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SCOPING ETHANOL VS. ELECTRIFICATION FOR DECARBONIZING BRAZIL'S URBAN MOBILITY: PATHWAYS TO CLEANER AIR AND REDUCED EMISSIONS

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EXECUTIVE SUMMARY

This Master's Project addresses a critical policy challenge at the intersection of climate change mitigation and air quality management in Brazil. For decades, Brazil has championed sugarcane ethanol as a cornerstone of its energy independence and a key strategy for reducing greenhouse gas (GHG) emissions in the transportation sector, notably through programs like Proálcool initiated in the 1970s and the more recent RenovaBio policy. While ethanol offers a lower carbon footprint compared to fossil fuels, due to its renewable nature and carbon sequestration by sugarcane plants, its widespread use has complex and often under examined consequences for air quality, particularly concerning the formation of tropospheric ozone.

The central policy question for this paper is: What is the baseline impact of ethanol use on air quality in Brazil, particularly on tropospheric ozone levels? How might planned policy changes, including adjustments to PROCONVE and RenovaBio toward the emission regulation and promotion of electric vehicles (EVs), influence these outcomes? This research employs a multi-source approach, including a Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) analysis, stakeholder analysis, expert interviews, and analysis of Life Cycle Assessment (LCA) studies.[1]

KEY FINDINGS

- Ethanol contributes to tropospheric ozone formation due to Nitrogen Oxides (NOx) and Volatile Organic Compound (VOC) emissions, despite lower GHG emissions than fossil fuels. Hazardous pollutants from ethanol plants also contribute to ground-level ozone.
- Brazil's air quality monitoring has gaps, with limited data outside major urban areas
- Brazil's air quality monitoring has improved with PNQAr, but still lacks a complete emissions inventory, broader coverage, and proper funding mechanisms.
- Historically, enforcement of air quality limits has been weak. Ethanol promotion has often prioritized economics over air quality.

- There's a public perception of ethanol as environmentally friendly that doesn't fully acknowledge its ozone-forming potential.
- LCA studies of Brazilian ethanol under-represent air quality impacts, particularly photochemical ozone formation potential (POCP) and particulate matter (PM2.5).
- Many of these LCA studies rely on secondary data.
- A diverse group of stakeholders, including government (MMA, CONAMA, ANP), industry (UNICA), and research institutions, influence air quality and ethanol policies.
- EV adoption in Brazil is in its early stages, facing challenges such as competition from the established ethanol industry, limited charging infrastructure, high import taxes, and public skepticism. However, recent initiatives and investments indicate a potential acceleration.
- Hybrid Electric Vehicles (HEVs) are currently more prevalent in the small EV market in Brazil and are seen by some as a transitional solution leveraging existing biofuel infrastructure.
- Brazil historically lacked vapor recovery systems at gas stations, leading to significant evaporative emissions of VOCs during refueling. While PROCONVE L8 now requires Onboard Refueling Vapor Recovery (ORVR) systems, it will take time to significantly decrease evaporative emissions

KEY RECOMMENDATIONS:

- Enhance and expand stakeholder collaboration among government, industry, researchers, and the public on air quality policy.
- Increase public awareness of ethanol's impact on ozone and the benefits of EVs and HEVs for cleaner air.
- Advocate for strengthened emissions regulations under PROCONVE to include stricter limits for ethanol-related pollutants (VOCs, ozone, PM2.5) and ensure transparent reporting. Explore VOC control in RenovaBio.
- Expand air quality monitoring and research to improve VOC, NOx, and PM2.5 tracking, and conduct comprehensive LCAs assessing ethanol's air quality impacts using primary data.
- Integrate full-spectrum air quality metrics (ozone, PM2.5, NOx) consistently into ethanol LCAs, moving beyond just GHG emissions.
- Align policies like PROCONVE and RenovaBio to holistically consider both climate and air quality impacts. Encourage multi-pollutant assessments.
- Address evaporative emissions by ensuring effective implementation and enforcement of ORVR systems in vehicles. Consider regulations for VOC recovery from stationary sources like gas stations under PROCONVE.

