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Trends in Greenhouse Gas (GHG) Emissions Attributable to the Waste Sector in Côte d'Ivoire

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Abstract

The waste sector is a growing contributor to greenhouse gas (GHG) emissions in Côte d'Ivoire, with methane (CH_4) as the dominant pollutant. This study examines GHG emission trends from this sector during the period 1990-2022, using data from Côte d'Ivoire's national GHG inventory reports. Findings reveal a consistent increase in GHG emissions, driven mainly by rapid urbanization, population growth, and the rising amount of municipal solid waste. The growing contribution of the waste sector to national GHG emissions highlights the urgent need for targeted and sector-specific mitigation strategies to align with national and international climate goals. Despite recent policy reforms, including the closure of the Akouédo landfill, the establishment of the Kossihouen sanitary landfill, the creation of the National Waste Management Agency, and the adoption of the 2023 Environmental Code prohibiting open burning and uncontrolled dumpsites, the waste sector remains widespread and continues to generate significant emissions, posing risks to air quality and public health. The results highlight the critical importance of implementing sustainable waste management practices, such as improved collection, sanitary landfilling, recycling, and methane recovery systems, to reduce emissions and support national climate change mitigation objectives.

Keywords

Greenhouse Gas (GHG), Methane, Waste Sector, Emissions Inventory, Côte d'Ivoire

1. Introduction

Climate change is defined as changes in climate that are directly or indirectly attributable to human activity that alters the composition of the atmosphere and that are in addition to the natural climate variability observed over comparable periods [1]. The waste sector, and particularly the solid waste subsector, significantly contributes to national GHG inventories through methane (CH_4) emissions, a potent GHG with a global warming potential 28 to 34 times greater than Carbon Dioxide (CO_2) over a 100-year horizon [2].

The management of waste in Africa is a major challenge that needs serious attention [3]. In Côte d'Ivoire, the rapid growth of the population, the urbanization, and the economic development have led to increased municipal solid waste (MSW) generation. The total quantity of waste landfilled ranges from 841,371 tons in 2019 to 1,048,154 tons in 2023, with a total of 4,945,640 tons over the five years of the period 2019-2023 [4]. Despite the increasing amount of waste landfilled and the government's efforts to improve waste management through the establishment of new sanitary landfill sites in urban areas, informal dumpsites still persist, where waste is openly burned. Consequently, these practices without methane recovery systems contribute to uncontrolled CH_4 emissions [3], which Côte d'Ivoire's 2022 Nationally Determined Contributions (NDC) in the waste sector seeks to address by aiming to reduce emissions by 13%, from 6.10 to 5.32 million tons of carbon dioxide equivalent, with actions mainly focusing on improving waste collection and urban sanitation and ensuring sustainable waste management and recovery [5]. Aside from the national communications, there is a lack of sector-specific, in-depth studies tracking the evolution of greenhouse gas (GHG) emissions, limiting decision-makers' capacity to design and implement climate strategies grounded in robust scientific evidence.

Indeed, the management of municipal and industrial solid waste has emerged as a critical environmental and climate concern in Côte d'Ivoire. Emissions generated from Solid Waste Disposal Sites (SWDS), biological treatment processes, open burning, and incineration constitute the core of the solid waste subsector and contribute significantly to national greenhouse gas (GHG) inventories. Understanding the evolution of these emissions is essential for designing mitigation strategies that support Côte d'Ivoire's commitments under the Paris Agreement and its long-term climate objectives. Despite its importance, the solid waste subsector is often analyzed independently, without reference to the broader Waste Sector, which also includes wastewater emissions.

In this study, the primary objective is to examine GHG emissions from the waste sector for the period 1990-2022, using official data from Côte d'Ivoire's National GHG Inventory and IPCC-recommended estimation methods. While the focus remains firmly on solid waste, emissions from wastewater are also included in the analysis to provide necessary context. Wastewater typically represents the dominant source of emissions within the Waste Sector in Côte d'Ivoire, and comparing these contributions allows for a clearer understanding of the relative magnitude, trends, and mitigation potential of the solid waste subsector.

This contextualized approach strengthens the analytical coherence of the study and improves sectoral prioritization for climate action.

The paper is structured as follows. First, the materials and the methods are described in Section 2. This part includes the description of the study area (Côte d'Ivoire), the data, and the methodology. The results and discussion are presented respectively in sections 3 and 4, followed by the conclusion in Section 5.

