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Forecasting emissions of Greenhouse Gases in West African Countries Under Business-As-Usual (BAU) Scenario

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Abstract

Greenhouse gas (GHG) emissions continue to rise in West Africa, posing a significant challenge to regional sustainability and global climate goals. This study employed the Holt-linear exponential smoothing model to forecast GHG emissions in West Africa under a business-as-usual scenario through 2099. Using historical data from 1970 to 2021 sourced from the EDGARv7.0 database, the research analyzes trajectories of CO_2, CH_4, and N_2O emissions. Results reveal model evaluation demonstrated robust prediction, with R^2 exceeding 0.90 for all three GHGs. Projections indicate that CO_2 emissions will rise, with Senegal expected to have the highest increase (808%) by 2099, while Ghana is projected to demonstrate a 16% reduction. Nigeria's share of regional emissions is projected to decline from 70.1% to 62.4%. CH_4 emissions exhibit contrasting trends, with Nigeria experiencing a 215% decline by 2099, while Gambia and Liberia have sharp increases of 467% and 320%, respectively. Generally, regional CH_4 emissions are projected to decrease. Conversely, N_2O emissions are predicted to grow with total regional emissions increasing from 295.2 Kt to 762.6 Kt, led by Sierra Leone's 461% rise. These findings provide critical insights for policymakers to develop targeted climate change strategies, align national development plans with international commitments, and foster regional cooperation to address the anticipated growth in GHG emissions.

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Keywords: Greenhouse Gases, Emissions, Forecasting, BAU Scenario, West African Countries

1. Introduction

Greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are primary contributors to global warming and climate change. The increasing concentration of these gases in the atmosphere, largely attributed to anthropogenic activities such as fossil fuel combustion, deforestation, and agricultural practices, presents significant environmental and socio-economic challenges globally (Mazahreh and Abu-Allaban 2023; Tudor and Sova, 2021). In West Africa, the rapid pace of urbanization and industrialization, coupled with limited mitigation measures, has accelerated GHG emissions under a business-as-usual (BAU) scenario (Adeoye and Spataru, 2019). The region's vulnerability to climate change, manifesting in erratic rainfall patterns, prolonged droughts, and rising temperatures, exacerbates critical issues such as food insecurity and water scarcity (Larbi et al., 2021). Despite commitments to international frameworks like the Paris Agreement, the lack of robust forecasting models impedes effective climate action and policy implementation in the region (Rahman et al., 2023). Achieving nationally determined contributions (NDCs) requires precise, localized data on emissions trends to inform evidence-based decision-making (Ntiamoah et al., 2024).

This study addresses the urgent need for accurate emissions forecasting in West Africa by employing the Emissions Database for Global Atmospheric Research (EDGAR) as the primary data source. The EDGAR database offers high-resolution global emission inventories, providing comprehensive datasets for analyzing trends and developing predictive models (EDGAR, 2023). The Holt-Winters exponential smoothing method, a time-series forecasting model, is utilized due to its demonstrated ability to capture seasonality and long-term trends in environmental and energy datasets (Ahmar et al., 2023; Yousefi et al., 2023). While such models have been extensively applied in regions like Europe and Asia, their application in West Africa remains limited (Ameyaw and Yao, 2018).

The importance of emissions forecasting extends beyond environmental management to encompass broader climate policy planning, particularly in rapidly developing regions like West Africa. Globally, models such as Holt-Winters have proven effective in forecasting GHG emissions and energy trends. Tudor and Sova (2021) highlighted its adaptability to seasonal variations and non-stationary trends, while Zhou et al. (2022) introduced an optimized fractional grey Holt-Winters model, improving prediction accuracy for energy-related datasets. Comparative analyses, such as those by Awe et al. (2023), demonstrate that while the Holt-Winters model performs well in many contexts, alternative approaches, including hybrid models and deep learning techniques, can surpass its accuracy for highly complex datasets. In Africa, Viljoen (2022) emphasized the need for region-specific models, including Holt-Winters, to predict emissions from industrial facilities in South Africa. In West Africa, Imhanze and Awe (2023) demonstrated the applicability of the Holt-

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Winters multiplicative model in urban air quality analysis, highlighting its potential for environmental datasets.

Despite these advancements, emissions forecasting in West Africa faces significant gaps. Many studies underscore the necessity of localized data and nuanced adjustments to account for the region's unique socio-economic and environmental contexts (Othoche et al., 2021). Incorporating datasets from comprehensive repositories, such as EDGAR, could enhance the reliability and policy relevance of forecasting efforts. Therefore, this study aims to forecast GHG emissions in West African countries under a BAU scenario using the Holt-Winters model. Specific objectives include analyzing historical GHG emission trends in West African countries, applying the Holt-Winters model to project future emissions, and evaluating the implications of the forecasts for climate policy and sustainable development in the region. By utilizing data exclusively from the EDGAR database, this study bridges critical knowledge gaps in GHG emissions forecasting for West Africa. The findings will provide actionable insights to guide investments in renewable energy, afforestation, and sustainable agricultural practices, which are the main drivers of GHG emissions (Hamdan et al., 2023).

2. Materials and Methods

2.1 Study Area Description

This study focuses on West Africa, a sub-region encompassing 16 countries: Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo. This region exhibits diverse geographical features, ranging from coastal areas to the Sahelian zone, resulting in varied ecological conditions and socio-economic contexts (AfDB, 2022). The economies of these countries are predominantly reliant on agriculture, natural resource extraction, and the development of industrial sectors. This economic diversity, coupled with varying levels of growth and national priorities, contributes to a complex emissions landscape (UNEP, 2021).

2.2 Data and Model Specification

The study analyzed greenhouse gas (GHG) emissions data from 16 West African countries, focusing the period from 1970 to 2021, with a focus on annual CO_2, CH_4, and N_2O emissions measured in kilotons (Kt). The Emissions Database for Global Atmospheric Research Seventh Version (EDGARv7.0) repository served as the source of the data. According to Crippa et al. (2022), the database provides emission data as national totals using global statistics and a consistent Intergovernmental Panel on Climate Change (IPCC) methodology. This dataset is widely used for emissions analysis and provides a consistent framework for comparison across countries (e.g., Güneralp et al., 2020).

The Holt-Winters linear exponential smoothing model was employed to forecast GHG emissions through 2099. This model was selected for its ability to capture both trend and seasonal patterns in time series data. This is computed mathematically as;

Level: $L_t = \alpha Y_t + (1 - \alpha)(L_{t-1} + T_{t-1})$ (1)

Trend: $T_t = \beta (L_t - L_{t-1}) + (1 - \beta) T_{t-1}$ (2)

Forecast: $F_{t+k} = L_t + k T_t$ (3)

Where:

L_t = level at time t
T_t = trend at time t
Y_t = observed value at time t
F_{t+k} = forecast at time t+k
α = smoothing parameter for the level ($0 < \alpha < 1$)
β = smoothing parameter for the trend ($0 < \beta < 1$)
k = number of periods into the future.

