-0.113**</td>
<td>0.153**</td>
</tr>
<tr>
<td></td>
<td>Air Velocity(m/s)</td>
<td>-0.202**</td>
<td>-0.276**</td>
<td>0.100</td>
</tr>
<tr>
<td>Rainy</td>
<td>Temperature(°C)</td>
<td>-0.149**</td>
<td>0.058</td>
<td>0.083**</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity (%)</td>
<td>0.203**</td>
<td>-0.011</td>
<td>-0.082**</td>
</tr>
<tr>
<td></td>
<td>Air Velocity(m/s)</td>
<td>-0.098</td>
<td>0.018</td>
<td>0.101</td>
</tr>
<tr>
<td>Winter</td>
<td>Temperature(°C)</td>
<td>-0.215**</td>
<td>0.031</td>
<td>0.138**</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity (%)</td>
<td>0.443**</td>
<td>-0.041</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td>Air Velocity(m/s)</td>
<td>-0.130</td>
<td>0.071</td>
<td>-0.059</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed).** Correlation is significant at the 0.05 level (2-tailed).

**Note:** The correlation coefficients are based on the assumption that the data are normally distributed. In cases where this assumption is not met, non-parametric tests may be more appropriate.
the concentration of CO₂ and CH₄ in barns, while relative humidity (RH) has a lesser impact (Joo et al. 2015). Studies by Kaasik and Maasikmets (2013), Saha et al. (2014), Joo et al. (2015) and D’Urso et al. (2021) have shown that higher ventilation rates and increased wind speed during the summer result in lower CO₂ and CH₄ concentrations. This indicates that improved airflow and higher wind speeds contribute to reducing CO₂ and CH₄ levels in barn environments.

The concentrations of carbon dioxide (CO₂) and methane (CH₄) tend to be higher during the winter season, which can be attributed to the presence of condensed and moist air. Conversely, ammonia concentrations are typically elevated during the summer seasons. The relationship between greenhouse gas (CO₂, NH₃) and NH₃ concentrations with climatic conditions during different seasons shows a weak association. However, there is a more substantial correlation observed between two cattle sheds, indicating that factors such as housing design, facilities and practices play a significant role. Further investigation is needed to understand the underlying factors influencing these correlations and to determine any potential causal links between the gases and climatic conditions in cattle sheds.

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