2. Materials and Methods

2.1. Study Area

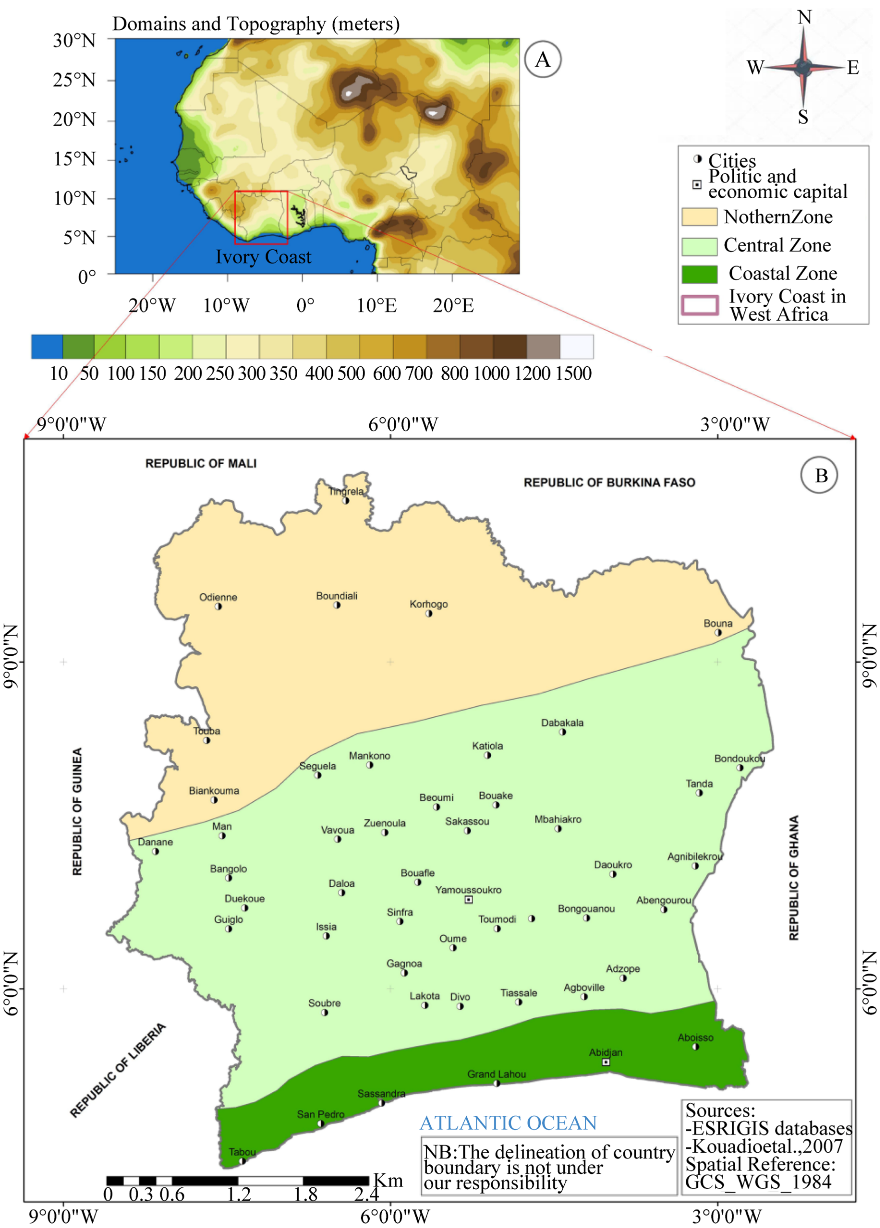

Figure 1. The study area: (A) Location of Côte d'Ivoire in West Africa; (B) The different climatic zones of Côte d'Ivoire [6].

Côte d'Ivoire is a West African country located in the intertropical zone along the Gulf of Guinea. Its territory lies between 4˚30 and 10˚30 North latitude and between 2˚30 and 8˚30 West longitude, covering an area of 322,462 km^2. The country is bordered to the south by the Atlantic Ocean, to the east by Ghana over 640 km, to the north by Burkina Faso (490 km) and Mali (370 km), and to the west by Guinea (610 km) and Liberia (580 km). Côte d'Ivoire is influenced by two air masses: the monsoon, a humid equatorial air mass, and the Harmattan, a dry tropical air mass with its drying wind [7]. The country is characterized by three types of climates with different rainfall variability (**Figure 1**). The Littoral climate area (along the Gulf of Guinea) is mainly dominated by abundant precipitation with two rainy seasons, with a major peak in June (up to 500 mm) and a second maximum less pronounced (120 mm) in October [6] [8]. The Centre climate zone is also characterized by two rainy seasons in June and September, while the North climate presents a unique rainy season in August. The country has been subject to climate change drawbacks in recent decades [6]. These climatic zones, combined with specific topographical features and long-standing human activity, have led to the formation of various vegetation types. Two major vegetation zones dominate: forest in the southern half and savannah in the northern half of the country [7]. The Ivorian population, which was about 5 million in 1960, increased to 29,389,150 according to the results of the last General Population and Housing Census [9], with 52.21% of men and 47.78% of women. As of 2025, the population is estimated to be about 32.8 million, with a population density of 100.8 inhabitants per km^2. The age structure remains heavily skewed toward youth, with a large proportion under the age of 15, representing both an opportunity and a challenge for the country's future development [10].

2.2. Data

This study utilizes data from Côte d'Ivoire's national GHG inventory reports from the Ministry of the Environment, see **Table 1**. Demographic statistics are from the National Institute of Statistics (ANSTAT), and solid waste management records originate from the National Waste Management Agency (ANAGED).

Table 1. Waste and total emissions data [11].

Years	Emissions (Gg CO_2 eq)	
	Waste	Total Emissions
1990	984.38	63,691.78
1991	1117.65	66,635.33
1992	1225.6	59,721.95
1993	1316.71	61,789.64
1994	1398.23	64,177.88
1995	1474.54	66,702.63
1996	1550.24	67,214.14
1997	1621.94	71,080.54

Continued

1998	1681.81	75,613.34
1999	1762.64	78,905.54
2000	1835.95	82,590.82
2001	1898.35	99,968.60
2002	1956.47	100,728.43
2003	2007.04	100,187.25
2004	2077.48	101,215.23
2005	2139.75	104,595.52
2006	2201.40	106,366.22
2007	2271.20	109,138.32
2008	2334.07	109,549.44
2009	2392.63	110,066.14
2010	2460.10	116,070.96
2011	2530.65	116,921.66
2012	2586.27	132,063.68
2013	2650.61	133,969.90
2014	2721.93	135,915.13
2015	2806.42	147,369.21
2016	2899.90	136,401.33
2017	3010.71	145,942.31
2018	3126.47	127,665.47
2019	3241.74	128,112.20
2020	3350.53	128,596.22
2021	3472.97	133,997.27
2022	3588.88	133,123.57

2.3. Methodology

Annually, greenhouse gas emissions from the waste sector and the total emissions are collected, and the evolution is compared. The annual trend values over the period 1990-2022 for aggregated direct GHG total emissions and in the waste sector were obtained using Equation (1) (source: [12]).

$$Trend\ (\%) = \frac{E_{x,t} - E_{x,0}}{E_{x,0}} \times 100 \quad (1)$$

with:

$\boldsymbol{E}_{x,t}$: Estimation of emissions from source category x for year t.