2.3 Forecasting and Analysis

The forecasts assume a business-as-usual (BAU) scenario, maintaining historical patterns without incorporating potential policy changes or technological disruptions. This approach provides a baseline projection against which the impact of future interventions can be assessed (IPCC, 2014). XLSTAT 2022.3.1 version was used for all statistical analyses (Addinsoft, 2022). Model optimization and validation for each country and GHG type were conducted as follows:

1. Model parameters (α,β) were optimized to minimize forecast error
2. Data was split into training (1970-2015) and validation (2016-2021) sets. This is consistent with established procedure for model validation in literature (Hussain et al., 2025).
3. Model performance was evaluated using multiple metrics:

i. Root Mean Squared Deviation (RMSD) or Root Mean Squared Error (RMSE)

$$\text{RMSD} = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \hat{x}_i)^2}{N}} \quad (4)$$

Where:

- *RMSD* = root-mean-square deviation
- *i* = variable i
- *N* = number of non-missing data points,
- X_i = actual values,
- $\hat{X}_i$ = forecast values.

ii. Mean Absolute Error (MAE)

$$\text{MAE} = \frac{\sum_{i=1}^{n}|y_i - x_i|}{n} \quad (5)$$

Where:

- *MAE* = mean absolute error
- y_i = prediction,
- X_i = true value,
- *n* = number of data points

iii. Mean Absolute Percentage Error (MAPE)

$$\text{M} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \quad (6)$$

Where:

- *M* = mean absolute percentage error
- *n* = the number of fitted points,
- A_t = the actual value,
- F_t = the forecast value.

iv. R-squared (R^2)

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2} \quad (7)$$

Where:

- R^2 = r squared
- y_i = the y value for observation i,
- $\bar{y}$ = the mean of y value,
- $\hat{y}_i$ = the predicted value of y for observation i.

The optimized models were used to generate forecasts from 2022 to 2099. Thus, the analysis included the evaluation of temporal trends and patterns, calculation of percentage changes in emissions (baseline vs. forecast periods), and assessment of regional emission shares by each West African country from 2022 to 2099.

3. Results and Discussion

3.1 CO_2 Emissions in West African Countries

3.1.1 Evaluation of ' 'Model's Performance for Forecasting CO_2 Emissions

Model performance evaluation for CO_2 forecasting (Table 1) demonstrates strong predictive performance across West African countries, with R^2 values ranging from 0.83 to 0.99, while showing relatively lower but still acceptable performance for Guinea (R^2 = 0.83). The MAPE values, range from 2.24% (Sierra Leone) to 8.87% (Cape Verde), suggesting reliable forecasting capabilities across different scales of emissions. The RMSE values vary significantly, with Nigeria showing the highest RMSE (10,639.75) due to its substantially larger emission volumes. Smaller countries, such as Gambia and Cape Verde, exhibit lower RMSE values (43.46 and 60.26, respectively), reflecting their smaller emission scales. The MAE values follow a similar pattern, with Nigeria having the highest (7,857.04) and Gambia the lowest (24.79), indicating that prediction errors scale proportionally with emission volumes.

Moreover, the optimization parameters (α and β) show considerable variation across countries, suggesting different underlying patterns in historical emissions data. The α values range from 0 to 1.84, while β values range from 0.01 to 248.8, reflecting diverse trend and seasonality patterns. These variations indicate that the model successfully adapts to country-specific emission characteristics, contributing to its overall strong predictive performance despite regional heterogeneity.

Table 1. Goodness of fit statistics for forecasting CO_2 emissions

Matrices Country	Best α	Best β	RMSE	MAE	MAPE	R^2
Benin	1. 22	0.08	448.31	234.96	2.96	0.96
Burkina Faso	1.25	0.03	1091.17	588.26	4.60	0.89
Cape Verde	1.20	0.08	60.26	33.68	8.87	0.95
Cote d'Ivoire	0.75	0.19	962.12	573.23	3.51	0.97
Gambia	1.17	0.11	43.46	24.79	2.88	0.98
Ghana	1.84	0.01	834.38	575.65	3.11	0.96
Guinea	0.00	248.8	1454.90	1067.42	8.01	0.83
Guinea-Bissau	1.16	0.11	73.96	52.69	2.37	0.99
Liberia	0.69	1.59	347.94	261.89	5.69	0.97
Mali	0.73	1.03	205.05	161.43	2.60	0.99
Mauritania	1.03	0.02	441.96	191.67	6.19	0.89
Niger	1.04	0.02	721.92	366.05	4.92	0.89
Nigeria	0.64	0.13	10639.75	7857.04	2.75	0.98
Senegal	0.77	0.83	385.30	235.90	3.19	0.97
Sierra Leone	0.93	0.08	216.42	163.19	2.24	0.95
Togo	1.12	0.13	308.64	180.78	3.72	0.97

3.1.2 Historical and Forecasted CO_2 Emissions Trend in West African Countries

Figure 1 shows the historical and forecasted CO_2 emissions trend in West African countries from 1970 to 2099. It reveals dramatic increases across most West African nations. The trend of CO_2 emissions in West African countries, over the period from 1970 to 2099, reveal a significant and consistent increase across all nations. The data indicate that emissions have grown exponentially, driven by population growth, industrialization, and energy consumption. For instance, Nigeria, as the region's largest economy, shows an increase from 161,348 ktons in 1970 to over 1,142,488 ktons by 2099, marking it as the largest emitter in the region. This sharp rise is attributed to its industrial activities and high population density. Similarly, countries such as Ghana, Côte d'Ivoire, and Senegal have demonstrated substantial growth, with emissions increasing by over 10 times during the same period. This pattern mirrors regional developmental shifts and increasing reliance on fossil fuels for energy generation. Countries with smaller populations or lower industrial activity, such as Cape Verde and Guinea-Bissau, exhibit slower growth in emissions compared to the larger economies. For example, Cape Verde's CO_2 emissions increased modestly from 277 ktons in 1970 to 4,127 ktons by 2099.

However, the proportional growth is still significant, indicating that even smaller nations are not immune to the impacts of modernization and energy demands. This growth underscores the widespread nature of the emissions problem across West Africa, as even nations with historically low emissions are contributing more significantly over time.

The future projections emphasize the urgency of sustainable energy policies in the region. By 2099, CO_2 emissions in countries, like Senegal and Burkina Faso, are predicted to rise to 178,083 and 43,309 ktons, respectively, reflecting their growing economies and energy needs. This trajectory suggests that without intervention, West Africa could face severe environmental challenges tied to global climate change. According to Ouédraogo et al. (2022), innovative energy solutions tailored to ' 'Africa's unique conditions are imperative for achieving sustainable growth and mitigating CO2 emissions across the region. Further exploration of these interventions will be crucial for striking a balance between economic development and environmental stewardship.

