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Regional N_2O Emission Factors From Bioethanol Crops in Brazil: Advances and Data Gaps

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ABSTRACT

The recognition of bioethanol as a key strategy for mitigating greenhouse gas (GHG) emissions is closely linked to the accuracy of N_2O emission factors (EF) used in life cycle assessments. However, previous studies have shown that the default N_2O EF values recommended by the IPCC do not accurately reflect the diverse edaphoclimatic conditions found in Brazil, leading to uncertainties in GHG inventories. Therefore, establishing regional N_2O EF is essential for improving the precision of bioethanol emission estimates. In this study, we conducted a systematic literature review compiling 293 measurements from 45 field studies across different regions of Brazil. This study focuses on sugarcane (20 studies) and corn (25 studies), which are the primary crops used for bioethanol production in Brazil. Our findings indicate that the average N_2O EF for these crops is 0.72%, lower than the value reported for the tropics and sub-tropics (1.6%). When analyzed separately, sugarcane showed an average N_2O EF of 0.65%, with higher emissions from the combined use of mineral and organic N fertilizers (0.79%) compared to mineral (0.55%) or organic fertilizers alone (0.77%). For corn, the average N_2O EF was 0.84%, with mineral N fertilizers presenting the lowest EF (0.40%), while emissions increased with the combination of mineral and organic sources (0.82%), reaching the highest levels with pig slurry application (1.72%). These variations highlight the limitations of using IPCC default values for mineral and organic N fertilizers in Brazil. Our results reinforce the need for Tier 2 methodologies incorporating region-specific data to enhance GHG inventory accuracy and support targeted mitigation strategies. Although Brazil's latitudinal range spans tropical and subtropical zones, regional stratification was not applied due to the limited number of studies within each climate category, especially when further disaggregated by crop type and N fertilizer source. Despite covering key crops, fertilizer types, and multiple biomes, the current dataset still lacks representation for important agricultural regions such as Brazil's midwest, north, and northeast regions. This study represents a significant step toward refining N_2O EF estimates for bioethanol crops, contributing to more precise assessments of the sector's climate impact. However, further research is needed to cover underrepresented areas, understand long-term field dynamics, and evaluate other crop systems and management practices. Future studies should also incorporate modeling tools and real-time monitoring to reduce uncertainties and support the development of Tier 3 estimates.

1 | Introduction

Global warming is among the most pressing societal challenges of the 21st century, driven by rising greenhouse gas (GHG) emissions from human activities, particularly the combustion of fossil fuels and changes in land use (IPCC 2022). Therefore, growing concerns regarding environmental sustainability have intensified the pursuit of renewable energy sources as viable alternatives to fossil fuels. In this context, ethanol production from crops like sugarcane and corn has emerged as a promising option to reduce GHG emissions and mitigate climate change, particularly in countries like Brazil and the United States (Carvalho et al. 2017; Moreira et al. 2020; Cantarella et al. 2023; Gurgel et al. 2024).

The Brazilian biofuel policy, initiated in the 1970s with the *Proálcool* (National Alcohol Program), combined with the development of flex-fuel vehicles in the early 2000s, which currently represent 79% of the light vehicle fleet in circulation in Brazil (Anfavea 2025), paved the way for the expansion of biofuel crops in the country, such as sugarcane (Cantarella et al. 2023) and, more recently, corn (Moreira et al. 2020; Gurgel et al. 2024). These advances have positioned Brazil as one of the world's leading producers and consumers of bioethanol. The Brazilian Energy Policy Law encourages the use of bioethanol by requiring the blending of 27% anhydrous ethanol into gasoline and by the direct consumption of hydrated ethanol by flex-fuel vehicles (IEA Bioenergy 2024). In addition, the Brazilian Biofuel Policy (RenovaBio) promotes the use of bioethanol by creating decarbonization targets for fuel distributors, issuing Decarbonization Credits (CBIOs), and promoting the use of sustainable biofuels (MME 2017). However, despite these advancements, the environmental benefits of biofuels are still being debated.

The GHG mitigation potential of ethanol largely depends on agricultural management practices, particularly the use of nitrogen (N) fertilizers, which are a primary source of nitrous oxide (N_2O) emissions, a potent GHG with a global warming potential 273 times greater than CO_2 (IPCC 2022). N_2O is a major contributor to the life cycle GHG emissions related to ethanol production from crops such as corn and sugarcane (Chagas et al. 2016; Moreira et al. 2020). These emissions are primarily linked to the use of N-based fertilizers and organic residues, which enhance crop yields but also stimulate microbial processes such as nitrification and denitrification in soils, leading to the release of N_2O (Butterbach-Bahl et al. 2013; Ussiri and Lal 2013). As N_2O emissions are highly influenced by local conditions such as soil type and climate conditions, establishing regional N_2O emission factors (EF) is a research priority in order to reduce the uncertainty in the carbon footprint calculation of the biofuels and their derivatives (Cayuela et al. 2017).

The environmental impacts of biofuel production, including those associated with major biofuel crops in Brazil, have been assessed through life cycle assessments (LCA) studies (Chagas et al. 2016; Cerri et al. 2017; Moreira et al. 2020; Bordonal et al. 2024). However, these studies estimated GHG emissions using the default N_2O EF proposed by the Intergovernmental Panel for Climate Change (IPCC), which relies on global average values (i.e., Tier 1) based on the amount of N fertilizer applied. These Tier 1 N_2O EF values are predominantly derived from studies conducted in temperate climates and may not accurately reflect the specific conditions of tropical agricultural systems, leading to high uncertainties (mostly overestimations) in GHG emission estimates (Crutzen et al. 2016). Therefore, with the ongoing expansion of bioethanol production in Brazil, it is timely and strategic to define regional N_2O EF that more accurately reflect the country's edaphoclimatic conditions and agricultural practices.

Given this context, we hypothesize that the default N_2O EFs currently used to estimate GHG emissions from Brazil's bioenergy sector do not adequately represent the country's diverse edaphoclimatic conditions and agricultural practices, particularly within sugarcane and corn cropping systems. Based on that, we conducted a national-scale systematic literature review to summarize and derive regional N_2O EFs for corn and sugarcane in Brazil, considering different N fertilizer sources. The regional N_2O EF generated herein will provide an opportunity for the Brazilian biofuel sector to move from IPCC Tier 1 to Tier 2, thereby reducing uncertainties in the carbon footprint assessments of bioethanol and other bioenergy products derived from sugarcane and corn across the country.

2 | Material and Methods

2.1 | Literature Search Data Extraction

A comprehensive systematic literature review was conducted to compile data on direct N_2O emissions from Brazilian agricultural soils under sugarcane and corn cultivation. We searched for studies published until 2024 using two major online databases: Scopus and Web of Science. A broad set of English and Portuguese keywords was employed to examine titles, abstracts, and keywords, focusing on studies related to N fertilization and the addition of organic residues in Brazilian agricultural systems. The search terms included "nitrous oxide emission," "greenhouse gas emission," "N_2O emission," combined with corn, maize, sugarcane, and sugar cane (and their variations).

A secondary search was performed to refine the results, excluding the studies that were not conducted in Brazil. Additionally, data from the Brazilian digital library of theses and dissertations were included. Grey literature, such as technical reports and conference papers, was excluded, while PhD theses and Master dissertations were included. The entire structured search methodology is outlined in Figure 1. Bibliometric data were downloaded from Scopus and Web of Science in *.bib* format and in *.xlsx* format. These datasets were merged, duplicates removed, and relevant bibliometric variables were selected using the "bibliometrix" package in R software (version 4.2.2, 2022).