$\boldsymbol{E}_{x,0}$: Estimation of emissions from source category x for base year 0, in this study, the base year is 1990.

The trends in emissions represent the rates of change in emissions relative to the year 1990, taken as the baseline year.

The contribution of the waste sector to overall greenhouse gas emissions was determined by calculating the ratio of emissions from the waste sector to total emissions, then multiplying this ratio by 100 to express it as a percentage.

The contribution of each greenhouse gas in the emissions of the waste sector was also determined by calculating the ratio of emissions from each greenhouse gas of the sector, then multiplying this ratio by 100 to express it as a percentage.

Multiple linear regression is used to assess the sources of variation in the emission of a given gas *Y*, based on the emissions of two other gases, X_1 and X_2, according to the equation:

$$Y = b + m_1 X_1 + m_2 X_2 \quad (2)$$

where m_1 and m_2 quantify the sensitivity of gas *Y* to changes in gases X_1 and X_2, respectively, while b captures potential nonlinear effects or influences on *Y* that are not directly explained by these predictors.

The trends in waste and total emissions are analyzed using the non-parametric Mann-Kendall test [13] [14], which is widely used for detecting monotonic trends in environmental and climatological data. This test is particularly suitable because it does not require the data to be normally distributed and is less sensitive to outliers. The Mann-Kendall statistic *S* is calculated when considering a time series of n observations x_1, $x_2, \ldots, x_n$, as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} signe\left(X_i - X_j\right) \quad (3)$$

where:

$$signe\left(X_i - X_j\right) = \begin{cases} +1, if \left(X_i - X_j\right) > 0 \\ 0, if \left(X_i - X_j\right) < 0 \\ -1, if \left(X_i - X_j\right) = 0 \end{cases} \quad (4)$$

Under the null hypothesis of no trend, the variance of S is given by:

$$var(S) = \frac{n(n-1)(2n+5)}{18} \quad (5)$$

And the standardized test statistic Z is calculated as:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{var(S)}}, if \ S > 0 \\ 0, if \quad S = 0 \\ \dfrac{S+1}{\sqrt{var(S)}}, if \ S < 0 \end{cases} \quad (6)$$

A positive *Z* value indicates an upward (increasing) trend, while a negative *Z* value indicates a downward (decreasing) trend. If |Z| exceeds the critical value of the standard normal distribution (e.g., 1.96 for a 5% significance level), the trend is considered statistically significant.

To investigate the relationships among the emissions of CH_4, CO_2, and N_2O, a correlation analysis was performed. Prior to selecting the appropriate correlation measure, the normality of each variable was assessed using standard diagnostic tests. When the normality assumption was satisfied for the pair of variables considered, Pearson's correlation coefficient was applied to quantify the strength and direction of their linear association. In cases where normality was not met, Spearman's rank correlation was used as a non-parametric alternative. All analyses were conducted in R software, and statistical significance was evaluated at the 5% level.

3. Results and Discussion

3.1. The Annual Trend of Emission of the Waste Sector and the Total Emission

Figure 2 shows the annual trend of total greenhouse gas (GHG) emissions compared to those from the Waste sector over the period from 1990 to 2022. Total emissions have increased significantly over this period, rising from 63,691.78 Gg CO_2-eq in 1990 to 133,123.57 Gg CO_2-eq in 2022 (a 109.01% increase compared to 1990, see Table 1), although some variability has been observed from 2010 onwards, followed by a significant decline starting in 2017.

The Waste sector, while accounting for a smaller share of overall emissions, has shown steady and continuous growth from 984.38 Gg CO_2-eq in 1990 to 3588.88 Gg CO_2-eq in 2022 (a 364.58% increase compared to 1990). This sector is becoming an increasingly notable contributor to GHG emissions, although its impact remains smaller compared to other sectors.

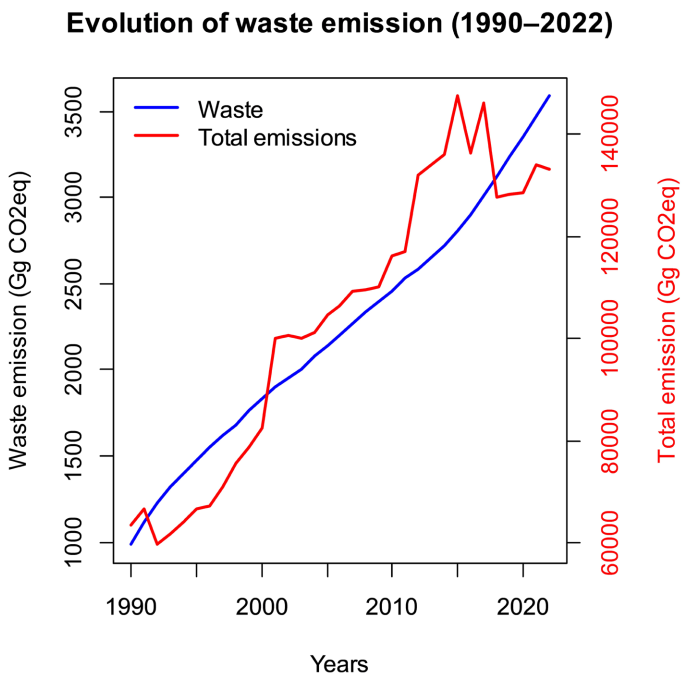

Figure 2. Trends in total GHG emissions and those of the waste sector from 1990 to 2022.