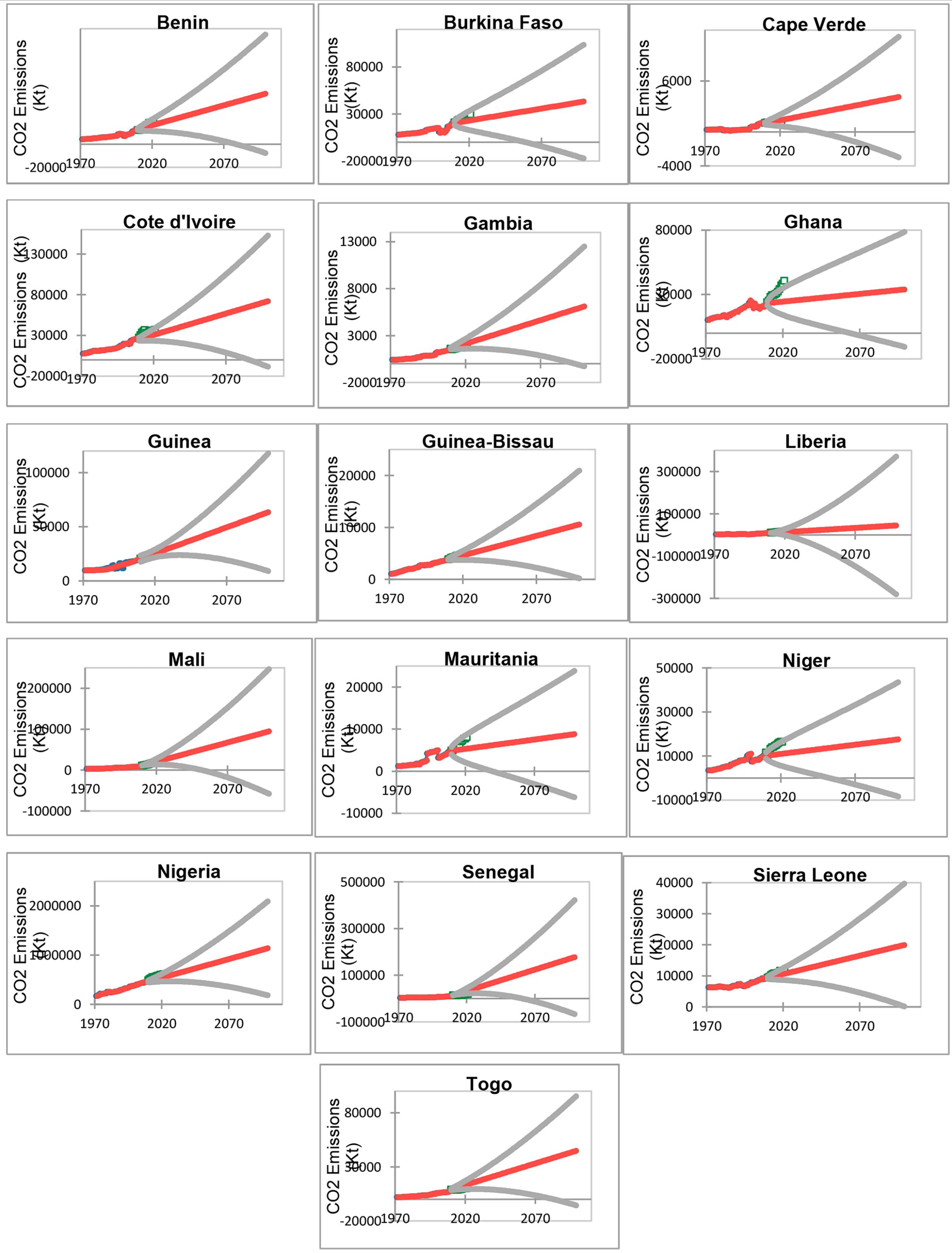

Figure 1. Historical and forecasted CO_2 emissions trend in West African countries

3.1.3 Percentage Change of CO_2 Emissions by Countries in West Africa

Table 2 presents the percentage change in CO2 emissions in West Africa from 1970 to 2099, revealing stark increases across most nations. Countries like Liberia (435%), Mauritania (532%), and Senegal (382%) experienced the steepest rises from 1970 to 2021, highlighting the rapid urbanization and industrialization driving these emissions. This aligns with the findings of Guo et al. (2024), who underscore the governance challenges contributing to emissions in the region. Such trends stress the need for targeted policy responses to mitigate emissions growth. Looking ahead, Senegal's emissions are forecasted to rise significantly, reaching an 808% increase by 2099, potentially due to economic expansion and changes in energy consumption patterns. Conversely, Ghana shows a projected decrease (-16% by 2099), suggesting early adoption of renewable energy or effective emissions controls (Kwakwa et al., 2019). This divergence highlights the importance of tailored approaches to emissions management in addressing distinct national circumstances (Ameyaw et al., 2020).

Table 2. Percentage change of CO_2 emissions by countries in West Africa (Unit: Kt)

Year / Country	1970	2021	2021 1970	2029 2021	2039 2021	2049 2021	2059 2021	2069 2021	2079 2021	2089 2021	2099 2021
Benin	4318.7	19019	340%	3%	22%	40%	58%	76%	94%	112%	130%
Burkina Faso	8158.1	29548	262%	-14%	-5%	3%	12%	21%	29%	38%	47%
Cape Verde	277.2	1204	334%	41%	70%	98%	127%	156%	185%	214%	243%
Cote d'Ivoire	7713.2	36799	377%	-4%	11%	25%	39%	53%	68%	82%	96%
Gambia	426.8	1891	343%	37%	64%	91%	117%	144%	171%	197%	224%
Ghana	10316	40606	294%	-37%	-34%	-31%	-28%	-25%	-22%	-19%	-16%
Guinea	9982.4	25484	155%	17%	36%	55%	74%	93%	112%	130%	149%
Guinea-Bissau	1069.1	4917	360%	8%	23%	39%	54%	69%	85%	100%	115%
Liberia	3033.7	16229	435%	8%	33%	58%	82%	107%	132%	156%	181%
Mali	3623.6	18789	419%	58%	108%	158%	208%	257%	307%	357%	406%
Mauritania	1280.1	8085	532%	-29%	-23%	-18%	-12%	-7%	-1%	4%	10%
Niger	3552.9	16459	363%	-28%	-23%	-18%	-13%	-8%	-3%	2%	7%
Nigeria	161348	611144	279%	0%	13%	25%	38%	50%	62%	75%	87%
Senegal	4073.1	19614	382%	154%	248%	341%	434%	528%	621%	715%	808%
Sierra Leone	6454	11356	76%	3%	13%	24%	34%	44%	55%	65%	76%
Togo	2227	10233	360%	67%	106%	145%	184%	223%	262%	301%	340%

' 'In addition, smaller nations such as Cape Verde and the Gambia display strong upward trends in emissions through 2099 (243% and 224%, respectively), despite their smaller economic footprints. This trend reflects the ongoing dependency on fossil fuels as these nations scale their infrastructure and industries (Musah et al., 2021). Meanwhile, Burkina Faso and Guinea show more moderate increases, suggesting potential early investments in greener technologies or slower industrial development. ' 'Nigeria's emissions, the highest in the region, are predicted to show more modest changes compared to those of smaller economies. With a significant share of the ' 'region's emissions (611,144 kt in 2021), this stabilization could indicate adherence to international climate commitments or the deployment of cleaner technologies (Aalbers et al., 2024).

However, balancing economic growth with emission reduction remains a persistent challenge. Therefore, the projected disparities in emissions growth across West African countries underscore the need for country-specific climate strategies. Rapid-growth nations like Senegal and Mali require aggressive mitigation policies, while those showing stabilization or reductions, such as Ghana and Mauritania, can serve as case studies for sustainable development (Kedir et al., 2023). Addressing these trends will be crucial for the region to effectively contribute to global climate goals.

3.1.4 Regional Percentage Share of CO_2 Emissions by West African Countries

Table 3 highlights the percentage contributions of West African countries to regional CO_2 emissions from 1970 to 2099, showing significant shifts in shares over time. Nigeria, which accounted for 70.8% of the region's emissions in 1970, continues to dominate with a projected 62.4% share by 2099. This percentage reflects its large population, industrial base, and energy use patterns. However, this declining trend indicates some progress in mitigating its carbon footprint, potentially due to policy interventions or shifts toward renewable energy (Ifelunini et al., 2023). In contrast, smaller nations like Senegal and Mali are projected to see a rising share of emissions. Senegal, for instance, is expected to contribute 9.7% by 2099, a sharp increase from 2.3% in 2021. This growth can be attributed to urbanization and increased energy consumption (Musah et al., 2021). Mali follows a similar trajectory, with its share increasing from 2.2% in 2021 to 5.2% in 2099, reflecting similar developmental trends (Matthew et al., 2020). Countries, like Ghana and

Niger, however, show declining contributions, with Ghana’s share decreasing from 4.7% in 2021 to 1.9% by 2099. This result suggests effective emission control strategies or structural economic changes toward less carbon-intensive activities (Espoir and Sunge, 2021). Niger’s trajectory, which decreased from 1.9% to 1.0%, may also reflect slower industrial growth or the success of climate policies (Ameyaw et al., 2020).