The search yielded studies based on the following inclusion criteria: field data obtained within Brazilian territory, experimental designs including replicates, and either reported N_2O EF or available data on cumulative N_2O emissions (when N_2O EF were not provided). This process yielded 293 observations from 45 publications from 2010 to 2024 (see Supporting Information S1 and S2), comprising 20 studies on sugarcane and 25 on corn. The selected studies were systematically organized

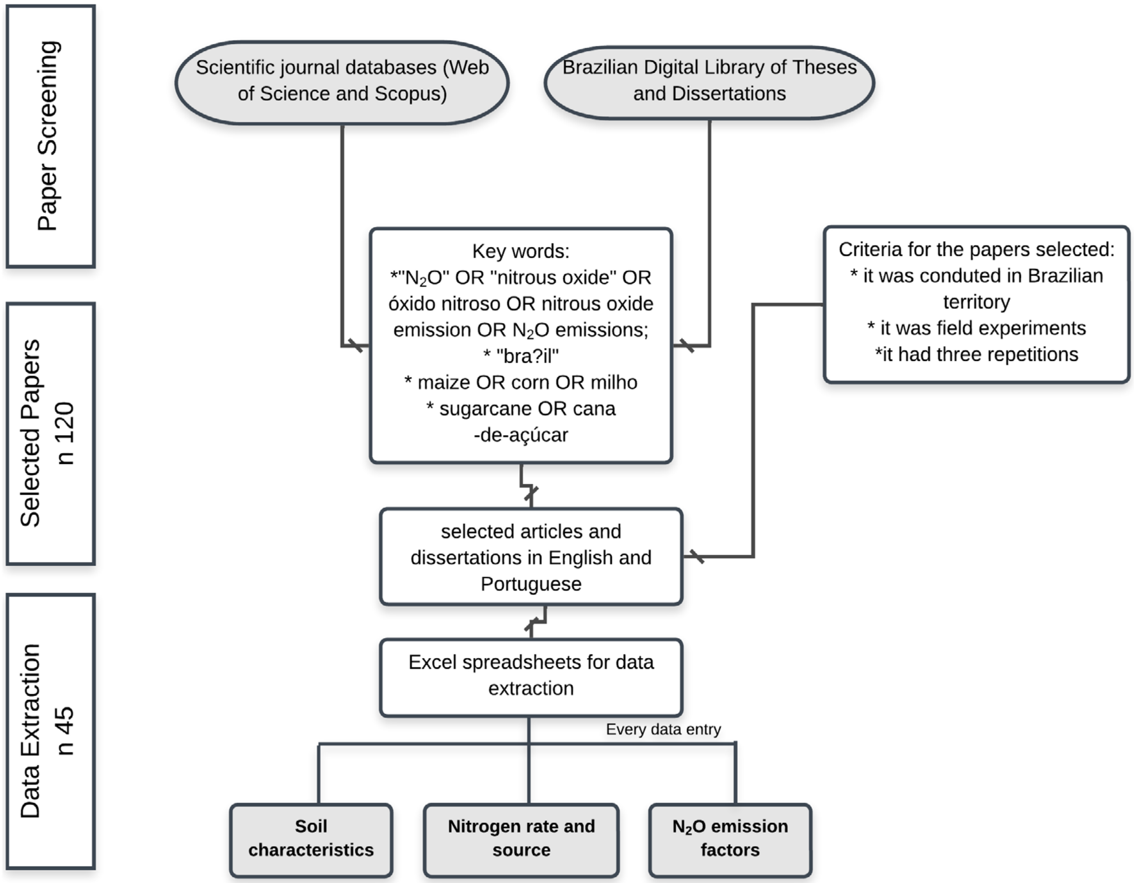

FIGURE 1 | Flow diagram illustrating the bibliographic research process, detailing the criteria applied.

in an Excel spreadsheet for subsequent data analysis. The geographical coordinates of each experimental site were extracted and standardized to the EPSG 4326 reference system, allowing the creation of a map depicting the locations of all studies (Figure 2). This map was generated using the Mapbiomas Collection plugin in QGIS 3.28 (QGIS 2014), and the Brazilian biomes cover shapefile from MapBiomas Collection 7.

The studies assessing N_2O emissions in sugarcane areas were mainly conducted in São Paulo state. The experimental areas are mostly located within the Atlantic Forest and Cerrado biomes (Figure 2), covering regions classified under the tropical savanna (Aw) and humid subtropical with dry winter (Cwa) climate zones.

For corn, the studies encompassed both conventional and no-till systems and spanned a greater diversity of biomes, including Cerrado, Atlantic Forest, Amazon, and Pampa. The climate conditions were also more diversified, including tropical savanna (Aw), humid subtropical with dry winter (Cwa), humid subtropical (Cfa), oceanic temperate (Cfb), and tropical with dry season (Awa) (Figure 2).

Most of the studies reported the N_2O EFs for each specific treatment. For studies reporting only cumulative N_2O emissions, the N_2O EF was calculated using the following equation:

$$\text{EF}\,(\%) = \left[(Ei - Eo)/N\right] \times 100 \quad (1)$$

where: EF is the percentage of applied nitrogen fertilizer that was emitted as N-N_2O; *Ei* is the total N-N_2O emitted (in kg N) from the fertilized sugarcane or corn system; *Eo* is the total N-N_2O emitted (in kg N) from the unfertilized (control) system; *N* is the amount of nitrogen fertilizer applied (in kg N); and 100 is a conversion factor used to express the resulting fraction as a percentage (%) (Fan et al. 2022).

2.2 | Overview of Methodological Gaps

We conducted a critical analysis of the methodologies employed across studies to identify potential improvements that could be employed in GHG emission assessments. Specifically, we evaluated the sampling methods and GHG measurement techniques used. We also evaluated the use of field replicates and the number of sampling points used to adjust the emission curves, as well as the length of the monitoring periods. All the methodological data were compiled into an Excel spreadsheet and subsequently analyzed to determine the total number of occurrences and their frequency.

2.3 | Statistical Analyses

The effect of different N fertilizers on the N_2O EF was evaluated by organizing and grouping the data according to the different N sources. Descriptive statistics analysis was performed, including

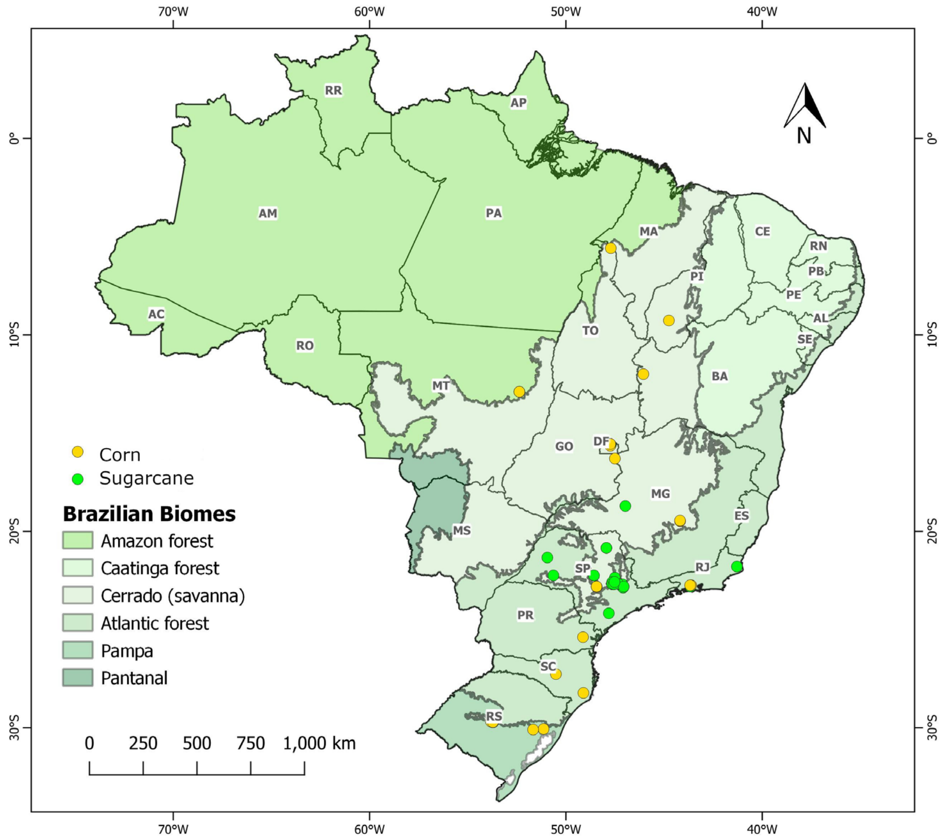

FIGURE 2 | Location of the study sites included in this analysis. Map colors delineate Brazilian biomes, with yellow and green points representing corn and sugarcane studies, respectively.

calculations of the mean, minimum, maximum, standard deviation, and confidence intervals.

The N_2O EFs were categorized and presented in boxplot graphs, where each box represents the distribution of values reported in the literature. The central line within each box indicates the median, while the box limits correspond to the interquartile range. In addition, the mean N_2O EF for each category was highlighted to facilitate comparisons between different fertilizer types. Tier 1 N_2O EF values from the IPCC were added in the graphics to facilitate the comparison with our data.

3 | Results

3.1 | Trajectory of Bioethanol Crop Production in Brazil

Between 2003 and 2013, sugarcane production in Brazil experienced significant growth, increasing by 84% from 320 million tons to approximately 589 million tons (Figure 3a). This expansion has historically supported Brazil's position as one of the world's leading bioethanol producers, with sugarcane serving as the primary feedstock for decades. However, sugarcane bioethanol production has stagnated in recent years, while corn-based bioethanol has emerged as a rapidly growing alternative.