The analysis of the trend in greenhouse gas (GHG) emissions between 1990 and 2022 reveals a marked divergence between the waste sector and overall national emissions (see Figure 3). While total GHG emissions experienced a moderate growth rate until around 2014, followed by relative stabilization, emissions from the waste sector displayed a continuous and significant upward trend throughout the period. Specifically, the waste sector's emissions increased by more than 250% compared to 1990 levels, in contrast to the overall emissions, which peaked slightly above 100% before levelling off. This increase in emissions is also driven by the improvement in the municipal solid waste collection rate, which rose from 50% to 70% [15].

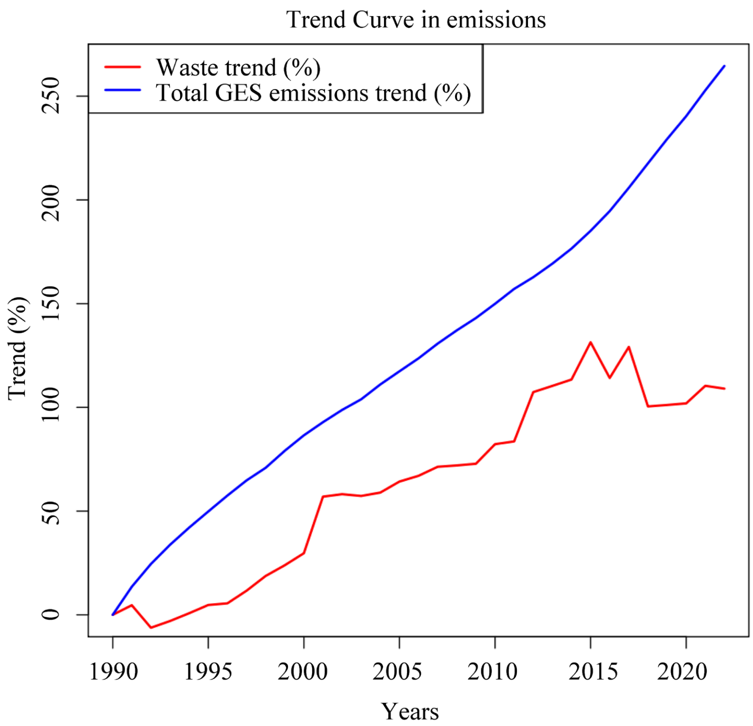

Figure 3. Trends of total GHG emissions and emissions from the waste sector in Côte d'Ivoire [11].

A comparison of trends in greenhouse gas (GHG) emissions for various countries and regions is presented in **Table 2**. Côte d'Ivoire recorded a significant increase in GHG emissions. Total emissions increased by 109.01% from 1990 to 2022. Emissions from the waste sector alone increased by a striking 264.58%, highlighting the growing contribution of waste management practices to national GHG outputs. In the same vein, Ghana experienced a 214.3% increase in total emissions during the same period, pointing to rapid emission growth likely tied to economic and population expansion. While in Morocco, despite a much shorter time frame (2010-2022), it recorded only a 2.5% increase in emissions from the waste sector, suggesting either effective mitigation or slower sectoral growth. In addition, Togo reported an increase of 21.11% between 1990 and 2008. At the global level, GHG emissions increased by 67% from 1990 to 2018, which serves as a reference for comparing national trends. Moreover, North American countries show relatively lower increases compared to Côte d'Ivoire and Ghana, West African countries. The United States of America (USA) registered only a 2% increase (1990-2019), suggesting stabilization or effective policy interventions, contrary to Canada, which reported a 21% increase over the same period, slightly below the global average. In contrast, Europe stands out with a decrease of 19% between 1990 and 2018, indicating that the region succeeds in implementing climate mitigation policies and transitioning to cleaner energy sources.

Table 2. Comparative trends in greenhouse gas emissions across countries, regions, and the whole world.

Country or Region	Trends	References
Côte d'Ivoire (Total emissions)	Increase of 109.01% (1990-2022)	[11]
Côte d'Ivoire (Emissions from waste sector)	Increase of 264.58% (1990-2022)	
Ghana's total aggregate GHG emissions	Increase of 214.3% (1990-2022)	[16]
Morocco (Emissions from the waste sector)	Increase of 2.5% (2010-2022)	[17]
Togo	Increase of 21.11% (1990-2008)	[12]
World	Increase of 67% (1990-2018)	[18]
United States of America (USA)	Increase of 2% (1990-2019)	
Canada	Increase of 21% (1990-2019)	
Europe	Decrease of 19% (1990-2018)	

3.2. The Part of the Waste Sector in the Total Greenhouse Gas Emissions

The results of the First Biennial Transparency Report [11] submitted to the United Nations Framework Convention on Climate Change (UNFCCC) show that the Waste sector ranked fifth in Côte d'Ivoire's total GHG emissions in 2022 (3%), after the Forestry sector (41%), Industrial Processes (31%), Energy (18%), and Agriculture (7%), see **Figure 4**.