Table 3. Regional percentage share of CO2 emissions by countries in West Africa (Unit: Kt)

Year	1970	2021	2029	2039	2049	2059	2069	2079	2089	2099
West Africa	227854	871376	903047	1035569	1168092	1300614	1433136	1565658	1698180	1830703
Benin	1.9%	2.2%	2.2%	2.2%	2.3%	2.3%	2.3%	2.4%	2.4%	2.4%
Burkina Faso	3.6%	3.4%	2.8%	2.7%	2.6%	2.5%	2.5%	2.4%	2.4%	2.4%
Cape Verde	0.1%	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
Cote d'Ivoire	3.4%	4.2%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%
Gambia	0.2%	0.2%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Ghana	4.5%	4.7%	2.8%	2.6%	2.4%	2.3%	2.1%	2.0%	1.9%	1.9%
Guinea	4.4%	2.9%	3.3%	3.3%	3.4%	3.4%	3.4%	3.4%	3.5%	3.5%
Guinea-Bissau	0.5%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%
Liberia	1.3%	1.9%	1.9%	2.1%	2.2%	2.3%	2.3%	2.4%	2.5%	2.5%
Mali	1.6%	2.2%	3.3%	3.8%	4.1%	4.4%	4.7%	4.9%	5.1%	5.2%
Mauritania	0.6%	0.9%	0.6%	0.6%	0.6%	0.5%	0.5%	0.5%	0.5%	0.5%
Niger	1.6%	1.9%	1.3%	1.2%	1.2%	1.1%	1.1%	1.0%	1.0%	1.0%
Nigeria	70.8%	70.1%	68.0%	66.6%	65.5%	64.6%	63.9%	63.3%	62.8%	62.4%
Senegal	1.8%	2.3%	5.5%	6.6%	7.4%	8.1%	8.6%	9.0%	9.4%	9.7%
Sierra Leone	2.8%	1.3%	1.3%	1.2%	1.2%	1.2%	1.1%	1.1%	1.1%	1.1%
Togo	1.0%	1.1%	1.9%	2.0%	2.1%	2.2%	2.3%	2.4%	2.4%	2.5%

’ Furthermore, another notable trend is the stability of emissions shares for smaller nations, like Guinea-Bissau and Cape Verde, which consistently remain below 1% throughout the period. This reflects their limited industrial bases and smaller populations, though there is potential for growth if their economies expand significantly (Abban et al., 2022). Liberia also shows a modest rise in its share, indicative of development but on a smaller scale compared to Senegal or Mali (Musah et al., 2021). Generally, the finding underscores the dynamic shifts in emissions contributions across West Africa, driven by varying rates of economic growth, policy interventions, and energy transitions. This regional heterogeneity highlights the necessity for tailored climate strategies to address the unique challenges and opportunities in each country (Tiemoko et al., 2020).

3.2 CH_4 Emissions in West African Countries

3.2.1 Evaluation of ‘ ‘Model’s Performance for Forecasting CH_4 Emissions

Table 4: The model evaluation for CH_4 emissions across West African countries, with R^2 values ranging from 0.82 to 0.99. Most countries show an excellent model fit; Sierra Leone shows slightly lower but still acceptable performance (R^2 = 0.82 and 0.84, respectively). MAPE values range from 1.69% (Benin) to 7.50% (Nigeria), indicating strong prediction accuracy across different emission scales. RMSE values vary significantly, with Nigeria showing the highest (741.64) due to its larger emission volumes, while smaller emitters, such as Cape Verde, show a minimal RMSE (0.25). The MAE values follow similar patterns, with Nigeria at 557.88 and Cape Verde at 0.16, indicating prediction errors scale proportionally with emission volumes. This result suggests that the model maintains consistent relative accuracy regardless of country size.

However, the optimization parameters exhibit notable variation, with α values ranging from 0.28 to 1.52 and β values from 0.02 to 1.79, reflecting diverse underlying patterns in the historical emissions data. These variations demonstrate the model’s adaptability to country-specific emission characteristics while maintaining high predictive accuracy. The consistently strong performance metrics across countries validate the model’s reliability for forecasting CH4 emissions in the region.

3.2.2 Historical and Forecasted CH_4 Emissions Trend in West African Countries

Historical and forecasted CH_4 emissions in West African countries are shown (Figure 2). The trend from 1970 to 2099 demonstrates an overall increase in emissions. However, notable fluctuations and anomalies emerged. For example, Nigeria, historically a high emitter due to its size and significant agricultural and oil industries, shows an unexpected negative emission projection starting from 2049, possibly due to data anomalies, shifts to greener technologies, or methane capture practices. Other countries such as Ghana, Côte d’Ivoire, and Senegal show consistent increases, with ‘ ‘Ghana’s emissions growing from 137.69 ktons in 1970 to a projected 3,710.22 ktons in 2099, reflecting its intensified agricultural and industrial practices.

Table 4. Goodness of fit statistics for forecasting CH4 emissions

Matrices **Country**	Best α	Best β	RMSE	MAE	MAPE	R^2
Benin	0.74	0.24	2.68	1.80	1.69	0.99
Burkina Faso	0.95	0.18	14.58	6.58	2.16	0.99
Cape Verde	0.85	0.16	0.25	0.16	3.58	0.98
Cote d'Ivoire	1.19	0.10	8.51	6.08	2.50	0.99
Gambia	1.43	0.21	1.15	0.78	3.09	0.97
Ghana	0.28	1.79	10.81	5.05	2.07	0.98
Guinea	1.52	0.11	8.41	5.53	2.50	0.99
Guinea-Bissau	1.38	0.02	2.70	1.82	4.64	0.90
Liberia	0.67	1.55	1.45	1.07	3.06	0.99
Mali	1.18	0.18	16.67	11.37	3.06	0.98
Mauritania	1.38	0.06	8.03	6.03	3.63	0.97
Niger	1.28	0.06	25.22	14.47	4.52	0.95
Nigeria	0.93	0.21	741.64	557.88	7.50	0.82
Senegal	0.96	0.31	6.33	4.95	2.23	0.98
Sierra Leone	1.07	0.04	6.61	4.41	4.11	0.84
Togo	0.88	0.19	2.75	2.07	2.58	0.99