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LIST OF ABBREVIATIONS

ANP	National Agency of Petroleum, Natural Gas, and Biofuels
BEVs	Battery Electric Vehicles
CARB	California Air Resources Board
CED	Cumulative Energy Demand
CETESB	São Paulo State Environmental Agency
CH4	Methane
CML	(Methodological approach for LCA)
CO	Carbon Monoxide
CO2	Carbon Dioxide
CONAMA	National Environment Council
EDF	Environmental Defense Fund
EDIP	Environmental Design of Industrial Products
ELCD	European Reference Life Cycle Database
EIO-LCA	Economic Input-Output-Based Life-Cycle Assessment
EPA	U.S. Environmental Protection Agency
EV	Electric Vehicle
FAOSTAT	Food and Agriculture Organization of the United Nations (Statistics)
FFVs	Flex-Fuel Vehicles
FU	Functional Unit
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GHG	Greenhouse Gas
GWP	Global Warming Potential

HEV	Hybrid Electric Vehicle
IBAMA	Brazilian Institute of Environment and Renewable Natural Resources
ICCT	(Implied as a relevant NGO)
IEMA	Institute for Energy and Environment
IFA	International Fertilizer Association
iLUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
IQAr	Air Quality Index (in Portuguese)
LAC	Latin America and the Caribbean
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LU	Land Use
MEM	Master of Environmental Management
MMA	Ministry of the Environment and Climate Change
MME	Ministry of Mines and Energy
MPP	Master of Public Policy
N2O	Nitrous Oxide
NDCs	Nationally Determined Contributions
NH3	Ammonia
NMOG	Non-Methane Organic Gases
NOx	Nitrogen Oxides
NVivo	(Qualitative Data Analysis Software)
O3	Ozone
ODP	Ozone Layer Depletion Potential
ORVR	Onboard Refueling Vapor Recovery

PESTLE	Political, Economic, Social, Technological, Legal, and Environmental
PM	Particulate Matter
PM2.5	Particulate Matter (with a diameter of 2.5 micrometers or less)
PNE 2050	National Energy Plan 2050
PNQAr	National Air Quality Policy
POCP	Photochemical Ozone Formation Potential
Proálcool	(Brazilian National Alcohol Program)
Proconve	(Brazilian vehicle emissions control program)
SDGs	Sustainable Development Goals
SMAC	Rio de Janeiro's Municipal Secretariat of Environment
TIS	Technology Innovation System
UNICA	The Brazilian Sugarcane Industry Association
UNEP	United Nations Environment Programme
USP	University of São Paulo
VOCs	Volatile Organic Compounds
WHO	World Health Organization
WtG	Well-to-Gate
WtT	Well-to-Tank
WtW	Well-to-Wheel
WRI	(Implied as a relevant NGO)

INTRODUCTION

Brazil is one of the major leaders in biofuel production, specifically in sugarcane-based ethanol. As national production continues to rise due to economic benefits and decarbonization goals, health and environmental challenges are emerging, going largely unnoticed due to a lack of robust air quality data in most of the country, as well as targeted monitoring, and research to enhance the understanding of the health impacts from ethanol related pollutants along the fuel supply and consumption chain.

Policies such as RenovaBio, which is aimed to reduce carbon emissions in Brazil's transportation sector by promoting biofuel use and establishing a market for carbon credits to offset fossil fuel emissions, are working to regularize supply and enhance the biofuel market in Brazil. The emission and air quality outcomes from the proposed increase in biofuel use in the urban transport sector emissions necessitate an analysis of their health impacts, particularly concerning ground level ozone.

Additionally, there is evidence that Brazil's slow adoption of EVs is partly due to the country's historical emphasis on ethanol-based fuels, supported by its position as the largest global producer of sugarcane.[2] Despite global electrification trends, Brazil is likely to continue prioritizing bioenergy through its RenovaBio policy which is expected to shape the energy landscape like the Proálcool program did in the past.[3]

TROPOSPHERIC OZONE FORMATION, ETHANOL USE, AND ITS IMPACT ON AIR QUALITY

Tropospheric Ozone, also known as ground level ozone, “is created from a chemical reaction of volatile organic compounds (VOCs), and nitrogen oxides (NOx)” and sunlight.[4] Elevated levels of ozone can negatively impact human health and the well-being of ecosystems.[5] While both VOCs and NOx are harmful, it should be noted that VOCs are deemed more significant in ozone formation. VOCs serve as the primary “fuel” for the reaction that produces the ozone. As a result, reductions in VOC emissions can have a more substantial impact on lowering ozone levels than focusing only on the reduction of NOx.[6]