This result differs from that of the Third National Communication [7] under the UNFCCC, which indicated that the Waste sector held the third position in total GHG emissions in 2012, following the Energy and Agriculture sectors.

The contribution of the Waste sector has evolved over time, as shown in **Figure 5**. The curve illustrates a moderately increasing trend in the relative contribution (%) of the Waste sector to total greenhouse gas (GHG) emissions. In 1990, the contribution was slightly above 1.5%, reaching approximately 2.8% by 2022.

From 1990 to 1996, there was a sharp initial increase, with the sector's contribution quickly surpassing 2.5%. Between 1999 and 2001, a significant decline was observed, with the contribution dropping below 2.2%. This may indicate either a faster growth in emissions from other sectors or a temporary stagnation in emissions from the Waste sector.

Finally, from 2018 to 2022, we observe a steady increase in the waste sector's contribution, reaching nearly 3%, reflecting a resurgence in emissions from this sector.

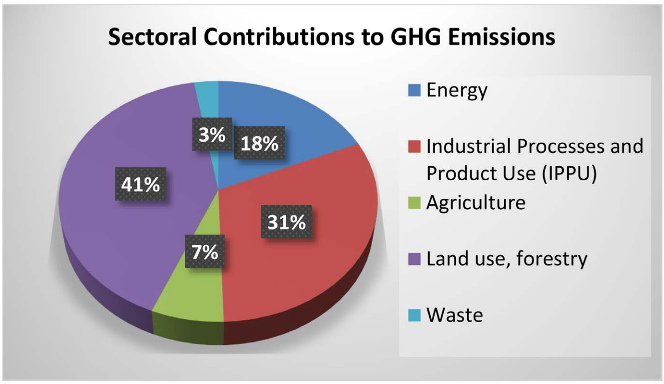

Figure 4. Sectoral contributions to national greenhouse gas emissions in 2022 [11].

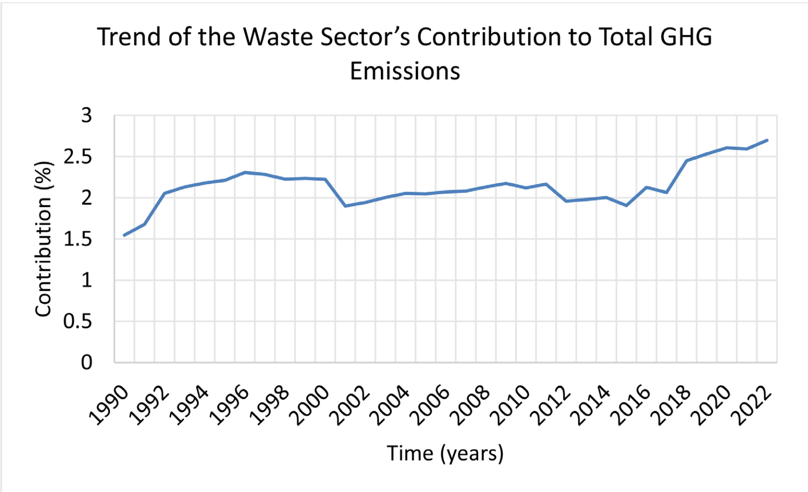

Figure 5. The annual trend of waste sector's contribution to total GHG emissions from 1990 to 2022.

3.3. The Contribution of Each Greenhouse Gas in the Waste Sector

Figure 6 illustrates the distribution of greenhouse gases (GHGs) emitted within the waste sector, distinguishing the three main GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Methane remained the predominant GHG emitted, accounting for over 90% of emissions, due to the high organic content of the waste and the anaerobic conditions present in unmanaged disposal sites, which are the most contributing waste sub-sectors in terms of GHG emissions (see Figure 7). N_2O is also present (8.47%), although to a lesser extent. These N_2O emissions mainly result from biological waste treatment processes, such as sludge digestion and composting. Its Global Warming Potential (GWP) is significantly higher than that of CH_4, about 265 times greater than CO_2 [2].

CO_2 appears to be almost negligible (0.18%) in the direct emissions from the waste sector. This is because biogenic CO_2 (from degradable biomass) is generally not included in national GHG inventories for the waste sector.

According to [19], among methane emissions, urban areas, particularly the city of Abidjan, contributed one-third of the total methane emissions from the waste sector in Côte d'Ivoire.

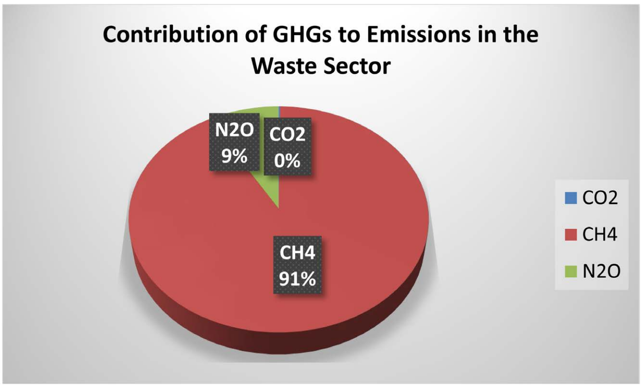

Figure 6. Distribution of greenhouse gas emissions from the waste sector by type of gas in 2022 [11].

The distribution of greenhouse gas (GHG) emissions by sub-sectors within the waste sector is shown in Figure 7.