Corn growth has mainly been driven by the increasing adoption of corn as a second crop in the soybean cultivation system in the Brazilian savannah (Cerrado biome) and the attractiveness of the biofuel market. Over the past 10 years, Mato Grosso state has seen the most significant increase in the area dedicated to second-crop corn, expanding from 3.2 to 7.4 million hectares. For the 2024/2025 season, Brazil's total corn cultivation area reached 22.1 million hectares, yielding approximately 119.6 million tons of corn grain (CONAB 2024; Figure 3b). Consequently, the production of corn bioethanol increased from 0.79 billion to 8 billion liters between the 2018/19 and 2024/25 seasons (UNEM 2025) (Figure 3c).

According to the National Agency of Petroleum, Natural Gas and Biofuels (ANP 2024), Brazil currently operates 359 bioethanol plants utilizing sugarcane and corn as feedstocks (Figure 3d). While sugarcane bioethanol plants (337) are predominantly located in the Central-South and Northeast regions, corn bioethanol plants (22) are mainly concentrated in the Midwest states (Cerrado biome), where corn cultivation is most prevalent (UNEM 2025).

3.2 | Methodological Variability and Temporal Sampling Patterns Across the Studies

The most commonly used method for quantifying N_2O emissions was the static chamber technique. In this approach, gas samples were collected using syringes, stored in vials, and subsequently analyzed using gas chromatography in laboratory settings. Regarding data collection design, 40% of the corn studies and 66% of the sugarcane studies used only three

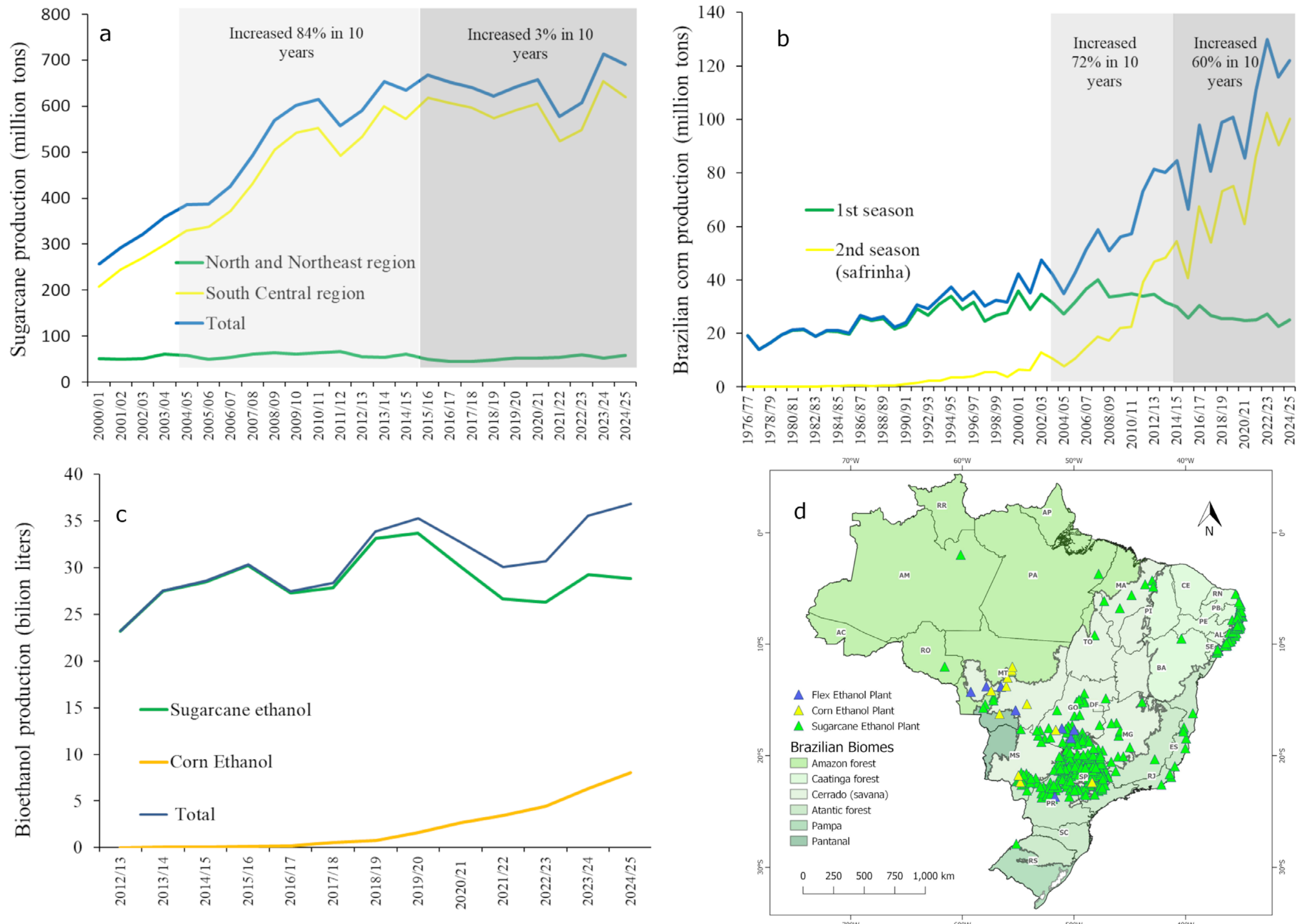

FIGURE 3 | Evolution of Brazilian production of sugarcane by regions and total (a), corn from first and second harvest (b) and sugarcane and corn-based ethanol. Map showing the distribution of sugarcane and corn bioethanol plants in Brazil (d). *Source:* CONAB (2024).

sampling time points during chamber incubations to construct and adjust the emission curve for GHG flux calculations. Additionally, 48% of the corn studies employed four sampling points. The number of sampling points per incubation is critical for accurately estimating gas fluxes, as it directly influences the precision of the emission curve and the reliability of the calculated N_2O fluxes. The interval of each sample was 10 and 15 min for most studies. Regarding chamber incubation times, no study used a period shorter than 30 min. Additionally, most studies used four or more field replicates, indicating an acceptable reasonable level of spatial representativeness in their experimental designs (see Supporting Information S3).

Overall, gas sampling was conducted using a range of temporal sampling strategies. In many cases, sampling frequency increased around key events such as N fertilizer application, residue management, and rainfall to capture N_2O emission peaks. In these most relevant events, sampling was performed every 1 to 3 days, then continued at regular intervals—weekly, biweekly, or monthly—towards the end of the cycle. The monitoring duration for corn typically lasted around 90 days in most studies, whereas for sugarcane, monitoring periods often extended beyond 6 months. Among the studies, most of the observations for corn reported N fertilizer rates between 120 and 180 kg N ha^{-1}, while for sugarcane, rates ranging from 80 to 120 kg N ha^{-1} were the most frequent.

3.3 | N_2O Emission Factors for Bioethanol Crops in Brazil

The dataset compiled from the selected studies included 293 N_2O EF, derived from measurements taken at different experimental sites across Brazil (Figure 1). The average N_2O EF observed in this study was 0.72% of the N applied (Figure 4). When focusing only on mineral fertilizers, the average N_2O EF was 0.50%; whereas organic N sources exhibited a higher average N_2O EF of 1.17%. Combining mineral and organic N fertilizers resulted in an average N_2O EF of 0.75% (Figure 4). The application of nitrification inhibitors alongside mineral N fertilizers reduced N_2O EF by 70% (0.50% vs. 0.15%); while the use of nitrification inhibitors with organic N sources reduced 21% (1.17% vs. 0.92%) and the use of inhibitors in combination with mineral and organic fertilizers reduced 36% (0.75% vs. 0.48%).