Ethanol is widely promoted as a biofuel, providing reduction in greenhouse gas emissions compared to regular fossil fuels. Although this factor makes it a prominent topic in climate policy discussions, ethanol's effects on air quality, particularly in the formation of ground level ozone, often go under examined. Recent reports by the U.S. EPA and the Environmental Integrity Project, highlight the significant VOCs and hazardous pollutants emitted from ethanol plants compared to petroleum refineries in the United States, including acetaldehyde, acrolein, formaldehyde, and hexane, all of which contribute to ground level ozone.[7]

Ethanol in Brazil is mostly used as a biofuel, either blended with gasoline (E27, 27% ethanol) or in pure form for flex-fuel vehicles (See Appendix A for historical ethanol blending mandates in Brazil).[8] Sugarcane ethanol has a lower carbon footprint than fossil fuels because of its renewable nature and carbon sequestration by sugarcane plants. While ethanol reduces carbon emissions, it can increase ground-level ozone and other pollutants, posing local and regional environmental and health risks.[9] Ethanol has been shown to reduce carbon dioxide and certain toxic emissions, such as benzene, compared to gasoline, but it also increases acetaldehyde emissions, a compound recognized as a probable human carcinogen and a contributor to ground-level ozone formation.[10]

High surface ozone levels in Brazil pose significant risks to human health, crops, and climate change, driven by urban pollution and biomass burning. Even though efforts to reduce fossil fuel use in transport, industry, and energy sectors are ongoing, Brazil's ethanol production has played a complex role in air quality issues. It has been found that ethanol, comprising 48.3% of Brazil's light-duty vehicle fuel matrix by 2019, reduces some pollutants but increases ozone levels.[11]

Rural areas continue to suffer from pollution linked to biofuel production and urban transport. Carbon dioxide emissions from bagasse-fired power plants, although significant, remain under-measured.[12] The lack of comprehensive air pollution monitoring, particularly in rural regions, reduces efforts to understand and mitigate these impacts. Monitoring ozone and its precursors is needed to grasp the full extent of regional pollution challenges.[13]

In São Paulo, the city's transport sector is a major source of ozone forming pollutants like Hydrocarbons (HCs), Carbon Monoxide (CO), Nitrogen Oxides (NOx), and Particulate Matter 10 (PM10).[14] Heavy traffic congestion increases emissions and exposure, leading to significant health impacts, including respiratory diseases and decreased quality of life.[15]

BRAZIL'S PAST AND PRESENT POLICIES AND INTERVENTIONS

BIOFUELS POLICY

Since the 1970s, Brazil's Proálcool program has positioned the country as a leader in sugarcane ethanol production. Initiated during the oil crisis, the Proálcool program aimed to reduce Brazil's dependence on imported fuel.[16] Since the program's inception, Brazil has become a leader in ethanol, ranking second in ethanol production globally, producing 31.2 billion liters in 2022 to 2023.[17]

Brazil's already low carbon energy matrix places the country in a position to lead renewable advancements.[18] However, the speed of the energy transition remains a concern, particularly in the transportation sector which is still heavily reliant on fossil fuels.[19] The decarbonization of this sector is a priority under plans such as the National Energy Plan 2050 (PNE 2050), which, along with other initiatives such as RenovaBio and Nationally Determined Contributions (NDCs), aim to regularize supply and enhance the biofuel market in Brazil.