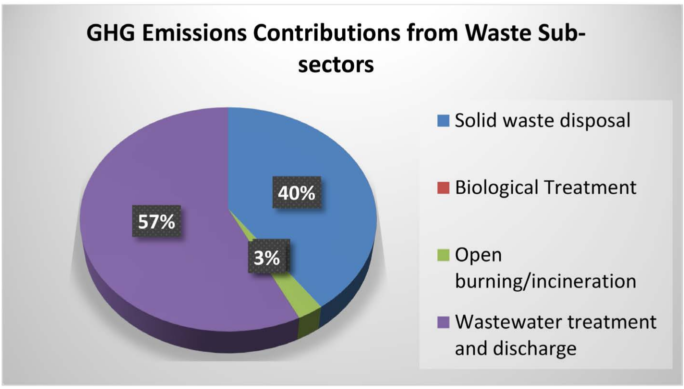

Figure 7. Contributions of sub-sectors to greenhouse gas emissions in the waste sector in Côte d'Ivoire [11].

Wastewater treatment and discharge are the main contributors, accounting for 57.25% of total GHG emissions in the waste sector in Côte d'Ivoire. Inadequate or incomplete treatment processes of domestic or industrial wastewater primarily release methane (CH_4) and nitrous oxide (N_2O). This highlights the urgent need to modernize sanitation infrastructure.

The Solid Waste Disposal sub-sector accounts for 40.16% of emissions. This includes both controlled and uncontrolled landfills, where the anaerobic decomposition of organic waste generates significant methane emissions. Improved and modernized landfill management, including biogas capture, could lead to substantial emission reductions.

The Biological Treatment sub-sector shows no recorded emissions, likely due to the absence of data on biological waste treatment in Côte d'Ivoire.

Open burning and waste incineration account for 2.60% (approximately 3%) of emissions. Although this practice is prohibited under Article 228 of the new Environmental Law [1], it is still carried out illegally in uncontrolled dumpsites, raising serious local concerns due to its impacts on air quality and public health.

3.4. Details: Emissions of the Concentration of the Different Gases by Sector of Activities

In order to get insight into the main contributions to greenhouse gas emissions by sector of activities, the analysis compared the contribution of each gas emitted by the sector of activities as represented in **Table 3**.

Table 3. Sectoral contribution to national emissions of CO_2, CH_4, and N_2O, with the relative share (%) of major emitting sectors for each greenhouse gas in bold. The key processes enabling these emissions are also enumerated.

Gas	Dominant Sector (s)	Share (%)	Key Processes
CO_2	Land Use	55.7%	Deforestation, land conversion, biomass loss
	Energy	24.1%	Fuel combustion for electricity, transport
	IPPU	20.1%	Cement production, industrial processes
CH_4	Agriculture	40.8%	Enteric fermentation, rice cultivation
	Waste + Wastewater	~54%	Landfills, anaerobic digestion, wastewater degradation
	Energy	4.4%	Fugitive emissions, incomplete combustion
N_2O	Agriculture	76.3%	Fertilizer use, manure management, soil nitrification/denitrification
	Waste + Energy	~23% combined	Wastewater N_2O, combustion processes

The sectoral distribution of greenhouse gas emissions reveals marked differences in the dominant sources of CO_2, CH_4, and N_2O. CO_2 emissions are primarily driven by land-use change, which accounts for 55.7% of the total and reflects the substantial impact of deforestation, biomass depletion, and land conversion. The energy sector contributes an additional 24.1%, largely through fuel combustion for transport and electricity generation, while industrial processes (IPPU) represent 20.1% of CO_2 emissions. Other sectors, including agriculture, waste, and open burning, contribute minimally to national CO_2 output.

CH_4 emissions display a different sectoral structure, with agriculture constituting the largest share (40.8%), mainly through enteric fermentation and rice cultivation. Waste-related activities collectively represent more than half of national methane emissions when considering general waste (27.4%), wastewater treatment (14.7%), and solid waste disposal (12%). These contributions highlight the dominant role of anaerobic decomposition processes in landfills and wastewater systems. Energy-related CH_4 emissions remain marginal (4.4%), with open burning contributing less than 1%.

N_2O emissions are overwhelmingly dominated by agricultural activities, which represent 76.3% of the total emissions. This is consistent with the central role of nitrogen-based fertilizers, manure management, and soil microbial processes in generating N_2O. Other sectors, including waste, waste treatment, and energy, each contribute between 7% and 8%, while open burning remains negligible (0.3%).

3.5. Sources of Variation in the Different Gas Emissions

In this section, the sources of variations for the emission of the respective GHG (i.e., CH_4, N_2O, and CO_2) are shown using the multiple regression analysis. This method ignores other parameters that can influence the concentration of a given gas in comparison to the others. The different multiple regression statistics are shown in Table 4 for each gas.

Table 4. Multiple regression coefficients and Fisher-Snedecor statistics test applied to the concentration of the different gases (CH_4, N_2O, and CO_2).