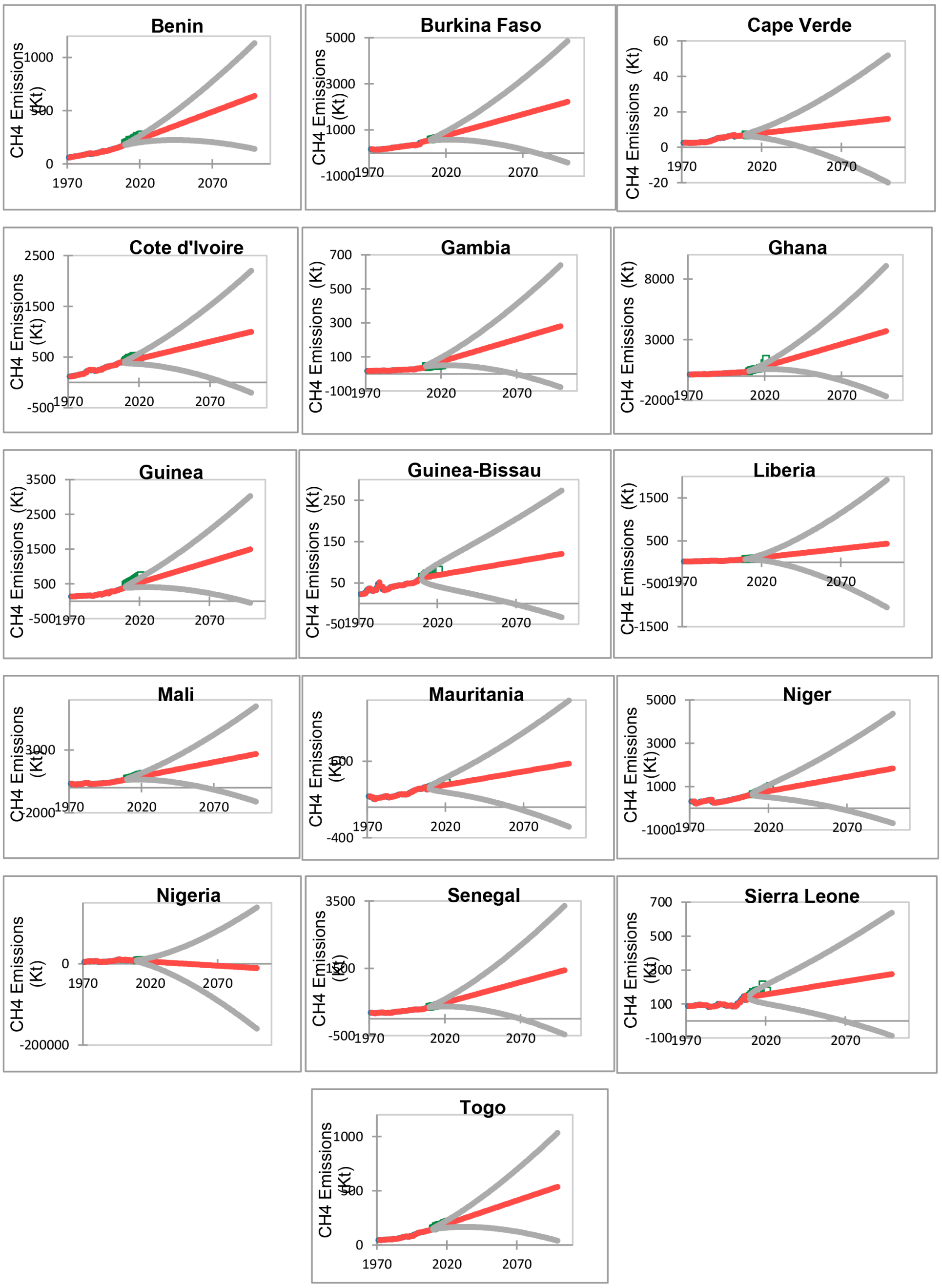

Figure 2. Historical and forecasted CH_4 emissions trend in West African countries

Furthermore, smaller nations like Cape Verde and Guinea-Bissau exhibit slower yet steady increases in methane emissions. Cape Verde, for example, saw its emission rise from 2.72 ktons in 1970 to a projected 16.13 ktons in 2099. This growth, while smaller in absolute terms, underscores the pervasive impact of modernization and agricultural expansion in smaller economies. Similarly, Guinea-Bissau's methane emissions, growing from 22.19 ktons in 1970 to 120.39 ktons in 2099, highlight the gradual intensification of agricultural activities and energy use in less industrialized nations. The steady upward trend in methane emissions across most countries points to challenges in balancing agricultural expansion and energy demands with climate commitments. The significant growth in emissions in countries such as Burkina Faso, projected to reach 2,229.79 ktons by 2099, further emphasizes the importance of methane mitigation strategies. Research, such as that by Smith et al. (2020), highlights that adopting sustainable farming practices and investing in methane-reducing technologies, including improved livestock feed and anaerobic digesters, are crucial for mitigating emissions. The data underscores the urgent need for regional cooperation and investment in innovative climate solutions to manage methane emissions while supporting sustainable economic growth.

3.2.3 Percentage Change of CH_4 emissions by Countries in West Africa

Table 5 presents the percentage change of CH_4 emissions across West African countries. The historical period (1970-2021) reveals substantial increases in CH4 emissions across West Africa. Most notable are Ghana (935%), Guinea (458%), and Liberia (440%), reflecting the possibility of significant agricultural expansion and industrialization. Lower growth rates were seen in Nigeria (76%), Sierra Leone (108%), and Mauritania (117%), suggesting more moderate sectoral changes during this period. However, future projections (2021-2099) reveal divergent trajectories. For instance, Nigeria is predicted to experience a substantial reduction in methane emissions by 2099, which can be attributed to advanced policy interventions and technological upgrades. In contrast, Gambia shows the highest projected increase (467%), followed by Liberia (320%) and Senegal (219%). Burkina Faso and Ghana also show significant increases of 189% and 160% respectively. Several countries display moderate growth trajectories, with Benin (131%), Mali (145%), and Togo (151%) showing steady increases. Guinea-Bissau and Sierra Leone project the lowest positive growth rates at 47% and 55% respectively. Some countries exhibit initial negative growth before trending positive. For example, Ghana shows a -20% growth rate by 2029, followed by an increase, while Guinea projects a -13% growth rate before growing to 101% by 2099. The forecasts indicate varying phases of industrial development and agricultural intensification across the region. Thus, the an urgent need for targeted methane mitigation strategies, particularly in agriculture (Goopy et al., 2018).

Table 5. Percentage change of CH_4 emissions by countries in West Africa (Unit: Kt)

Year / Country	1970	2021	2021 1970	2029 2021	2039 2021	2049 2021	2059 2021	2069 2021	2079 2021	2089 2021	2099 2021
Benin	61.9	277.4	348%	1%	20%	38%	57%	75%	94%	112%	131%
Burkina Faso	173.7	772.1	345%	21%	45%	69%	93%	117%	141%	165%	189%
Cape Verde	2.7	7.2	167%	24%	38%	52%	66%	80%	94%	108%	123%
Cote d'Ivoire	116.8	495.9	324%	7%	20%	34%	48%	61%	75%	88%	102%
Gambia	18.8	49.6	164%	98%	150%	203%	256%	309%	362%	414%	467%
Ghana	137.7	1424.4	935%	-20%	6%	32%	57%	83%	109%	135%	160%
Guinea	132.8	740.5	458%	-13%	3%	20%	36%	52%	69%	85%	101%
Guinea-Bissau	22.2	81.7	268%	-9%	-1%	7%	15%	23%	31%	39%	47%
Liberia	19.2	103.9	440%	44%	84%	123%	162%	202%	241%	280%	320%
Mali	326.4	1097.8	236%	2%	22%	43%	63%	84%	104%	125%	145%
Mauritania	147.9	319.2	117%	1%	12%	23%	34%	46%	57%	68%	79%
Niger	305.3	1018.7	234%	-10%	3%	16%	29%	42%	55%	68%	81%
Nigeria	5051.5	8896.8	76%	-56%	-79%	-101%	-124%	-147%	-169%	-192%	-215%
Senegal	186.5	453.2	143%	30%	57%	84%	111%	138%	165%	192%	219%
Sierra Leone	85.7	178.6	108%	-4%	4%	13%	21%	30%	38%	46%	55%
Togo	48.6	214.3	341%	9%	30%	50%	70%	90%	111%	131%	151%

Furthermore, regional initiatives, like climate-smart agriculture (CSA), have shown promise in reducing emissions while supporting agricultural productivity (Zougmoré et al., 2016). International frameworks, such as the Paris Agreement, provide a critical platform for integrating these local efforts into global methane reduction targets. Moreover, satellite observations and modeling efforts are becoming increasingly critical for monitoring emissions and guiding interventions (Goopy et al., 2018). Addressing the challenge of methane emissions not only helps mitigate climate change but also supports the achievement of sustainable development goals across West Africa.