PNE 2050 outlines targets for the expansion of biofuels in Brazil's energy mix, aiming to reduce carbon emissions. This includes expanding biomass use in both the electricity and transportation sector.[20]

RenovaBio complements these efforts by aiming to regularize supply and enhance the competitiveness of Brazil's biofuel market. RenovaBio sets national carbon dioxide emissions reduction targets for the fuel matrix, with annual and individual targets for fuel distributors, and establishes a carbon credit market to boost efficiency and reduce costs in biofuel production.[21]

In alignment with Brazil's climate commitments under the Paris Agreement, Brazil's NDCs also outline some targets applicable to the transportation sector, such as achieving an "18% share of bioenergy in the energy mix," promoting ethanol supply and fuel blends.[22] These efforts are complemented by initiatives aimed at enhancing transport efficiency and investing in urban infrastructure.[23]

According to Climate Transparency's report on the Energy Transition in Brazil, "Brazil is on track to meet its transport related NDC targets, although more efforts are needed to be in line with a 1.5°C-compatible development pathway. It is important to emphasize that greenhouse gas emission reductions in the transport sector are politically significant, due to the close relationship between transport activity and GDP."[24]

Brazil's RenovaBio, NDCs, and PNE2050 all focus on promoting biofuel use to decarbonize the transport sector. These policies aim to increase the use of first-generation ethanol and biodiesel, regularize supply, and develop a competitive biofuel market. Even though these initiatives effectively address carbon dioxide emissions, they lack guidelines for monitoring and reducing other pollutants.[25]

EMISSIONS POLICY

The PROCONVE regulation, enforced by Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) and the MMA, has progressively lowered the permissible threshold for automotive pollutant emissions in Brazil since 1990.[26] The L7 phase includes limits on pollutants such as NMOG + NOx, PM, CO, and aldehydes, while L8 will introduce an ammonia (NH3) limit.[27] Stricter standards are set for the L8 phase in 2025.[28] These emission limits are planned to become progressively stricter and fully implemented by 2029 for passenger vehicles and by 2031 for light commercial vehicles.[29] It should be noted that concerns have been raised about transparency and data availability regarding vehicle emissions, as IBAMA has not yet met the requirement to publicly share this data, a mandate also present in the earlier L6 phase.[30,31]

AIR QUALITY POLICY

A direct air quality policy did not form in Brazil until the late 1980s. In 1990, air quality regulations were written into the law through PRONAR, under the oversight of the National Environmental Council (CONAMA).[32] Since its establishment, air quality

standards have evolved. Even though air quality standards have become more rigorous overtime, Brazil still has been delayed in implementing international standards from organizations like the World Health Organization (WHO). To be noted, is Brazil's adoption of the WHO's 2005 air quality standards in 2018. In addition to slow adoption compared to international standards, Brazil has also faced critiques in their unclear objectives, unspecified timelines, and limited accountability in achieving their proposed air quality standards.[33]

In 2024 Brazil introduced PNQAr, as well as a revision to the current legal framework, to begin to reflect a shift in Brazil's commitment to air quality policy. This revision highlights the need for Brazil to "expand its air quality monitoring systems beyond just a few urban areas" that they are currently present in.[34] Although changes are being seen on paper, Tavella Et al. feels that the "proposed revision still has room for improvement," are not ambitious enough, and lack an outline for the mechanisms for obtaining funding and resources, something essential to support these changes.[35] Tavella Et al. continues to share that Brazilian Citizens must be proactive to prevent this policy from becoming merely symbolic.[36]

BACKGROUND ON ELECTRIC VEHICLES

Biofuel programs in Brazil have made introducing electric vehicles (EVs) in the country competitive and challenging.[37] This challenge has resulted in a lack of policies promoting EV adoption in Brazil. In addition to biofuel competition, pressure from political and economic groups has influenced slow adoption. Some studies suggest that the Brazilian government may be reluctant to invest in this technology due to fears of diverting resources from the ethanol sector.[38]

It is important to note that according to the IEA, there have been recent initiatives like the Green Mobility and Innovation Programme (MOVER) and investments by automakers such as BYD, that plan to start domestic manufacturing and partner with Raízen for charging infrastructure, which are accelerating the shift towards electric mobility.[39]

Sales of electric cars in Brazil are expected to increase, with EVs accounting for 3.6% of total vehicle sales in 2023, up from 2.29% in 2022.[40] The EV market in Brazil is growing rapidly, with a projected "compound annual growth rate (CAGR) of approximately 17% from 2022 to 2028."[41] This growth comes from rising

gasoline prices, government emission reduction efforts, and increasing demand for cleaner mobility options in urban areas.[42] Improved policy coordination between biofuel and EV sectors will be crucial in decarbonizing transportation and achieving long-term sustainability goals.