3.4 | N_2O Emissions Factors From N Fertilizer Sources in Sugarcane Fields

For sugarcane, the selected studies ($n=20$) provided a dataset of 180 N_2O EFs, predominantly based on field measurements in Southeast Brazil (Figure 2), particularly in São Paulo state within the Atlantic Forest and Cerrado biomes. However, it is important to emphasize that the dataset is geographically limited. There is

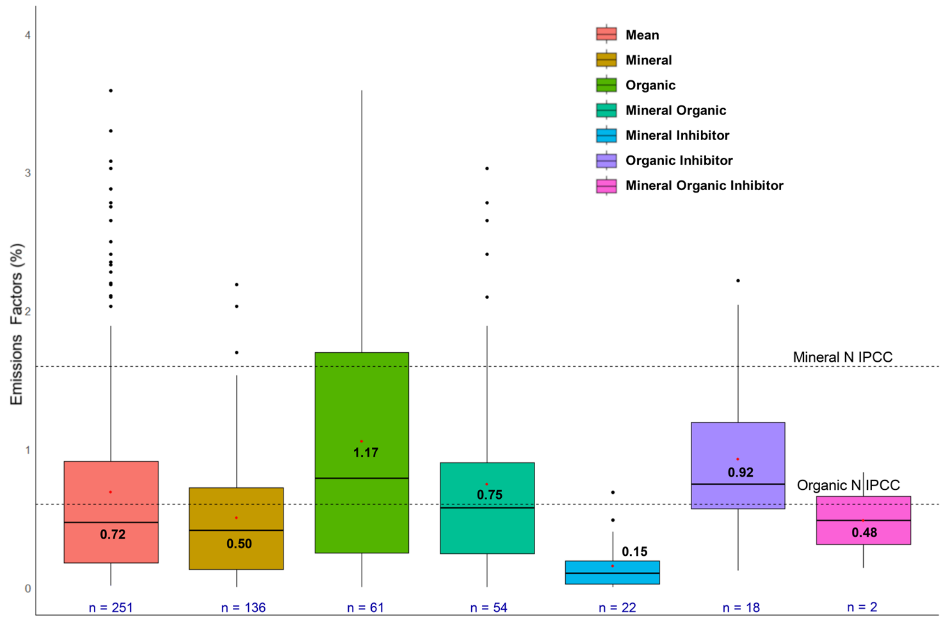

FIGURE 4 | N_2O emission factors from N fertilizers and organic residues in corn and sugarcane production systems. The dashed line represents the values proposed by the IPCC (2019) for mineral (1.6%) and organic N (0.6%) inputs. Inner black lines in the boxplots represent the median. Number and red dots represent the mean values. n = number of observations, the reported means (boxplot on the left) includes all values except data from treatments involving nitrification inhibitors.

a lack of data from key sugarcane-producing regions such as the Northeast region, as well as from other major production states, including Goiás, Mato Grosso do Sul, Paraná, and Mato Grosso.

Considering all N fertilizer sources together, the overall average N_2O EF was 0.65%. Combined applications of mineral and organic fertilizers resulted in slightly higher average EF (0.79%) compared to mineral (0.55%) or organic (0.77%) fertilizers used alone (Figure 5a). The application of nitrification inhibitors was associated with a lower N_2O EF (0.16%) reflecting a ~70% reduction compared to mineral N fertilizers alone (Figure 5a). For mineral N fertilizer sources, the application of urea resulted in a higher N_2O EF (0.73%) than ammonium nitrate (0.48%), ammonium sulfate (0.45%), and calcium ammonium nitrate (0.52%) (Figure 5b). Organic sources such as vinasse exhibited high variability, with N_2O EF ranging from 0.13% to 3.03% and a mean of 0.94%. When vinasse or filter cake was applied together with mineral fertilizers, average N_2O EFs were 0.80% and 0.66%, respectively (Figure 5c).

3.5 | N_2O Emissions Factors From N Fertilizer Sources in Corn Fields

The selected publications (n = 25) provided a dataset of 120 N_2O EFs from various regions of Brazil, including the South, Southeast, Central-West, and Northeast (Figure 2). However, despite covering a broader range of biomes than the sugarcane studies, the dataset still underrepresents major corn producing states such as Mato Grosso, Goiás, and Mato Grosso do Sul. Considering all N fertilizer sources, the average N_2O EF was 0.84%. Mineral N fertilizers resulted in a N_2O EF of 0.40%, which was consistently lower than those observed for mineral and organic N sources combined (0.82%) and for pig slurry alone (1.72%) (Figure 6a). The addition of nitrification inhibitors reduced N_2O EF to 0.13% (mineral N) and to 0.92% (organic—pig slurry).

As observed for the sugarcane crop, the N_2O EF varied according to the N fertilizer sources in the corn data. Urea showed a higher N_2O EF (0.53%) compared to ammonium nitrate (0.41%) and ammonium sulfate (0.14%) (Figure 6b). For pig slurry, the EF was 1.72%, with a wide variation from 0.1% to 4.07% of applied nitrogen, while for the combination of mineral N and pig slurry, the EF was 1.23%, and with the use of biochar, 0.48% (Figure 6c).

4 | Discussion

4.1 | Regional N_2O EF for Sugarcane and Corn Production in Brazil: Variability, Drivers, and Data Gaps

The mean N_2O EF across N fertilizer sources in Brazilian sugarcane and corn systems was lower than the IPCC default value. Considering only mineral N fertilizers, the mean N_2O EF value (0.5%) was 69% lower than the 1.6% established by the IPCC (2019) for tropical/wet climate conditions. Our results are consistent with those reported in tropical regions, such as Thailand (Welutung et al. 2023) and China (Aliyu et al. 2019), where the mean N_2O EF was also 0.5%. The mean N_2O EF observed in this study (0.72%) was also lower than the 1.2% reported by Albanito et al. (2017) for tropical and subtropical agricultural systems worldwide. More recently, Cui et al. (2021) estimated a global mean N_2O EF for corn of 1.02%, with values ranging from 0.08% to 3.77%, highlighting the high variability of EF across different corn-producing regions. This variability underscores the importance of considering region-specific EF

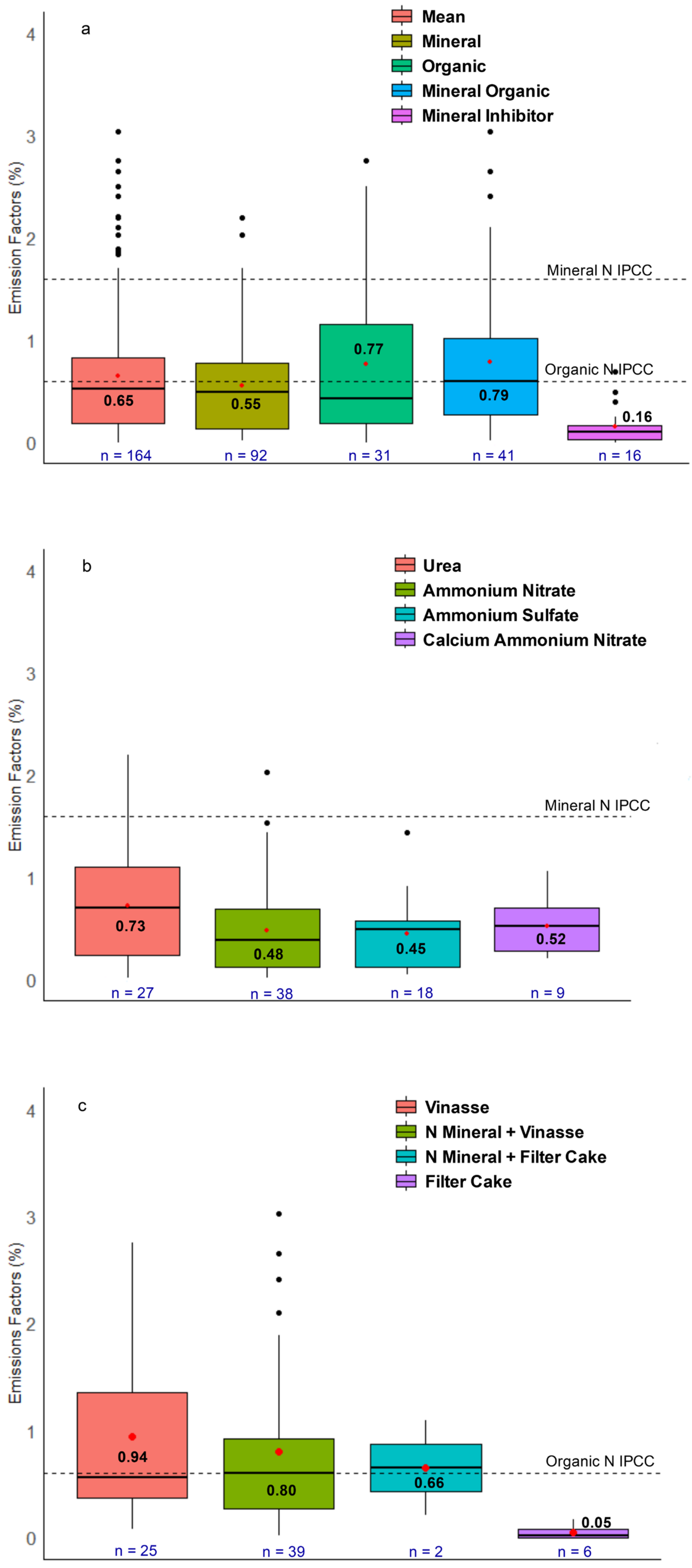

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FIGURE 5 | N_2O emission factors from N fertilizers and organic residues in sugarcane fields in Brazil. The dashed line represents the values proposed by the IPCC (2019) for mineral (1.6%) and organic N (0.6%) inputs. Inner black lines in the boxplots represent the median. Numbers and red dots represent the mean values. n = number of observations. (a) N_2O emission factors by N source category: mineral fertilizers, organic residues, and treatments with nitrification inhibitors (b) N_2O emission factors by type of mineral nitrogen source. (c) N_2O emission factors by type of organic residue.

rather than relying on default IPCC values, as emissions can vary significantly depending on local edaphoclimatic conditions and management practices.