$CO_2 = f(CH_4, N_2O)$				
	Estimate	**Std Error**	**t-value**	**Pr(>|t|)**
Intercept	12012.0	13279.5	0.905	0.532
CH_4	−110.7	217.4	−0.509	0.700
N_2O	798.2	3533.1	0.226	0.859
R^2	**F**	**V_1**	**V_2**	**p-value**
0.2726	0.1874	2	1	0.8529
$CH_4 = f(CO_2, N_2O)$				
	Estimate	**Std Error**	**t-value**	**Pr(>|t|)**
Intercept	50.018	53.69	0.932	0.523
CO_2	−0.0018	0.0036	−0.509	0.700
N_2O	12.100	8.59	1.407	0.393
R^2	**F**	**V_1**	**V_2**	**p-value**
0.7235	1.449	2	1	0.5064
$N_2O = f(CH_4, CO_2)$				
	Estimate	**Std Error**	**t-value**	**Pr(>|t|)**
Intercept	−1.413	4.737	−0.298	0.815
CH_4	5.492×10^{-2}	3.902×10^{-2}	1.407	0.393
CO_2	6.084×10^{-5}	2.693×10^{-4}	0.226	0.859
R^2	**F**	**V_1**	**V_2**	**p-value**
0.6927	1.127	2	1	0.5544

The multiple regression analyses revealed no significant linear relationships among CO_2, CH_4, and N_2O emissions. For all models, the regression coefficients were associated with large standard errors and high p-values, indicating that none of the explanatory variables contributed meaningfully to predicting the response variable. Although some models exhibited moderately high R^2 values, the corresponding F-tests were not significant, confirming that none of the emissions of a given gas can explain another.

3.6. Correlation Analysis between the Gas Emissions

Figure 8 indicates the correlation matrix between the emissions of the different gases.

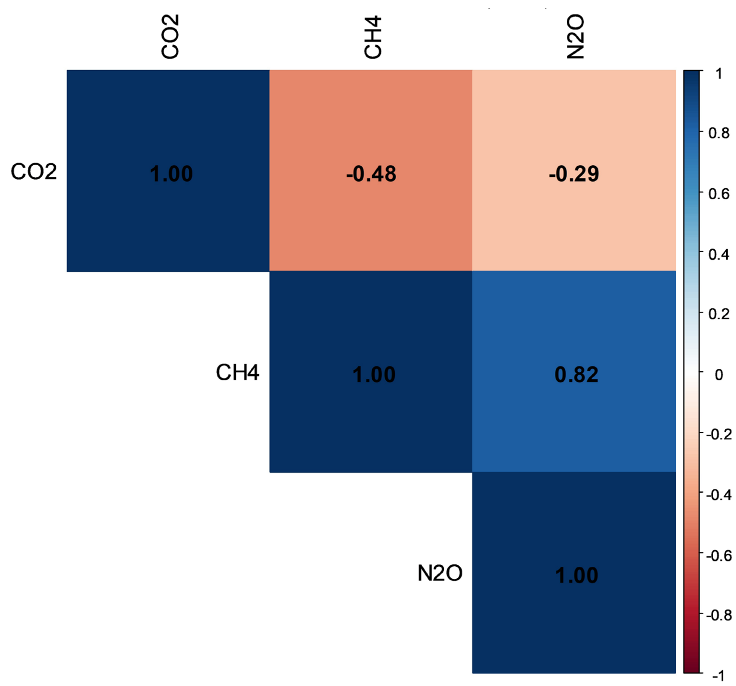

Figure 8. Correlation matrix of greenhouse gas emissions (CO_2, CH_4, N_2O).

Table 5. Correlation matrix of greenhouse gas emissions (CO_2, CH_4, N_2O). The upper triangle shows Pearson correlation coefficients, and the lower triangle shows Spearman rank correlation coefficients. Values in bold indicate stronger relationships, but none were statistically significant at the 5% level. Data normality was assessed with the Shapiro-Wilk test to determine the appropriate correlation method.

	CO_2	CH_4	N_2O
CO_2	1.000	−0.485 (Pearson)	−0.289 (Pearson)
CH_4	0.210 (Spearman)	1.000	0.822 (Pearson)
N_2O	0.210 (Spearman)	1.000 (Spearman)	1.000

The correlation matrix revealed weak to moderate associations among the gas emissions: CO_2 exhibited moderate negative correlations with CH_4 ($r = -0.485$, ρ

= 0.21) and N_2O (r = −0.289, ρ = 0.21), whereas CH_4 and N_2O showed a strong positive correlation (r = 0.823, ρ = 1.00). However, none of these correlations were statistically significant (Pearson p > 0.17; Spearman p > 0.08) (see **Table 5**). The strong Spearman correlation between CH_4 and N_2O reflects tied values in the dataset, which prevented the computation of an exact p-value.

3.7. Trend Analysis in Waste and Total Waste Emission

The Mann-Kendall test was applied to assess the presence of monotonic trends in waste-related emissions and national total emissions. The results reveal highly significant positive trends for both variables (**Table 6**). Waste emissions show a particularly strong increase (S = 528, Z = 8.16, p = 3.19×10^{-16}), indicating a consistent upward trajectory throughout the study period. Similarly, total emissions exhibit a robust increasing trend (S = 456, Z = 7.05, p = 1.78×10^{-12}), reflecting a sustained rise across all major contributing sectors.

Table 6. Trend statistics based on the Mann-Kendall test for waste emissions and total emissions in Côte d'Ivoire during the period 1990-2022.

Variables	S	Z	p-value
Waste emissions	528	8.16	3.19×10^{-16}
Total emissions	456	7.05	1.78×10^{-12}

4. Discussion

The significant increase in GHG emissions from the Waste sector can be attributable to several factors, including population growth, rapid urbanization, and prevailing production and consumption patterns. Globally, approximately one-third of food produced for human consumption is lost or wasted, amounting to 1.3 billion tons per year [20]. This scale of material loss contributes substantially to rising. Indeed, in Côte d'Ivoire, municipal solid waste is primarily composed of more than 70% biodegradable material [21].