RESEARCH METHODOLOGY

This master's project adopts a multi-source research approach, drawing from academic literature, industry and government reports, interviews, stakeholder insights, media sources, as well as legal and policy documents. The primary objective is to analyze the baseline impacts of ethanol use on air quality in Brazil. Additionally, the study aims to assess the current state of air quality and explore potential policy changes.

TRIANGULATION METHOD FOR INFORMATION COLLECTION

This study employs triangulation to enhance the validity and reliability of findings. By incorporating multiple types of sources, this approach mitigates potential biases associated with relying on a single method or observer.

Figure 1: Triangulation Visualization

INTERVIEW METHODOLOGY

To gather expert insights on vehicular emissions, air quality, and EV adoption in Brazil, a qualitative interview-based study was conducted, utilizing primary and secondary data sources. The methodology involved the following steps:

Expert Interviews: Interviews were conducted with five experts in the emissions and air quality sectors. For those available and consenting, interviews were done via Zoom and recorded for transcription. In cases where scheduling a virtual meeting was not possible, the interview questions were sent via email, allowing respondents to provide written answers at their convenience. Interviewee information, summaries, and backgrounds can be found in Appendix C.

Supplementary Media Interviews: To broaden the scope of expert perspectives, I identified and analyzed publicly available media interviews with experts in the field whom I was unable to contact directly. These included interviews published in reputable news outlets, industry reports, and conference proceedings. Information on these referenced experts via media content can be found in Appendix C.

Translation of Transcriptions: Since some interviews were conducted or published in Portuguese, the transcriptions/media were translated into English to facilitate qualitative analysis in NVivo, a qualitative data analysis software.

Qualitative Coding in NVivo: All transcriptions, including both primary interviews and supplementary media sources, were imported into NVivo. Using an inductive coding approach, key themes were identified, insights were categorized, and relevant quotes were highlighted to support the study's analysis.

After coding and thematic analysis in NVivo, the insights were used in various sections of this study, including:

- **PESTLE Analysis:** To contextualize external macro-environmental factors affecting emissions and air quality policies in Brazil.
- **Stakeholder Analysis:** To understand the perspectives, roles, and influences of different actors in the ethanol, air quality, and EV sector.
- **Recommendations:** To inform evidence-based policy and strategic actions for addressing air quality challenges.

- **Implementation Strategies:** To outline practical steps for executing the proposed recommendations based on the findings.