Our data represent an important step forward in synthesizing existing literature and deriving regional N_2O EFs for sugarcane and corn in Brazil. Additionally, our analysis highlights regions with the greatest data availability, as well as areas with little or no data coverage. For example, data on sugarcane were predominantly concentrated in São Paulo State (Southeastern Brazil), which alone accounts for 59.7% of national production (CONAB 2024). This concentration of data in São Paulo State reflects the proximity of universities and research institutions with farms and experimental stations specializing in sugarcane cultivation. Conversely, other major sugarcane-producing areas, including the states of Goiás, Minas Gerais, Mato Grosso do Sul, Paraná, and the northeast region, are poorly or not represented in the current database. Brazil is a vast country where sugarcane is cultivated under a wide range of edaphoclimatic conditions, which significantly influence soil N_2O emissions. A similar scenario was observed for corn studies. Although studies were relatively more widespread across the Brazilian territory, a notable limitation of the current dataset is the underrepresentation of the largest contributors to national corn production, particularly Mato Grosso, Paraná, and Mato Grosso do Sul State. Therefore, although our study represents a step forward in the use of Tier 2 values, the lack of N_2O emissions data limits our ability to extrapolate our findings across the diverse edaphoclimatic conditions present in the country.

High variability in N_2O emission factors was observed for both sugarcane and corn, depending on the N fertilizer source. The three main N fertilizers evaluated were urea, ammonium sulfate, and ammonium nitrate. Urea exhibited the highest N_2O EF, followed by ammonium nitrate and ammonium sulfate. In well-drained Oxisols, the predominant soils used for sugarcane and corn production in Brazil, N_2O is primarily produced by ammonia-oxidizing bacteria and archaea through the nitrification process, in which ammonium (NH_4^+) is oxidized to nitrite (NO_2^-) and subsequently to nitrate (NO_3^-), releasing N_2O as a byproduct (Suleiman et al. 2018; Lourenco et al. 2019; Soares et al. 2016). The predominance of these microbial communities in Oxisols, combined with the high aeration and drainage of these soils, enhances nitrification rates, leading to greater N_2O emissions, particularly when N fertilizers that release large amounts of NH_4^+ (such as urea) are applied. Consequently, our findings corroborate previous studies showing that urea application often leads to higher N_2O emissions compared to nitrate-based fertilizers (Snyder et al. 2014; Soares et al. 2016; Siqueira Neto et al. 2016; Tenuta and Beauchamp 2011).

However, it is important to note that urea is the primary N fertilizer used for sugarcane and corn production in Brazil (Cassim et al. 2024; Cantarella et al. 2018). Therefore, substituting urea with ammonium-based fertilizers could be a feasible strategy to further reduce N_2O emissions in Brazilian bioethanol crops. Over the past two decades, N fertilizer inputs in sugarcane production have increased significantly, nearly doubling from 42 kg ha^{-1} in 2000 to 78 kg ha^{-1} in 2020, and reaching 86 kg ha^{-1} by 2023 (Otto et al. 2022; ANDA 2023). Moreover, N fertilizer rates applied in Brazilian sugarcane fields remain much lower than those observed in other major producer countries, such as India (150–400 kg N ha^{-1}; Robinson et al. 2011; Hemalatha 2015) and China (400–800 kg N ha^{-1}; Li and Yang 2015; Yang et al. 2021).

For sugarcane, our N_2O EF (ranging from 0.55% to 0.79%) was lower than the global value (1.2%) observed by Yang et al. (2021) and those reported in other major producing regions, such as Australia (1.77% in Grace et al. 2023 and 2.8% in Denmead et al. 2010) and China (2.6% in Li et al. 2025), but comparable to values reported in Thailand (0.68% in Sriphirom et al. 2023 and 0.70% in Welutung et al. 2023). For corn, our values align with those observed in northeast China (0.72% in Zhang et al. 2023), Thailand (0.59% and 0.82% in Yuttitham et al. 2020), and India (0.8% in Sahil et al. 2023), but are lower than those reported in the United States (1.2% in Xia et al. 2024).

Moreover, the variability in N_2O emissions observed in our dataset likely results not only from differences in N fertilizer sources but also from complex interactions among soil characteristics, climate conditions, microbial dynamics, and management practices. Additionally, the limited number of observations for several N fertilizer categories (in some cases $n < 10$) constrained our ability to conduct more robust statistical analyses or to stratify the data by climate zones (e.g., tropical versus subtropical). Despite these limitations, clear patterns emerged regarding the effects of different fertilization strategies on N_2O emissions. Practices such as the co-application of organic and mineral fertilizers or the use of residues like vinasse and pig slurry, while offering agronomic and environmental benefits, tended to increase N_2O emissions, particularly when high C and N inputs stimulated microbial activity (Carmo et al. 2013; Paredes et al. 2014; Pitombo et al. 2016; Silva et al. 2017; Suleiman et al. 2018; Oliveira et al. 2023). Although recycling organic residues is a sustainable strategy to enhance circularity, reduce dependence on mineral fertilizers, and improve soil health (Cherubin et al. 2021; Luz et al. 2024), our findings suggest that this practice tends to increase soil N_2O emissions in sugarcane and corn cultivation areas in Brazil. Conversely, mitigation strategies, such as the use of nitrification inhibitors or biodigested residues, show potential to reduce emissions but require further validation under real-world conditions.

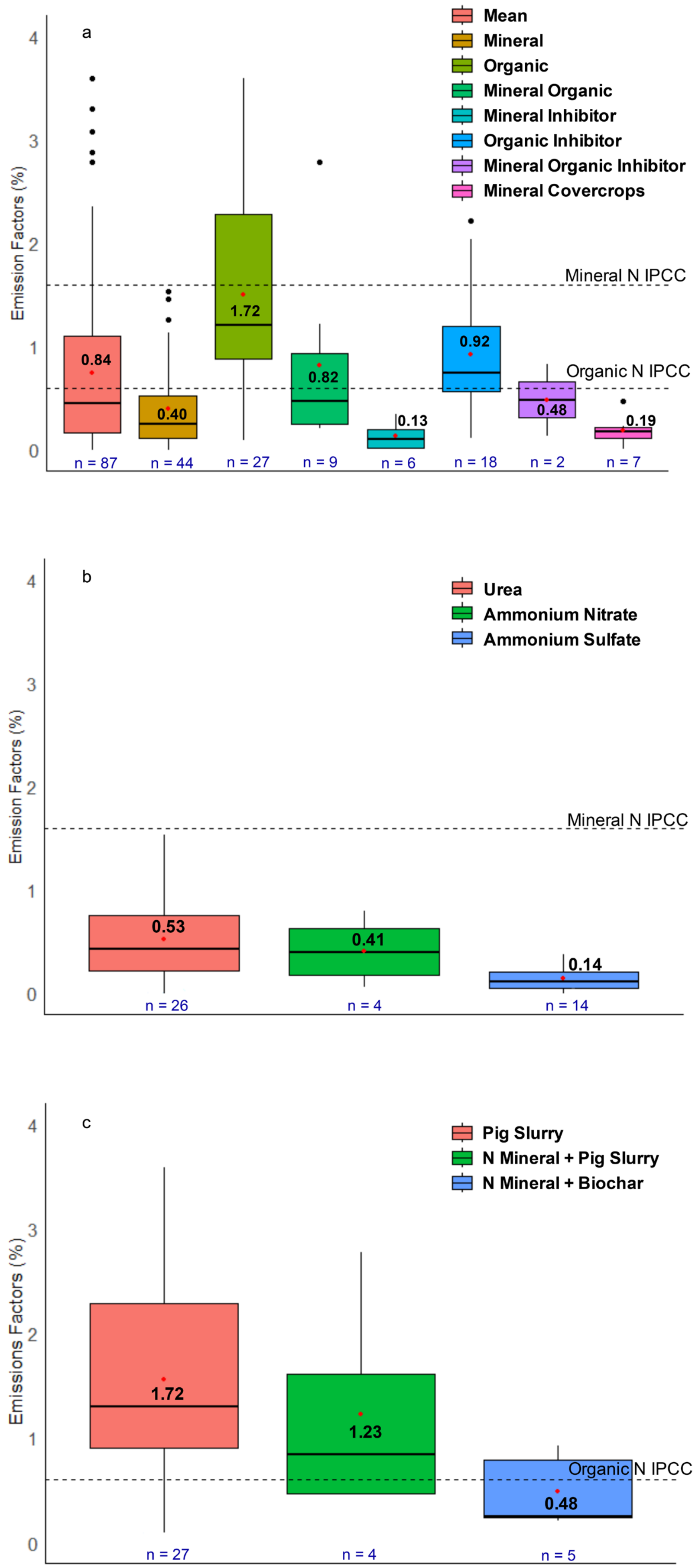

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FIGURE 6 | N_2O emission factors from N fertilizers and organic residues in corn fields in Brazil. The dashed line represents the values proposed by the IPCC (2019) for mineral (1.6%) and organic residues (0.6%) inputs. Inner back lines in the boxplots represent the median. Numbers and red dots represent the mean values. n = number of observations. (a) N_2O emission factors by N source category: mineral fertilizers, organic residues, and treatments involving nitrification inhibitors (b) N_2O emission factors by type of mineral nitrogen source. (c) N_2O emission factors by type of organic residue.