3.2.4 Regional Percentage Share of CH_4 Emissions by West African Countries

Table 6 highlights the changing percentage share of CH_4 emissions from West African countries from 1970 to 2099. Regional emissions peaked at 16,131 kilotons in 2021 before steadily declining to an estimated 7,086.5 kilotons by 2099. This overall reduction reflects global and regional efforts to mitigate methane emissions. However, the proportional contributions of individual countries to total emissions show a dramatic redistribution, driven by varying national policies, economic development, and population growth (Zhang et al., 2021). Nigeria, the largest methane emitter in West Africa in 1970 (73.9%) and 2021 (55.2%), is projected to experience a stark decline in its share, reaching negative contributions by 2049 and beyond. Despite Nigeria's declining dominance, its historical emissions have had significant implications for regional trends.

Table 6. Regional percentage share of CH4 emissions by countries in West Africa (Unit: Kt)

Year	1970	2021	2029	2039	2049	2059	2069	2079	2089	2099
West Africa	6837	16131	11120	10544	9967.7	9391.5	8815.2	8238.9	7662.7	7086.5
Benin	0.9%	1.7%	2.5%	3.1%	3.8%	4.6%	5.5%	6.5%	7.7%	9.0%
Burkina Faso	2.5%	4.8%	8.4%	10.6%	13.1%	15.9%	19.0%	22.6%	26.7%	31.5%
Cape Verde	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.2%	0.2%	0.2%
Cote d'Ivoire	1.7%	3.1%	4.7%	5.6%	6.7%	7.8%	9.1%	10.5%	12.2%	14.1%
Gambia	0.3%	0.3%	0.9%	1.2%	1.5%	1.9%	2.3%	2.8%	3.3%	4.0%
Ghana	2.0%	8.8%	10.2%	14.3%	18.8%	23.9%	29.6%	36.1%	43.6%	52.4%
Guinea	1.9%	4.6%	5.8%	7.3%	8.9%	10.7%	12.8%	15.2%	17.9%	21.0%
Guinea-Bissau	0.3%	0.5%	0.7%	0.8%	0.9%	1.0%	1.1%	1.3%	1.5%	1.7%
Liberia	0.3%	0.6%	1.3%	1.8%	2.3%	2.9%	3.6%	4.3%	5.2%	6.2%
Mali	4.8%	6.8%	10.0%	12.7%	15.7%	19.1%	22.9%	27.2%	32.2%	38.0%
Mauritania	2.1%	2.0%	2.9%	3.4%	3.9%	4.6%	5.3%	6.1%	7.0%	8.1%
Niger	4.5%	6.3%	8.2%	9.9%	11.8%	13.9%	16.4%	19.1%	22.3%	26.0%
Nigeria	73.9%	55.2%	35.2%	18.0%	-1.2%	-22.8%	-47.1%	-74.9%	-106.9%	-144.0%
Senegal	2.7%	2.8%	5.3%	6.8%	8.4%	10.2%	12.3%	14.6%	17.3%	20.4%
Sierra Leone	1.3%	1.1%	1.5%	1.8%	2.0%	2.3%	2.6%	3.0%	3.4%	3.9%
Togo	0.7%	1.3%	2.1%	2.6%	3.2%	3.9%	4.6%	5.5%	6.5%	7.6%

Nevertheless, contrary to Nigeria's decline, smaller emitters like Burkina Faso, Ghana, and Mali are projected to increase their shares substantially. Ghana, for example, rises from 2% in 1970 to an estimated 52.4% by 2099, becoming the largest contributor to regional emissions. This trend highlights the increasing influence of agriculture and urbanization on methane production in these countries (Goopy et al., 2018). Burkina Faso and Mali also demonstrate significant increases, reflecting the expansion of livestock and land-use activities (Dangal et al., 2017). Countries like Benin, Côte d'Ivoire, and Senegal are emerging as notable contributors to methane emissions. Their shares are projected to rise steadily, indicating increasing economic activities and agricultural intensification (Kouazounde et al., 2015). For example, ' 'Benin's share rises from 0.9% in 1970 to 9% by 2099, marking one of the sharpest proportional rises in the region. Addressing these increases will require targeted interventions, particularly in the agricultural and waste management sectors. Regional cooperation, under frameworks like the African ' 'Union's Climate Action Plan, could enable knowledge sharing and policy alignment to address these disparities effectively (Zougmoré et al., 2016). In addition, international financial and technical support will be critical in helping emerging contributors manage their growing emissions.

3.3 N_2O Emissions in West African Countries

3.3.1 Evaluation of ' 'model's Performance for forecasting N_2O emissions

Examining Table 7, the model exhibits strong predictive performance across West African countries, with R^2 values consistently above 0.94, indicating an excellent goodness of fit. The MAPE ranges from 1.17% (Guinea-Bissau) to 8.34% (Cape Verde), suggesting generally reliable forecasting capabilities, though with varying degrees of accuracy across countries. The α and β show considerable variation between countries, reflecting different underlying patterns in their N_2O emissions. Notable examples include Nigeria with a relatively low α (0.44), indicating less weight is given to recent observations. In contrast, countries like Guinea and Senegal have higher α values (1.39 and 1.36, respectively), suggesting a stronger influence of recent data points in their forecasts.

Table 7. Goodness of fit statistics for forecasting N_2O emissions

Matrices Country	Best α	Best β	RMSE	MAE	MAPE	R^2
Benin	0.71	0.16	0.13	0.09	3.29	0.98
Burkina Faso	0.92	0.15	0.56	0.24	2.39	0.98
Cape Verde	0.52	0.10	0.02	0.01	8.34	0.94
Cote d'Ivoire	0.74	0.17	0.18	0.13	2.65	0.96
Gambia	1.14	0.19	0.02	0.01	1.55	0.98
Ghana	0.64	0.97	0.12	0.19	2.14	0.99
Guinea	1.39	0.15	0.17	0.11	2.90	0.99
Guinea-Bissau	1.33	0.26	0.02	0.01	1.17	0.99
Liberia	0.64	1.51	0.02	0.02	2.97	0.98
Mali	0.92	0.99	0.61	0.39	3.53	0.97
Mauritania	1.32	0.05	0.27	0.20	4.28	0.95
Niger	1.27	0.08	0.94	0.55	5.62	0.95
Nigeria	0.44	0.66	1.08	0.74	1.35	0.97
Senegal	1.36	0.13	0.16	0.13	2.18	0.99
Sierra Leone	0.77	0.59	0.07	0.05	3.36	0.94
Togo	1.06	0.08	0.19	0.07	4.44	0.97

In addition, the model's error metrics (RMSE and MAE) indicate larger absolute errors for countries with higher emission volumes, such as Nigeria (RMSE: 1.08, MAE: 0.74) and Niger (RMSE: 0.94, MAE: 0.55), while smaller countries like Cape Verde and Gambia show minimal absolute errors (RMSE: 0.02, MAE: 0.01). This pattern suggests that the model maintains relative accuracy across different scales of emissions, although absolute errors increase with the volume of emissions.

