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Temporal Behaviour and Future Trajectories of Methane and Nitrous Oxide Emissions from the Livestock Sector

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ABSTARCT

Background: Livestock production is a major source of methane and nitrous oxide, two greenhouse gases with high global warming potential and long-term climate implications. Understanding how these emissions evolve over time is essential for designing effective mitigation strategies, particularly in regions where livestock systems are expanding and emission pressures are increasing.

Methods: Annual data on livestock-related methane and nitrous oxide emissions covering the period 1980-2024 were analysed using time-series forecasting approaches. Autoregressive integrated moving average (ARIMA), exponential smoothing and TBATS models were applied to examine emission dynamics and generate future projections. Stationarity properties were assessed and model performance was evaluated using diagnostic checks and forecast accuracy measures.

Result: The analysis revealed a persistent upward trend in emissions of both gases over the study period, with methane exhibiting greater interannual variability than nitrous oxide. Both emission series were non-stationary at levels but became stationary after first-order differencing. Among the competing models, ARIMA specifications showed superior performance and produced well-behaved residuals with no evidence of remaining serial correlation. Forecasts indicate that, in the absence of targeted mitigation measures, livestock-related methane and nitrous oxide emissions are likely to continue increasing, with substantially wider uncertainty associated with methane projections.

Key words: Autoregressive integrated moving average, Greenhouse gas emissions, Livestock sector, Methane emissions, Nitrous oxide emissions, Sustainable development.

INTRODUCTION

Climate change has emerged as one of the most pressing global challenges, with greenhouse gas emissions playing a central role in altering atmospheric processes and long-term climatic patterns. Among these gases, methane and nitrous oxide are of particular concern due to their high global warming potential and their close association with agricultural activities. While carbon dioxide receives significant attention, non-CO, gases from agriculture often remain underrepresented in policy discussions, despite their substantial contribution to overall warming (Nisbet *et al*., 2021; Jones *et al*., 2023).

The livestock sector is a major source of methane and nitrous oxide emissions, primarily through enteric fermentation, manure management and associated production practices. In countries where livestock forms an integral component of rural livelihoods and food systems, these emissions tend to follow long-term growth patterns driven by population pressure, changing consumption habits and intensification of production systems. Understanding how such emissions evolve over time is essential for designing realistic mitigation strategies that balance environmental concerns with economic and social objectives (Oenema *et al*., 2005; Dangal *et al*., 2017).

In the Indian context, livestock production occupies a unique position within the agricultural economy. The sector supports millions of small and marginal households and contributes significantly to nutritional security and farm income diversification (Ivanovich *et al.,* 2023). At the same

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time, the expansion of cattle populations and gradual shifts toward more intensive management practices have raised concerns regarding the environmental footprint of livestock farming. Methane emissions from ruminants and nitrous oxide emissions from manure and soil interactions represent persistent and cumulative sources of atmospheric greenhouse gases, making their long-term assessment particularly important (Aggarwal, 2008; Kuraz *et al*., 2021).

Reliable forecasting of livestock-related greenhouse gas emissions is a critical input for climate policy, agricultural planning and sustainability assessments. Unlike short-term projections, long-run forecasts help identify underlying emission trajectories and provide early signals of potential future pressures (Greatorex, 2000; Lahoti *et al*., 2015). However, emission data often exhibit non-linear trends, gradual structural changes and random fluctuations, which limit the usefulness of simple extrapolation techniques. In this context, time-series modelling offers a practical and data-driven approach for capturing historical patterns and generating informed projections without requiring extensive assumptions about causal mechanisms (Bates *et al*., 2009; Kamyab *et al*., 2024).

Time-series methods have been widely applied in environmental and energy research due to their ability to handle trend-dominated data and temporal dependence effectively. By analysing past behaviour embedded in emission series, these models allow for systematic evaluation of alternative forecasting structures and objective comparison of predictive performance. Such approaches are particularly suitable for long-term national or sectoral datasets, where consistent annual observations are available but detailed micro-level drivers may be difficult to quantify (Singh *et al*., 2022; Yalcinkaya, 2024).

Given India's expanding livestock population and its commitments under international climate agreements, understanding long-term emission trajectories is particularly important for aligning agricultural development with national climate mitigation planning.