In sugarcane, the addition of nitrification inhibitors to mineral N fertilizers reduced N_2O EF by 70%; while in corn, reductions of 72% and 48% were observed with mineral and organic fertilizers, respectively. These inhibitors act by suppressing the enzyme ammonia monooxygenase, thereby preventing the oxidation of NH_4^+ to NO_2^-. This slows nitrification, maintaining N in its ammoniacal form for longer periods and reducing N_2O emissions (Oliveira et al. 2023). These findings highlight the potential of nitrification inhibitors to mitigate N_2O emissions while preserving N availability for crop growth. Although this study provides a valuable first step in consolidating regional data, further field-based research is urgently needed in key agricultural regions to improve the reliability and applicability of N_2O EF across Brazil.

Finally, it is essential to highlight that all studies in this review adopted the static chamber method, consistent with findings in other agricultural systems (Bieluczyk et al. 2024; Locatelli et al. 2024). While this approach allows for simultaneous sampling and good spatial coverage, its limited temporal resolution remains a key constraint. The frequent use of only three sampling points per incubation is below best practice guidelines, which recommend preferably four or more collections within 30–40 min to ensure reliable flux estimates (Costa et al. 2006; Parkin and Venterea 2010; Zanatta et al. 2014). Prolonged incubation times, on the other hand, can alter the conditions inside the chamber, compromising data accuracy (Rochette and Eriksen-Hamel 2008; Cerri et al. 2013). To overcome these challenges, future research should consider alternative technologies, such as portable infrared gas analyzers, which enable real-time, high-resolution measurements with minimal environmental interference.

4.2 | Implications of the Use of Regional N_2O EF for N Fertilizer Sources

Over the past two decades, considerable attention has been given to the environmental impacts of bioethanol crops, particularly concerning the effects of land-use change and management practices on soil GHG emissions (Bordonal et al. 2018; Cherubin et al. 2021). In this context, some studies have raised questions about the environmental benefits of bioethanol (Fargione et al. 2008; Searchinger et al. 2008). However, it is important to note that these analyses relied on global datasets and models, as Brazil lacked region-specific data at the time. Consequently, Brazilian funding agencies, research institutes, and universities have prioritized generating data that more accurately represents the country's prevailing conditions. This collective research effort has produced a substantial dataset (although not definitive), which we summarize here, providing an opportunity to refine the carbon footprint estimates of bioethanol derived from sugarcane and corn in Brazil.

Despite the growing volume of data generated in recent years, several life cycle assessment (LCA) studies (Seabra et al. 2011; Chagas et al. 2016; Moreira et al. 2020; Bordonal et al. 2024) and the calculations performed within the Brazilian Biofuel Law Platform (RenovaCalc) still rely on default IPCC emission factors. In a pioneering study, Carvalho et al. (2021) demonstrated that using regional N_2O EF reduced GHG emissions from sugarcane bioethanol by 19%, highlighting the critical need for locally derived data to improve the accuracy of GHG estimates and decarbonization credits. To our knowledge, no comparable study has assessed the impact of regional data on GHG emission calculations for corn ethanol in the country.

Furthermore, our study revealed that GHG measurements remain insufficient to capture the full diversity of climate, soil, and cropping systems in Brazil (Bieluczyk et al. 2024). The scarcity of data is particularly critical in regions with expanding agricultural frontiers, such as the Northeast, Midwest, and North regions. The lack of region-specific data in these areas hinders the refinement of emission estimates used in life cycle assessment models and policy frameworks (Locatelli et al. 2024). Given these limitations, future research should prioritize expanding field measurements in these poorly represented regions and biomes, particularly those with significant agricultural production and unique environmental conditions. Establishing long-term monitoring networks and adopting harmonized methodologies for N_2O quantification will also be essential to improve data quality and comparability.

This study represents a valuable first step in establishing regional N_2O emission factors for the primary crops, accounting for nearly 100% of the biomass used in bioethanol production in Brazil. Our findings indicate that regional N_2O EFs for mineral N fertilizers are 65% and 75% lower than the IPCC default values for corn and sugarcane, respectively. Conversely, the regional EF for organic fertilizers exceeds the IPCC value. These results suggest that the default IPCC factors do not adequately reflect Brazil's prevailing edaphoclimatic conditions. Incorporating regional N_2O EF can improve the accuracy of GHG assessments, better reflect local agricultural practices, and promote the selection of inputs with lower environmental impacts. Understanding these regional factors is crucial for informed decision-making on fertilizer use and supports strategies related to RenovaBio and carbon credit programs.

5 | Conclusions

The average N_2O emission factors presented in this study represent the best estimates based on currently available data. Covering Brazil's two main bioethanol crops, sugarcane and corn, our assessment included various mineral and organic fertilizers, a wide range of fertilization rates (60–280 kg N ha^{-1} $year^{-1}$), multiple biomes, and a total of 293 observations. We found that the average N_2O EF for mineral fertilizers ranged from 0.40% to 0.55%, substantially lower than the IPCC default value of 1.6%. Conversely, regional N_2O EF for organic fertilizers ranged from 0.77% to 1.72%, exceeding the IPCC default of 0.6%. These findings underscore the importance of employing region-specific emission factors (Tier 2) to enhance the accuracy of carbon footprint assessments and better inform mitigation strategies.

Despite advances in recent decades, the current dataset on field-scale N_2O emissions remains insufficient to capture the full heterogeneity of Brazil's agricultural landscapes. Significant spatial gaps persist, particularly in key corn-producing states such as Mato Grosso and Mato Grosso do Sul, as well as in the Northern and Northeastern regions, which are emerging agricultural frontiers. Moreover, the limited dataset restricts the ability to stratify emission factors by tropical and subtropical climates, factors that can significantly influence N_2O emissions. Overcoming these limitations will require expanded field measurements, long-term experiments, and regionally stratified studies to support the development of more accurate Tier 2 emission factors.

Author Contributions

Graciele Angnes: conceptualization, methodology, investigation, formal analysis, data curation, visualization, writing – original draft, writing – review and editing; **João Luis Nunes Carvalho:** conceptualization, methodology, investigation, validation, writing – original draft, writing – review and editing; **Carlos Eduardo P. Cerri:** conceptualization, methodology, validation, resources, funding acquisition, writing – review and editing; **Maurício Roberto Cherubin:** conceptualization, methodology, validation, resources, funding acquisition, project administration, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets supporting the findings of this study are publicly available on Zenodo at the following DOI: https://doi.org/10.5281/zenodo.16747985.

References

Albanito, F., U. Lebender, T. Cornulier, et al. 2017. "Direct Nitrous Oxide Emissions From Tropical and Sub-Tropical Agricultural Systems—A Review and Modelling of Emission Factors." *Scientific Reports* 7: 44235. https://doi.org/10.1038/srep44235.

Aliyu, G., J. Luo, H. J. di, et al. 2019. "Nitrous Oxide Emissions From China's Croplands Based on Regional and Crop-Specific Emission Factors Deviate From IPCC 2006 Estimates." *Science of the Total Environment* 669: 547–558.

ANDA. 2023. *Relatório Anual 2023. Associação Nacional Para Difusão de Adubos*. ANDA.

Anfavea. 2025. "Relatório de Produção e Frota de Veículos Leves no Brasil."

ANP. 2024. "Mapa Dinâmico Produtores de Etanol." https://www.gov.br/anp/pt-br.