3.3.2 Historical and Forecasted N_2O Emissions Trend in West African Countries

Figure 3 illustrates the historical and forecasted N_2O emissions trend in West African countries. It indicates that Nigeria has the highest N2O emissions, with a significant increase from 31.40 ktons in 1970 to 325.51 ktons in 2099. Other countries, such as Ghana, Côte d'Ivoire, and Senegal, are also involved. For example, Ghana's N_2O emissions increased from 3.07 kton in 1970 to 41.37 kton in 2099, while Burkina Faso's emissions increased from 5.48 kton to 70.39 kton over the same period. Population growth, urbanization, and economic development are key drivers of N_2O emissions in West Africa (Kumi et al., 2020). The projections to 2099 suggest that the region's emissions will continue to increase, with significant implications for climate change and environmental sustainability. Therefore, the implementation of sustainable agriculture practices and the promotion of renewable energy can help reduce N_2O emissions in West Africa (Oluwafemi et al., 2020). Thus, stakeholders in the region need to develop and implement effective strategies to mitigate N_2O emissions and promote sustainable development.

3.3.3 Percentage change of N_2O emissions by West African countries

Table 8 presents the percentage change in N_2O emissions by West African countries, highlighting significant environmental concerns linked to agricultural expansion, population growth, and policy differences. From 1970 to 2021, emissions increased dramatically, with Guinea experiencing a 455% rise. This finding aligns with Yeboah et al. (2023), who identified agricultural intensification as a major contributor to N_2O emissions in developing regions. Similarly, Burkina Faso and Nigeria show comparable trends, underscoring the interconnection of economic growth and environmental challenges (Nkegbe and Sekyi, 2022). Addressing these issues requires a combination of sustainable agricultural practices and regional policy interventions, as outlined by UNEP (2023). Projections from 2021 to 2099 suggest diverse trajectories across the region. Emissions are expected to rise in most countries but stabilize in others. For instance, Cape Verde and Guinea-Bissau are projected to experience over 300% increases, reflecting growing agricultural outputs and insufficient environmental regulations (World Bank, 2023). Conversely, Niger and Togo exhibit early declines in emission growth (-6% by 2029), potentially signaling the emergence of environmental policies or developmental slowdowns. These regional disparities align with the findings of the African Development Bank (2023), underscoring the need for tailored solutions to achieve sustainability.

Additionally, smaller nations, like Sierra Leone, are projected to face a 461% rise in emissions by 2099, driven by deforestation and unsustainable farming practices (FAO, 2023). This underscores the urgency for targeted interventions beyond larger emitters. UNEP (2023) advocates innovative policies tailored for nations experiencing exponential emission growth to ensure equitable climate action. These trends highlight the necessity of balancing development with ecological preservation, especially in less industrialized nations. Nigeria, as the ' 'region's largest emitter, demonstrates consistent growth in N_2O emissions (293% by 2021 and 164% by 2099). This trend reflects pressures from industrialization and urbanization, paralleling patterns seen in other rapidly developing economies (Osei et al., 2022). UNEP (2023) identifies Nigeria as a case study for integrating green technologies and international cooperation to mitigate emissions while promoting development. Furthermore, strategies, proposed by Alhassan et al. (2023), offer promising blueprints for high-emission countries like Nigeria to achieve green growth.

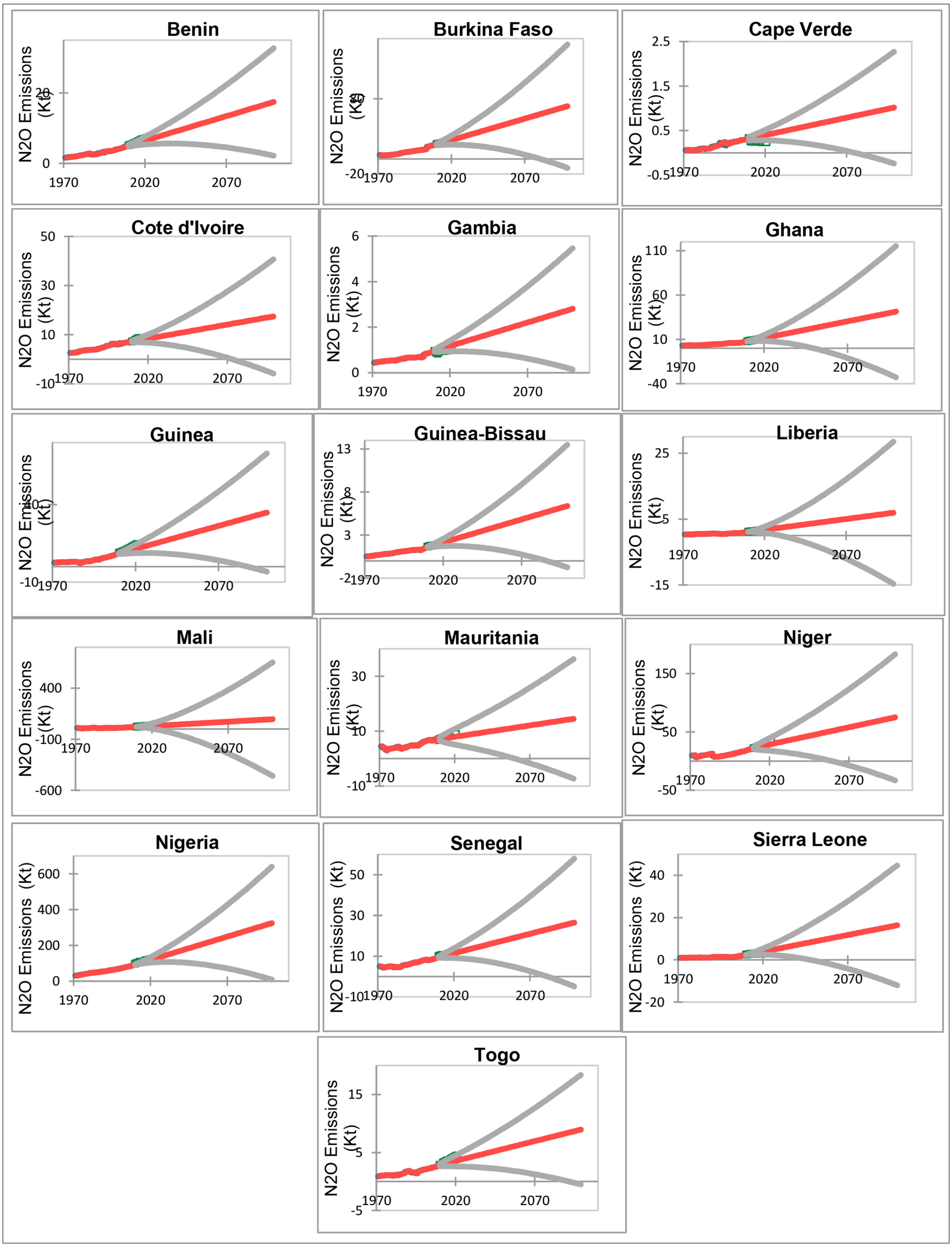

Figure 3. Historical and forecasted N_2O emissions trend in West African countries consistent increase in emissions across all countries in the region from 1970 to 2099.