Against this backdrop, the present study examines the temporal behaviour of methane and nitrous oxide emissions originating from the livestock sector and develops statistically robust forecasts for future periods. By employing multiple time-series modelling frameworks and comparing their predictive accuracy, the study aims to identify the most reliable approach for long-term emission forecasting. The findings are expected to contribute to a clearer understanding of emission dynamics and support evidence-based discussions on sustainable livestock development and climate mitigation planning.

MATERIALS AND METHODS

Data source and period of analysis

The study used annual time-series data on methane (CH_4) and nitrous oxide (N_2O) emissions generated from the livestock sector for the period 1980-2024. Emissions were expressed in kilotonnes (kt) and analysed at the aggregate level to capture long-term emission behaviour. The selected period reflects structural changes in livestock production systems and provides sufficient observations for robust time-series modelling.

The dataset was examined for missing values and inconsistencies. Occasional gaps were addressed using mean-based interpolation to preserve the temporal structure. No observations were removed to retain natural variability in emission patterns.

For model validation, the dataset was divided into a training sample (1980-2016) and a validation sample (2017-2024).

Analytical framework

The analysis followed a comparative time-series modelling approach. First, descriptive and distributional properties of the emission series were examined. Second, stationarity was tested to determine the appropriate level of differencing. Third, alternative forecasting models were estimated and diagnostically evaluated. Finally, the most suitable model was selected for forecasting future emissions.

Three forecasting approaches were considered: autoregressive integrated moving average (ARIMA), exponential smoothing state-space models (ETS) and the TBATS framework. These models were chosen to represent different assumptions regarding trend evolution and temporal dependence.

Stationarity testing

Stationarity of the emission series was examined using the Augmented Dickey-Fuller (ADF) test. The test equation can be expressed as:

$$\Delta y_t = \alpha + \beta t + \gamma y_{\{t-1\}} + \sum_{i=1}^{k} \delta_i \Delta y_{t-i} + \varepsilon_t$$

Where,

y_t= Emission levels at time t.

Δ= The first-difference operator.

t= The time trend.

ε_t= A white-noise error term.

A statistically significant value of γ indicates stationarity. When non-stationarity was detected at levels, first-order differencing was applied.

Autoregressive integrated moving average (ARIMA) model

The ARIMA model was used to capture temporal dependence in the emission series after achieving stationarity. The general ARIMA (p, d, q) specification is given by:

$$\Delta^d y_t = c + \sum_{i=1}^{p} \phi_i \Delta^d y_{t-i} + \sum_{j=1}^{q} \theta_j \varepsilon_{t-j} + \varepsilon_t$$

Where,

p= The autoregressive order.

d= The degree of differencing.

q= The moving average order.

ϕ_i and θ_j= Model parameters.
ε_t= A white-noise disturbance term.

Based on autocorrelation and partial autocorrelation patterns together with information criteria, the selected specifications were ARIMA (1,1,1) for methane emissions and ARIMA(0,1,1) for nitrous oxide emissions. These models provided the best balance between parsimony and forecast accuracy among competing alternatives. Diagnostic tests were applied to ensure that residuals exhibited no serial correlation.

Exponential smoothing state-space (ETS) model

The ETS framework models emissions through recursive updating of level and trend components. For a series without seasonality, the additive ETS formulation is expressed as:

$$\ell_t = \alpha y_t + (1 - \alpha)(\ell_{t-1} + b_{t-1})$$
$$b_t = \beta(\ell_t - \ell_{t-1}) + (1 - \beta)b_{t-1}$$
$$\hat{y}_{t+h} = \ell_t + h\, b_t$$

Where,
ℓ_t = The level component.
b_t= The trend component,
α and β= Smoothing parameters.
h= The forecast horizon.

ETS models were included to assess whether smooth trend-based structures could adequately represent emission dynamics.

TBATS model

The TBATS model was employed as a flexible alternative capable of handling complex trend behaviour and autocorrelated errors. After applying an optional Box-Cox transformation, the model can be expressed as:

$$y_t^{(\lambda)} = \ell_{t-1} + b_{t-1} + d_t + \varepsilon_t$$

Where,
$y_t^{(\lambda)}$ = The transformed emission series.
ℓ_{t-1} and b_{t-1} = Level and trend components.
d_t= ARMA-type residual dependence.
ε_t= A random error term.

Given the annual frequency of the data, seasonal components were not retained in the final specifications.

Model evaluation criteria

Model performance was assessed using information criteria and forecast accuracy measures. The Akaike Information Criterion (AIC) was used to compare model fit:

$$AIC = 2k - 2 \ln(L)$$

Where,
k= The number of estimated parameters.
L= The likelihood function.