Bieluczyk, W., M. R. Cherubin, C. E. P. Cerri, et al. 2024. "Greenhouse Gas Fluxes in Brazilian Climate-Smart Agricultural and Livestock Systems: A Systematic and Critical Overview." *Journal of Cleaner Production* 464: 142782.

Bordonal, R. O., J. L. N. Carvalho, R. Lal, E. B. Figueiredo, B. G. de Oliveira, and N. La Scala Junior. 2018. "Sustainability of Sugarcane Production in Brazil: A Review." *Agronomy for Sustainable Development* 38: 13. https://doi.org/10.1007/s13593-018-0490-x.

Bordonal, R. O., S. Tenelli, D. M. Oliveira, et al. 2024. "Carbon Savings From Sugarcane Straw-Derived Bioenergy: Insights From a Life Cycle Perspective Including Soil Carbon Changes." *Science of the Total Environment* 947: 174670. https://doi.org/10.1016/j.scitotenv.2024.174670.

Butterbach-Bahl, E. M., M. Baggs, R. Dannenmann, S. Kiese, and S. Zechmeister-Boltenstern. 2013. "Nitrous Oxide Emissions From Soils: How Well Do We Understand the Processes and Their Controls?" *Philosophical Transactions of the Royal Society, B: Biological Sciences* 368: 1621. https://doi.org/10.1098/rstb.2013.0122.

Cantarella, H., J. F. Leal Silva, L. A. H. Nogueira, et al. 2023. "Biofuel Technologies: Lessons Learned and Pathways to Decarbonization." *GCB Bioenergy* 15: 1190–1203. https://doi.org/10.1111/gcbb.13091.

Cantarella, H., R. Otto, J. R. Soares, and A. G. B. Silva. 2018. "Agronomic Efficiency of NBPT as a Urease Inhibitor: A Review." *Journal of Advanced Research* 13: 19–27. https://doi.org/10.1016/j.jare.2018.05.008.

Carmo, J. B., S. Filoso, L. C. Zotelli, et al. 2013. "In Field Greenhouse Gas Emissions From Sugarcane Soils in Brazil: Effects From Synthetic and Organic Fertilizer Application and Crop Trash Accumulation." *GCB Bioenergy* 5: 267–280. https://doi.org/10.1111/j.1757-1707.2012.01199.x.

Carvalho, J. L. N., R. C. Nogueirol, L. M. S. Menandro, et al. 2017. "Agronomic and Environmental Implications of Sugarcane Straw Removal: A Major Review." *GCB Bioenergy* 9, no. 7: 1181–1195.

Carvalho, J. L. N., B. G. Oliveira, H. Cantarella, et al. 2021. "Implications of Regional N_2O–N Emission Factors on Sugarcane Ethanol Emissions and Granted Decarbonization Certificates." *Renewable and Sustainable Energy Reviews* 149: 111423.

Cassim, B. M. A. R., I. P. Lisboa, M. R. Besen, et al. 2024. "Nitrogen: From Discovery, Plant Assimilation, Sustainable Usage to Current Enhanced Efficiency Fertilizers Technologies—A Review." *Revista Brasileira de Ciência do Solo* 48: e0230037. https://doi.org/10.36783/18069657rbcs20230037.

Cayuela, M. L., E. Aguilera, A. Sanz-Cobena, et al. 2017. "Direct Nitrous Oxide Emissions in Mediterranean Climate Cropping Systems: Emission Factors Based on a Meta-Analysis of Available Measurement Data." *Agriculture, Ecosystems and Environment* 238: 25–35. https://doi.org/10.1016/j.agee.2016.10.006.

Cerri, C. E. P., M. V. Galdos, J. L. N. Carvalho, B. J. Feigl, and C. C. Cerri. 2013. "Quantifying Soil Carbon Stocks and Greenhouse Gas Fluxes in the Sugarcane Agrosystem: Point of View." *Scientia Agricola* 70: 361–368.

Cerri, C. E. P., X. You, M. R. Cherubin, et al. 2017. "Assessing the Greenhouse Gas Emissions of Brazilian Soybean Biodiesel Production." *PLoS One* 12, no. 5: e0176948.

Chagas, M. F., R. O. Bordonal, O. Cavalett, J. L. N. Carvalho, A. Bonomi, and N. La Scala Junior. 2016. "Environmental and Economic Impacts of Different Sugarcane Production Systems in the Ethanol Biorefinery." *Biofuels, Bioproducts and Biorefining* 10: 89–106. https://doi.org/10.1002/bbb.

Cherubin, M. R., J. L. N. Carvalho, C. E. P. Cerri, L. A. H. Nogueira, G. M. Souza, and H. Cantarella. 2021. "Land Use and Management Effects on Sustainable Sugarcane-Derived Bioenergy." *Land* 10, no. 1: 72.

CONAB. 2024. "Relatório Anual. Brasília, Brasil."

Costa, F. S., J. Gomes, C. Bayer, and J. Mielniczuk. 2006. "Methods for the Assessment of Greenhouse Gases Emissions in the Soil-Atmosphere System." *Ciência Rural* 36: 693–700. https://doi.org/10.1590/s0103-84782006000200056.

Crutzen, P. J., A. R. Mosier, K. A. Smith, and W. Winiwarter. 2016. "A Liberação de N_2O da Produção de Agrobiocombustíveis Nega a Redução do Aquecimento Global ao Substituir Combustíveis Fósseis." In *Paul J. Crutzen: Um Pioneiro em Química Atmosférica e Mudança Climática no Antropoceno*, edited by P. J. Crutzen and H. Brauch, vol. 50. Springer. https://doi.org/10.1007/978-3-319-27460-7_12.

Cui, X., F. Zhou, P. Ciais, et al. 2021. "Global Mapping of Crop-Specific Emission Factors Highlights Hotspots of Nitrous Oxide Mitigation." *Nature Food* 2, no. 11: 886–893.

Denmead, O. T., B. C. T. Macdonald, G. Bryant, et al. 2010. "Emissions of Methane and Nitrous Oxide From Australian Sugarcane Soils." *Agricultural and Forest Meteorology* 150, no. 6: 748–756. https://doi.org/10.1016/j.agrformet.2009.06.018.

Fan, D., W. He, W. N. Smith, et al. 2022. "Global Evaluation of Inhibitor Impacts on Ammonia and Nitrous Oxide Emissions From Agricultural Soils: A Meta-Analysis." *Global Change Biology* 28: 5121–5141. https://doi.org/10.1111/gcb.16294.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. "Land Clearing and the Biofuel Carbon Debt." *Science* 319, no. 5867: 1235–1238. https://doi.org/10.1126/science.1152747.

Grace, P., D. De Rosa, I. Shcherbak, et al. 2023. "Revised Emission Factors for Estimating Direct Nitrous Oxide Emissions From Nitrogen Inputs in Australia's Agricultural Production Systems: A Meta-Analysis." *Soil Research* 62: SR23070. https://doi.org/10.1071/SR23070.

Gurgel, A. C., J. E. Seabra, S. M. Arantes, M. M. Moreira, L. R. Lynd, and R. Galindo. 2024. "Contribution of Double-Cropped Maize Ethanol in Brazil to Sustainable Development." *Nature Sustainability* 7, no. 11: 1429–1440.

Hemalatha, S. 2015. "Impact of Nitrogen Fertilization on Quality of Sugarcane Under Fertigation." *IJRSI* 2, no. 3: 37–39.

IEA Bioenergy. 2024. "Relatório Nacional do Brasil 2024." https://www.ieabioenergy.com/wp-content/uploads/2024/12/CountryReport2024_Brazil_final.pdf.

IPCC. 2019. "N_2O Emissions From Managed Soils, and CO_2 Emissions From Lime and Urea Application." In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, vol. 4. IPCC.

IPCC. 2022. *Summary for Policymakers. In Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC.

Li, Y. R., and L. T. Yang. 2015. "Sugarcane Agriculture and Sugar Industry in China." *Sugar Tech* 17, no. 1: 1–8.

Li, Z., Q. Xu, Y. Lu, et al. 2025. "Reducing Nitrogen Fertilizer Applications Mitigates N_2O Emissions and Maintains Sugarcane Yields in South China." *Agriculture, Ecosystems & Environment* 377: 109250.

Locatelli, J. L., G. V. Popin, R. S. Santos, et al. 2024. "A Comprehensive Assessment of Greenhouse Gas Emissions Research in the Cerrado Region, Brazil." *Catena* 247: 108538.

Lourenco, K. S., R. Rossetto, A. C. Vitti, et al. 2019. "Strategies to Mitigate the Nitrous Oxide Emissions From Nitrogen Fertilizer Applied With Organic Fertilizers in Sugarcane." *Science of the Total Environment* 650: 1476–1486.