Consequently, the persistent rise in GHG emissions from waste suggests that current waste management measures are insufficient to mitigate their environmental impact. Furthermore, the strong linear correlation of emissions in the Waste sector suggests a predictable growth pattern that could be effectively targeted by dedicated climate policies.

In addition, this sustained increase in waste-related emissions suggests that mitigation efforts in this sector have lagged behind other sectors, potentially due to inadequate waste management practices, increased organic waste generation, and limited implementation of methane recovery technologies. As a result, the Waste sector's growing contribution to national GHG emissions underscores the urgency of implementing targeted, sector-specific mitigation strategies aligned with national and international climate objectives.

Conversely, the observed decline in the sector's ranking in certain years may reflect improvements in waste management policies and the implementation of measures aimed at reducing emissions. For example, a temporary 2% decrease between 2016 and 2017 may be linked to revised inventory data or short-term waste management efforts. Notably, this period corresponds to the preparation of the Third National Communication under the UNFCCC, which involved revising national GHG inventories, and to the establishment of the National Waste Management Agency (ANAGED) in 2017. ANAGED, created by Decree No. 2017-692 of October 25, 2017, is responsible for regulating solid waste management and supporting local governments and private stakeholders under the supervision of the Ministry of Water, Sanitation, and Hygiene [22].

Overall, the Waste sector's growing though still modest share of total national emissions reflects the combined effects of increasing waste generation driven by demographic and urban growth, alongside the slow modernization of waste management infrastructure, particularly the absence of methane capture at disposal sites. This trend indicates that current efforts are insufficient to offset rising waste volumes or to limit their associated environmental impacts. Periods of apparent stabilization may therefore conceal a lack of innovation or the absence of additional mitigation measures.

Given this context, the distribution of emissions highlights the strategic importance of reducing methane (CH_4), a potent greenhouse gas and short-lived climate pollutant (SLCP) with an atmospheric lifetime of 12.4 years [2]. Key mitigation options include landfill methane capture for energy recovery, source reduction of organic waste, and expanded adoption of controlled composting. Similarly, effective mitigation in the Waste sector requires prioritizing wastewater treatment through enhanced and better-controlled systems, as well as improved landfill management practices, particularly the reduction of biodegradable waste and the promotion of biogas recovery.

This distribution indicates that GHG mitigation policies in the waste sector should primarily focus on wastewater treatment systems through more efficient and controlled processes, and on landfill management, particularly by reducing biodegradable waste and promoting biogas recovery.

Several initiatives are currently underway, including the Methane Emissions from Landfills in Côte d'Ivoire (MELCI) project, whose main objective is to reduce methane emissions from the waste sector. These projects will contribute to achieving Côte d'Ivoire's INDC targets in the waste sector.

Overall, the results indicate that each greenhouse gas exhibits a distinct sectoral emission profile, with implications for targeted mitigation strategies. CO_2 emissions are predominantly associated with land-use dynamics and energy systems, highlighting the need for interventions in forest conservation, sustainable land management, and cleaner energy production. By contrast, CH_4 is largely driven by agricultural and waste-related processes, suggesting that improvements in livestock management, rice production practices, landfill gas recovery, and wastewater treatment could yield substantial reductions. Meanwhile, N_2O emissions are almost entirely agricultural, underscoring the importance of optimizing fertilizer application, enhancing nitrogen-use efficiency, and promoting integrated soil fertility management.

The dominance of single sectors for CH_4 and N_2O contrasts with the more balanced distribution of CO_2 emissions across land-use change, energy, and industrial processes. This highlights the importance of adopting gas-specific strategies rather than uniform mitigation approaches. Moreover, sectors producing small absolute emissions, such as open burning, should not be overlooked in accounting systems, even if their impact on overall inventories is minimal.

Uncertainty remains a limiting factor, particularly for land-use change and agricultural emissions, where data quality, emission factors, and reporting methodologies can vary considerably. Despite these uncertainties, the observed patterns provide a robust basis for identifying mitigation priorities at the national scale.

The generally weak correlations among CO_2, CH_4, and N_2O are likely due to multiple factors. The small sample size severely limits statistical power, reducing the ability to detect meaningful associations. Deviations from normality for CO_2 and N_2O required the use of non-parametric methods, which are less sensitive in small datasets. Additionally, the dynamics of greenhouse gas emissions are complex, potentially involving nonlinear interactions, temporal variability, or external environmental and anthropogenic drivers that cannot be captured by simple pairwise correlations. Therefore, the lack of strong correlations does not necessarily indicate an absence of relationships among these gases, but rather reflects limitations inherent to the dataset.

5. Conclusions

The waste sector in Côte d'Ivoire has witnessed a steady and substantial rise in greenhouse gas (GHG) emissions over the past 25 years. This trajectory reflects both structural inadequacies in waste management and the lack of emission mitigation technologies. Compared to other regional GHG emission trends, significant efforts will be undertaken to reduce emissions of GHG, particularly methane, a short-lived pollutant.

By examining solid waste emissions alongside wastewater, the study highlights the growing significance of SWDS and other solid waste pathways, identifies key emission drivers over the 1990-2022 period, and supports informed decision-making for sustainable waste management in Côte d'Ivoire.

To achieve its climate objectives, Côte d'Ivoire must implement integrated waste management strategies that include prevention, minimization, reuse, recycling, energy recovery, and safe disposal. It must also prioritize climate-resilient infrastructure investments and strengthen data governance. Such measures will be crucial not only for reducing emissions but also for improving public health, environmental quality, and urban resilience.

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Conflicts of Interest

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

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