Forecast accuracy was evaluated using the following metrics:

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(y_t - \hat{y}_t)^2}$$

$$MAPE = \frac{100}{n}\sum_{t=1}^{n}\left|\frac{y_t - \hat{y}_t}{y_t}\right|$$

$$MASE = \frac{\frac{1}{n}\sum_{t=1}^{n}\left|y_t - \hat{y}_t\right|}{\frac{1}{T-1}\sum_{t=2}^{T}\left|y_t - y_{t-1}\right|}$$

The model with the most consistent performance across these criteria was selected for forecasting.

Software implementation

All analyses were carried out using the R statistical environment. Time-series estimation and forecasting were implemented using the forecast, tseries and fable packages, which provide established tools for stationarity testing, model estimation, diagnostic evaluation and forecast generation. The use of open-source software ensures transparency and reproducibility.

RESULTS AND DISCUSSION

Temporal behaviour and distribution of emissions

The evolution of livestock-related methane (CH_4) and nitrous oxide (N_2O) emissions during 1980-2024 reveals a clear and persistent upward trend, reflecting the gradual accumulation of emission pressures over time. As illustrated in both gases exhibit steady growth without sharp structural breaks. However, the degree of variability differs noticeably between the two emission series. Methane emissions show greater year-to-year fluctuations, whereas nitrous oxide emissions follow a comparatively smoother trajectory. Similar long-term increases in livestock-related methane and nitrous oxide emissions have been reported at global and regional scales, indicating that such trends are not country-specific but structurally embedded in livestock production systems (Oenema *et al.*, 2005; Dangal *et al.*, 2017).

The distributional properties of the emission series, summarised in Table 1, provide further insight into these differing patterns. Nitrous oxide emissions ranged from about 76.1 kt to 96.4 kt over the study period, with an average level of 87.3 kt and a relatively low standard deviation of 5.9 kt. This limited dispersion indicates a stable emission-generating process, consistent with manure management and nitrogen cycling mechanisms that tend to change gradually over time (Davidson *et al.*, 2000; Pires *et al.*, 2015).

In contrast, methane emissions display a much wider spread, varying between approximately 5,712 kt and 7,429

Table 1: Statistical profile of livestock-related greenhouse gas emissions, 1980-2024.

Indicator	Nitrous oxide (kt)	Methane (kt)
Lower observed level	76.1	5712.4
Average level	87.3	6573.6
Upper observed level	96.4	7428.9
Standard deviation	5.9	468.7
Skewness	0.04	-0.31

Table 2: Stationarity assessment of emission series using unit root tests.

Gas	Test at level	Inference	Test after differencing	Inference
N_2O	-2.11	Non-stationary	-7.94	Stationary
CH_4	-2.26	Non-stationary	-8.62	Stationary

Table 3: Residual independence diagnostics for selected ARIMA models.

Gas	Test statistic	Lag length	Probability
N_2O	10.87	10	0.37
CH_4	7.42	10	0.59

kt, with a mean value of 6,573.6 kt and a substantially higher standard deviation of 468.7 kt. This higher dispersion reflects the greater sensitivity of methane emissions to changes in livestock population size, feeding practices and productivity conditions. Comparable variability in methane emissions has been observed in both national and international studies, highlighting methane's responsiveness to management and technological shifts (Nisbet *et al*., 2021; Kang *et al*., 2026). The slightly negative skewness observed for methane emissions suggests that periods of slower growth or temporary stabilisation occurred alongside the long-term upward trend. Together, these distributional features highlight the more volatile nature of methane emissions and underscore the need for flexible time-series models capable of capturing both long-term trends and short-run fluctuations.

Stationarity properties of emission series

Before estimating the forecasting models, the time-series properties of methane and nitrous oxide emissions were examined to assess their suitability for time-series analysis. Stationarity is essential for reliable modelling, as the use of non-stationary data can result in biased or spurious inference. The results of the Augmented Dickey-Fuller tests are reported in Table 2.

At the level form, both emission series failed to reject the null hypothesis of a unit root, with test statistics of -2.11 for nitrous oxide and -2.26 for methane, indicating non-stationarity. These outcomes are consistent with the pronounced upward trends observed in and with earlier empirical evidence showing persistent growth in livestock-related greenhouse gas emissions over long periods (Dangal *et al*., 2019; Jones *et al*., 2023). After applying first-order differencing, the test statistics declined sharply to -7.94 for nitrous oxide and "8.62 for methane, both of which were statistically significant at conventional levels. This confirms that the emission series become stationary after differencing once, implying that emission growth follows an integrated process of order one. On this basis, ARIMA models incorporating a differencing component were considered appropriate for subsequent forecasting analysis.