Luz, F. B., L. C. Gonzaga, M. R. Cherubin, G. A. F. Castioni, and J. L. N. Carvalho. 2024. "Soil Health Impact of Long-Term Sugarcane Vinasse Recycling." *Biofuels, Bioproducts and Biorefining* 18: 2064–2077. https://doi.org/10.1002/bbb.2688.

MME. 2017. *RenovaBio Programme*. Ministério de Minas e Energia. https://www.gov.br/anp/pt-br/assuntos/renovabio/arq/law-13576-2017.pdf.

Moreira, M. M., J. E. Seabra, L. R. Lynd, S. M. Arantes, M. P. Cunha, and J. J. Guilhoto. 2020. "Socio-Environmental and Land-Use Impacts of Double-Cropped Maize Ethanol in Brazil." *Nature Sustainability* 3, no. 3: 209–216.

Oliveira, B. G., K. S. Lourenço, J. L. N. Carvalho, et al. 2023. "New Trends in Sugarcane Fertilization: Implications for NH_3 Volatilization, N_2O Emissions and Crop Yields." *Journal of Environmental Management* 342: 118233.

Otto, R., R. Ferraz-Almeida, G. M. Sanches, I. P. Lisboa, and M. R. Cherubin. 2022. "Nitrogen Fertilizer Consumption and Nitrous Oxide Emissions Associated With Ethanol Production: A National-Scale Comparison Between Brazilian Sugarcane and Corn in the United States." *Journal of Cleaner Production* 350: 131482. https://doi.org/10.1016/j.jclepro.2022.131482.

Paredes, D. S., A. C. R. Lessa, S. A. C. de Sant'Anna, R. M. Boddey, S. Urquiaga, and B. J. R. Alves. 2014. "Nitrous Oxide Emission and Ammonia Volatilization Induced by Vinasse and N Fertilizer Application in a Sugarcane Crop at Rio de Janeiro, Brazil." *Nutrient Cycling in Agroecosystems* 98: 41–55. https://doi.org/10.1007/s10705-013-9594-5.

Parkin, T. B., and R. T. Venterea. 2010. "Chapter 3. Chamber-Based Trace Gas Flux Measurements." In *Sampling Protocols*, edited by R. F. Follett. USDA-ARS. www.ars.usda.gov/research/GRACEnet.

Pitombo, L. M., J. B. do Carmo, M. de Hollander, et al. 2016. "Exploring Soil Microbial 16S rRNA Sequence Data to Increase Carbon Yield and Nitrogen Efficiency of a Bioenergy Crop." *GCB Bioenergy* 8: 867–879. https://doi.org/10.1111/gcbb.12284.

QGIS. 2014. "Sistema de Informações Geográficas do QGIS. Projeto Open Source Geospatial Foundation."

Robinson, N., R. Brackin, K. Vinall, et al. 2011. "O Paradigma do Nitrato Não se Sustenta Para a Cana-De-Açúcar." *Plos O Ne* 6, no. 4: e19045.

Rochette, P., and N. S. Eriksen-Hamel. 2008. "Chamber Measurements of Soil Nitrous Flux: Are Absolute Values Reliable?" *Soil Science Society of America Journal* 72: 331–342.

Sahil, F., N. Mohammad, I. Mukund, and N. Idhayachandhiran. 2023. "Nitrous Oxide Emissions Dynamics in Indian Agricultural Landscapes: Revised Emission Rates and New Insights." *Agriculture, Ecosystems & Environment* 356: 108639. https://doi.org/10.1016/j.agee.2023.108639.

Seabra, J. E. A., I. C. Macedo, H. L. Chum, C. E. Faroni, and C. A. Sarto. 2011. "Life Cycle Assessment of Brazilian Sugarcane Products: GHG Emissions and Energy Use." *Biofuels, Bioproducts and Biorefining* 5: 519–532. https://doi.org/10.1002/bbb.289.

Searchinger, T., R. Heimlich, R. A. Houghton, et al. 2008. "Use of US Croplands for Biofuels Increases Greenhouse Gases Through Emissions From Land-Use Change." *Science* 319, no. 5867: 1238–1240.

Silva, J. F., A. Moreira de Carvalho, T. A. Rein, et al. 2017. "Nitrous Oxide Emissions From Sugarcane Fields in the Brazilian Cerrado." *Agriculture, Ecosystems & Environment* 246: 55–65. https://doi.org/10.1016/j.agee.2017.05.019.

Siqueira Neto, M., M. V. Galdos, B. J. Feigl, C. E. P. Cerri, and C. C. Cerri. 2016. "Direct N_2O Emission Factors for Synthetic N-Fertilizer and Organic Residues Applied on Sugarcane for Bioethanol Production in Central-Southern Brazil." *GCB Bioenergy* 8: 269–280. https://doi.org/10.1111/gcbb.12251.

Snyder, C. S., E. A. Davidson, P. Smith, and R. T. Venterea. 2014. "Agriculture: Sustainable Crop and Animal Production to Help Mitigate Nitrous Oxide Emissions." *Current Opinion in Environmental Sustainability* 9, no. 10: 46–54. https://doi.org/10.1016/j.cosust.2014.07.005.

Soares, J. R., N. A. Cassman, A. M. Kielak, et al. 2016. "Nitrous Oxide Emission Related to Ammonia-Oxidizing Bacteria and Mitigation Options From N Fertilization in a Tropical Soil." *Scientific Reports* 6: 30349. https://doi.org/10.1038/srep30349.

Sriphirom, P., B. Rossopa, and N. Boonapatcharoen. 2023. *Evaluating Direct Nitrous Oxide Emissions and Emission Factors of Different Chemical Fertilizer Application Rates in Sugarcane Plantations in Western Thailand*. SSRN. https://doi.org/10.2139/ssrn.4608536.

Suleiman, A. K. A., K. S. Lourenço, L. M. Pitombo, et al. 2018. "Recycling Organic Residues in Agriculture Impacts Soil-Borne Microbial Community Structure, Function and N_2O Emissions." *Science of the Total Environment* 631: 1089–1099. https://doi.org/10.1016/j.scitotenv.2018.03.116.

Tenuta, M., and E. Beauchamp. 2011. "Nitrous Oxide Production From Granular Nitrogen Fertilizers Applied to a Silt Loam Soil." *Canadian Journal of Soil Science* 83: 521–532. https://doi.org/10.4141/s02-062.

UNEM. 2025. "Etanol de Milho Cresce e Contribui Com o Recorde de Produção Dos Biocombustíveis." https://digital.agrishow.com.br/sustentabilidade/etanol-de-milho-cresce-e-contribui-com-o-recorde-de-producao-dos-biocombustiveis.

Ussiri, D., and R. Lal. 2013. *Soil Emission of Nitrous Oxide and Its Mitigation*. Springer Science & Business Media.

Welutung, P., P. Pengthamkeerati, and B. Kachenchart. 2023. *Soil Nitrous Oxide Emissions From Sugarcane Field Affected by Nitrogen Fertilizer Rate and Inhibitors of Urea Hydrolysis and Nitrification Process*. Research Square. https://doi.org/10.21203/rs.3.rs-2618897/v1.

Xia, Y., H. Kwon, and M. Wander. 2024. "Estimating Soil N_2O Emissions Induced by Organic and Inorganic Fertilizer Inputs Using a Tier-2, Regression-Based Meta-Analytic Approach for US Agricultural Lands." *Science of the Total Environment* 927: 171930.

Yang, L., Y. Deng, X. Wang, et al. 2021. "Global Direct Nitrous Oxide Emissions From the Bioenergy Crop Sugarcane (*Saccharum* spp. Inter-Specific Hybrids)." *Science of the Total Environment* 752: 141795.

Yuttitham, M., A. Chidthaisong, and U. Ruangchu. 2020. "N_2O Fluxes and Direct N_2O Emission Factors From Maize Cultivation on Oxisols in Thailand." *Geoderma Regional* 20: e00244.

Zanatta, J. A., B. J. R. Alves, C. Bayer, et al. 2014. *Protocolo Para Medição de Fluxos de Gases de Efeito Estufa do Solo*. 1st ed. Embrapa Florestas. https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/1014351/protocolo952para-medicao-de-fluxos-de-gases-de-efeito-estufa-do-solo.

Zhang, L., X. Zhang, Q. Gao, and L. Yan. 2023. "Nitrogen Application Effect on Maize Yield, NH_3, and N_2O Emissions in Northeast China by Meta-Analysis." *Agronomy* 13, no. 6: 1479.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** gcbb70071-sup-0001-Supinfo.docx.