3.3.4 Regional percentage share of N_2O emissions by West African Countries

Table 9 depicts the regional percentage share of N_2O emissions in West Africa. The N_2O emissions from 1970 to 2099 reveal significant disparities in contributions among countries. Nigeria, with its share increasing from 39.6% in 1970 to 41.8% by 2021, and projected to stabilize at 42.7% by 2099. However, smaller nations like Cape Verde, Liberia, and Guinea-Bissau contribute minimally to the regional total, with shares of less than 1% throughout the period. This result aligns with Thompson et al. (2014), who identified West Africa as a critical region for increasing emissions due to urbanization and industrial growth. Nigeria's reliance on agriculture and fossil fuels to support its burgeoning population highlights the need for targeted policies that integrate industrial efficiency with sustainable urbanization (Wang et al., 2023). However, other significant contributors, including Mali, Niger, and Burkina Faso, collectively account for a considerable portion of emissions. Mali, with a share of 12.7% by 2099, highlights the enduring impact of livestock and traditional agricultural practices, as noted by Assouma et al. (2017). Niger's slight decline from 12% in 1970 to 9.8% by 2099 could reflect shifts in agricultural methods or land-use practices influenced by climate adaptation. These trends support the arguments of Delon et al. (2020), who emphasize the role of climate-smart agriculture in mitigating emissions within the region's ecosystems. Table 9 also reveals contrasting trajectories, such as Mauritania's decline from 5.8% in 1970 to 1.9% by 2099, suggesting potential structural shifts or successful mitigation strategies (Atakora et al. 2019; Albanito et al., 2017). Conversely, Sierra Leone's rise from 1.2% to 2.1% by 2099 can be attributed to agricultural intensification and deforestation, consistent with the observations regarding land-use changes in tropical Africa (Ossohou et al., 2019). These variations highlight the intricate interplay between economic development, resource management, and policy implementation in shaping emission dynamics. Thus, as emphasized by Wang et al. (2023), a comprehensive approach combining emissions reduction for high contributors and sustainable development support for smaller nations will be essential for balancing environmental and developmental priorities in West Africa.

Table 8. Percentage Change of N_2O Emissions by Countries in West Africa (Unit: Kt)

Year	1970	2021	2021	2029	2039	2049	2059	2069	2079	2089	2099
Country			1970	2021	2021	2021	2021	2021	2021	2021	2021
Benin	1.6	7.2	342%	8%	27%	46%	65%	84%	104%	123%	142%
Burkina Faso	5.5	25.4	363%	20%	42%	65%	87%	110%	132%	155%	177%
Cape Verde	0.1	0.2	252%	98%	131%	164%	197%	229%	262%	295%	328%
Cote d'Ivoire	2.5	8.7	240%	9%	22%	36%	49%	62%	75%	88%	101%
Gambia	0.4	1.9	128%	39%	60%	81%	102%	123%	144%	165%	185%
Ghana	3.1	11.6	276%	30%	62%	95%	128%	160%	193%	226%	258%
Guinea	2.6	14.6	455%	-3%	17%	38%	58%	79%	99%	119%	140%
Guinea-Bissau	0.5	2.9	270%	33%	60%	87%	114%	140%	167%	194%	221%
Liberia	0.4	1.8	378%	35%	72%	109%	146%	183%	220%	257%	294%
Mali	10.1	34.3	241%	10%	34%	59%	83%	108%	133%	157%	182%
Mauritania	4.6	8.9	95%	-2%	7%	16%	25%	35%	44%	53%	63%
Niger	9.5	36.4	282%	-6%	10%	26%	42%	58%	74%	90%	106%
Nigeria	31.4	123.4	293%	16%	37%	58%	79%	101%	122%	143%	164%
Senegal	5.9	12.4	149%	7%	23%	38%	53%	69%	84%	99%	115%
Sierra Leone	0.9	2.9	199%	84%	138%	192%	246%	300%	353%	407%	461%
Togo	0.9	4.4	380%	-6%	9%	25%	40%	55%	71%	86%	101%

Table 9. Regional percentage share of N2O emissions by West African countries (Unit: Kt)

Year	1970	2021	2029	2039	2049	2059	2069	2079	2089	2099
West Africa	79.2	295.2	330.5	392.2	453.9	515.7	577.4	639.1	700.8	762.6
Benin	2.1%	2.4%	2.4%	2.3%	2.3%	2.3%	2.3%	2.3%	2.3%	2.3%
Burkina Faso	6.9%	8.6%	9.2%	9.2%	9.2%	9.2%	9.2%	9.2%	9.2%	9.2%
Cape Verde	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Cote d'Ivoire	3.2%	2.9%	2.9%	27%	2.6%	2.5%	2.4%	2.4%	2.3%	2.3%
Gambia	0.5%	0.3%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
Ghana	3.9%	3.9%	4.5%	4.8%	5.0%	5.1%	5.2%	5.3%	5.4%	5.4%
Guinea	3.3%	4.9%	4.3%	4.4%	4.4%	4.5%	4.5%	4.5%	4.6%	4.6%
Guinea-Bissau	0.7%	0.7%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
Liberia	0.5%	0.6%	0.7%	0.8%	0.8%	0.8%	0.9%	0.9%	0.9%	0.9%
Mali	12.7%	11.6%	11.4%	11.8%	12.0%	12.2%	12.4%	12.5%	12.6%	12.7%
Mauritania	5.8%	3.0%	2.6%	2.4%	2.3%	2.2%	2.1%	2.0%	2.0%	1.9%
Niger	12.0%	12.3%	10.3%	10.2%	10.1%	10.0%	10.0%	9.9%	9.9%	9.8%
Nigeria	39.6%	41.8%	43.4%	43.2%	43.1%	43.0%	42.9%	42.8%	42.7%	42.7%
Senegal	6.3%	4.2%	4.0%	3.9%	3.8%	3.7%	3.6%	3.6%	3.5%	3.5%
Sierra Leone	1.2%	1.0%	1.6%	1.8%	1.9%	2.0%	2.0%	2.1%	2.1%	2.1%
Togo	1.2%	1.5%	1.3%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%

4. Conclusion

Greenhouse gas (GHG) emissions continue to pose a critical environmental challenge in West Africa, with significant implications for climate change and sustainable development. This study employed the Holt-Winters exponential smoothing model to forecast emissions trends under a BAU scenario through 2099. The findings reveal that CO_2 emissions will experience substantial growth in several countries, particularly Senegal, while ' 'Nigeria's share of regional emissions is projected to decline. CH_4 emissions are expected to decrease regionally, with notable reductions in Nigeria but significant increases in countries such as Gambia and Liberia. N_2O emissions, on the other hand, are predicted to rise across most of the region, reflecting the expansion of agricultural activities and industrial development.

These results stress the urgent need for policy interventions to curb emissions growth and promote sustainable development. West African nations can implement a range of strategies to mitigate emissions, including carbon pricing mechanisms to incentivize lower emissions, large-scale adoption of renewable energy technologies to reduce fossil fuel dependency, and reforestation initiatives to enhance carbon sequestration. Additionally, countries should strengthen their participation in global climate frameworks such as the Paris Agreement and the African ' 'Union's climate action plans to access financial and technical support for emissions reduction initiatives.

For developing economies, the study highlights the importance of integrating climate policies with economic development goals. Investments in clean energy infrastructure, climate-smart agriculture, and green urbanization can provide financial benefits while reducing emissions. Moreover, regional cooperation in data sharing, climate research, and policy harmonization will be essential to address emissions challenges collectively. However, while this study provides valuable insights into future emissions trajectories, its limitations include reliance on historical trends and the exclusion of potential technological and policy shifts. Future research should explore scenario-based modeling approaches that account for varying mitigation efforts and socio-economic developments. Policymakers, researchers, and international stakeholders must work collaboratively to ensure that West Africa transitions toward a low-carbon and climate-resilient future.

Conflict of Interests

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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