Model adequacy and residual behaviour

ARIMA, ETS and TBATS models were estimated using the training sample to evaluate their suitability for forecasting livestock-related emissions. Model adequacy was assessed primarily through residual diagnostics, as the presence of residual autocorrelation would indicate that important temporal patterns remained unexplained. The results of the residual independence tests for the selected ARIMA models are presented in Table 3, with corresponding visual diagnostics.

For nitrous oxide emissions, the Ljung-Box test statistic was 10.87 with a probability value of 0.37, while methane emissions recorded a test statistic of 7.42 with a probability value of 0.59. In both cases, the null hypothesis of no serial correlation could not be rejected, indicating that the residuals were independently distributed. This statistical evidence is consistent with the residual plots and autocorrelation functions displayed in where residuals fluctuate randomly around zero and autocorrelation coefficients do not exhibit systematic patterns across lags, as commonly observed in well-specified emission forecasting models (Dangal *et al*., 2017; Yalcinkaya, 2024; Barman *et al*., 2025).

The absence of statistically significant residual autocorrelation confirms that the selected ARIMA models adequately captured the time dependence present in both emission series. As no systematic structure remained in the residuals, the models were considered well specified, providing a reliable basis for subsequent forecasting and interpretation, consistent with earlier time-series applications in greenhouse gas emission analysis (Bates *et al*., 2009; Singh *et al*., 2022).

Comparative performance of alternative models

To identify the most appropriate forecasting framework, the performance of ARIMA, ETS and TBATS models was assessed using multiple criteria related to information efficiency, forecast accuracy and stability. Rather than relying solely on numerical indicators, the comparative behaviour of the models across these dimensions is synthesised in Table 4.

The results indicate that ARIMA models consistently outperformed the alternative approaches across all evaluation criteria. ARIMA provided the most efficient representation of the emission series, achieving higher accuracy while maintaining a parsimonious structure. In contrast, ETS models were able to capture the overall trend in emissions but showed weaker performance in terms of forecast accuracy and stability, particularly during the validation period. TBATS models, despite their greater flexibility, did not offer additional predictive gains and exhibited more variable forecast behaviour, a pattern also observed in comparative forecasting studies of

Table 4: Relative assessment of forecasting model performance.

Criterion	ARIMA	ETS	TBATS
Information efficiency	High	Moderate	Moderate
Short-term accuracy	Strong	Acceptable	Weaker
Forecast stability	Consistent	Moderately stable	Variable
Overall suitability	Highest	Intermediate	Secondary

Table 5: Projected livestock-related greenhouse gas emissions with uncertainty ranges.

Year	N_2O estimate (kt)	Uncertainty interval	CH_4 estimate (kt)	Uncertainty interval
2025	97.4	95.1-99.6	7486	7210-7762
2027	98.6	95.8-101.4	7568	7189-7947
2030	100.2	96.7-103.8	7694	7145-8243

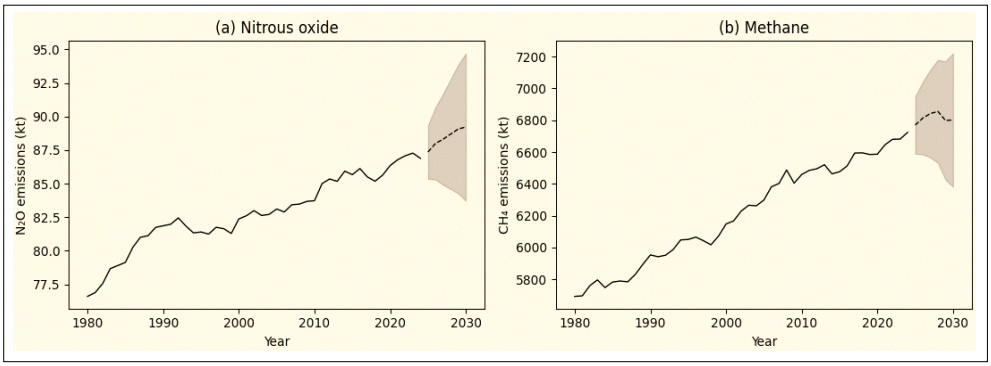


Fig 1: Forecast trajectories of livestock-related greenhouse gas emissions.

environmental and agricultural emissions (Bates *et al*., 2009; Kamyab *et al*., 2024).

These findings suggest that the dynamics of livestock-related greenhouse gas emissions are strongly influenced by historical dependence rather than by complex smoothing or transformation structures. Consequently, ARIMA models were identified as the most suitable framework for forecasting methane and nitrous oxide emissions in this study, consistent with earlier evidence highlighting the effectiveness of autoregressive models for long-term emission forecasting (Singh *et al*., 2022; Yalcinkaya, 2024).

Emission projections and uncertainty patterns

Using the preferred ARIMA specifications, emission forecasts were generated for both nitrous oxide and methane beyond the observed period. The forecast trajectories, along with their associated uncertainty bands, are shown in Fig 1 in a side-by-side format, while the corresponding numerical projections are reported in Table 5.

The projections indicate a continued rise in emissions of both gases over the forecast horizon. Nitrous oxide emissions are projected to increase from about 97.4 kt in 2025 to 100.2 kt by 2030. The associated uncertainty intervals remain relatively narrow, expanding from 95.1-99.6 kt in 2025 to 96.7-103.8 kt in 2030. This smooth upward pattern reflects the gradual and stable nature of nitrogen-related emission processes in livestock systems, as documented in long-term nitrogen emission studies (Oenema *et al*., 2005; Pires *et al*., 2015).

Methane emissions, in contrast, are projected to increase from approximately 7,486 kt in 2025 to 7,694 kt by 2030. The uncertainty ranges for methane are substantially wider, widening from 7,210-7,762 kt in 2025 to 7,145-8,243 kt in 2030. As illustrated in Fig 1, this broader spread highlights the greater sensitivity of methane emissions to future changes in livestock population dynamics, feeding practices and productivity levels, a feature widely reported in methane-focused mitigation assessments (Nisbet *et al*., 2021; Ocko *et al*., 2021).

In percentage terms, nitrous oxide emissions are projected to increase by approximately 2.9% between 2025 and 2030, while methane emissions are expected to rise by about 2.8% over the same period. Although these percentage changes appear modest, their cumulative climate implications are significant given the large absolute emission base of the livestock sector.

For both gases, the confidence intervals widen as the forecast horizon extends, which is a typical feature of long-term projections. However, the more pronounced expansion of uncertainty for methane underscores the higher degree of unpredictability associated with its emission pathways. These results suggest that while the direction of future emission growth is relatively robust for both gases, the magnitude of methane emissions remains more

dependent on management practices and technological interventions than that of nitrous oxide.

Integrated interpretation

The combined evidence from Table 1-5 and Fig 1 indicates strong persistence in livestock-related greenhouse gas emissions. Past emission behaviour plays a dominant role in shaping future trajectories, suggesting that delayed mitigation efforts may result in long-lasting emission lock-ins. The distinct variability patterns of methane and nitrous oxide further imply that mitigation strategies should be gas-specific rather than uniform across emission sources.

While the forecasting results provide useful insights into long-term emission dynamics, the analysis relies on univariate time-series models that primarily capture historical dependence patterns. Such approaches do not explicitly incorporate structural drivers such as technological change, policy interventions, feed efficiency improvements, or shifts in livestock management practices. Consequently, future emission pathways may deviate from projections if substantial structural transformations occur. Integrating econometric or system-based models with explanatory variables could therefore represent a useful direction for future research.

CONCLUSION

This study analysed the temporal behaviour and future trajectories of methane and nitrous oxide emissions from the livestock sector during 1980-2024 using alternative time-series forecasting models. The results show a persistent increase in emissions of both gases, with methane exhibiting greater interannual variability than nitrous oxide, reflecting differences in their underlying emission processes. Among the models evaluated, ARIMA specifications provided the most reliable representation of emission dynamics, as confirmed by diagnostic tests and forecast accuracy measures. Forecast projections suggest that livestock-related greenhouse gas emissions are likely to continue rising in the absence of targeted interventions, with methane emissions displaying wider uncertainty due to their sensitivity to management and productivity changes. The findings indicate that mitigation efforts should be gas-specific and implemented early to avoid long-term emission lock-in. Overall, the study highlights the value of time-series modelling as a practical approach for tracking emission trends and supporting evidence-based planning for sustainable livestock development.

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Informed consent

NA.

Conflict of interest

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