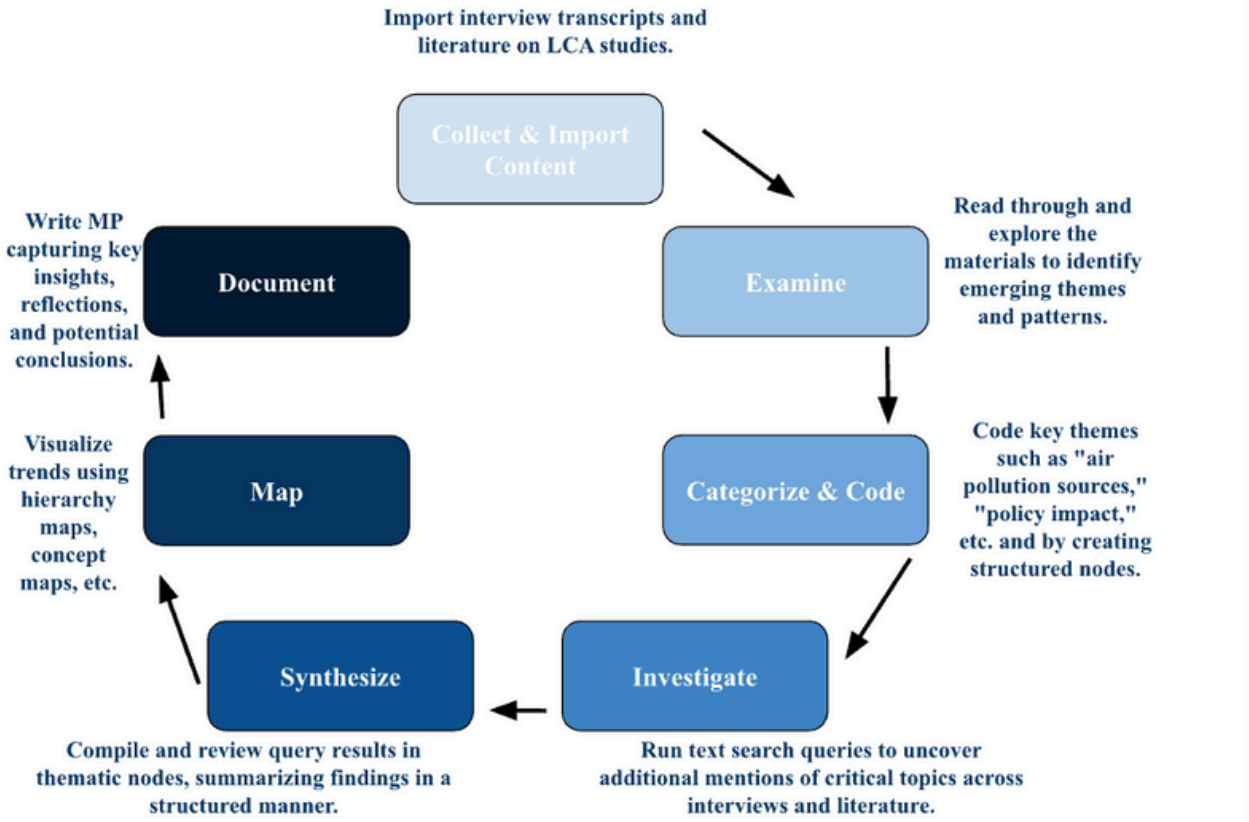


Figure 2: NVivo Qualitative Method Flow Chart for Interviews & LCA literature Analysis

LCA STUDIES ANALYSIS METHODOLOGY

To find gaps in current literature on the Life Cycle Assessment (LCA) of sugarcane-based ethanol in Brazil, a total of fourteen studies related to this process in Brazil were analyzed in NVivo. Appendix F contains a list of the selected literature/authors and the coding schema that was developed to examine these studies.

I. Project Setup and Data Import

LCA documents were imported into NVivo. These included journal articles, reports, conference papers, book chapters, and theses/dissertations.

II. Coding Schema Development

A detailed coding schema was developed which can be found in appendix F. This involved creating a list of coding categories covering key aspects of the LCA studies, such as impact categories, data sources, and software used.

III. Coding Process

Each document was reviewed and coded. A preliminary review of the imported documents was conducted to familiarize with the content. Coding was then applied at both deductive and inductive levels: pre-defined coding categories guided by the research questions were used alongside emerging themes identified throughout the review. Passages, sentences, and key phrases relevant to the LCA codes were tagged accordingly. NVivo's query functions, such as word frequency analysis and matrix coding, were also utilized to identify patterns and relationships between themes across different studies.

IV. Analysis and Interpretation

NVivo's visualization tools, such as hierarchy charts and mind maps, were used to visually present the coded data. Query results and visualizations were analyzed to identify patterns and trends in the LCA literature. Conclusions about the current state of LCA research on sugarcane ethanol in Brazil and how it relates to EDF's air quality research needs were made based on the coding results.

FURTHER CONTEXT & FINDINGS

PESTLE ANALYSIS

Political Factors

Political factors have shown to considerably influence air quality monitoring and policies in Brazil, presenting both obstacles and opportunities for advancement. A primary challenge involves a historical lack of accountability and enforcement in meeting air quality limits, compounded by legal uncertainties and regression stemming from new resolutions.[43] Both literature and interviews highlighted that there have been disconnects between federal, state, and municipal responsibilities regarding air quality.[44]

The federal government is responsible for setting laws and homogenizing regulations across all states, but many states lack the capacity to measure pollution.[45,46,47] Varying regional realities and the absence of clear municipal-level accountability create additional governance challenges.[48] These challenges hinder what is essential for establishing effective programs.

Brazil has historically been slower in adopting international standards. Just in 2018, Brazil adopted the 2005 WHO guidelines years after their recommendation.[49] Beyond this national delay, there have also been significant geographically related political factors affecting air quality in Brazil. In an interview with Dr. Lucia Guardani from the State of São Paulo's Environmental Company (CETESB), she highlighted that there is a lack of political will and prioritization, particularly outside the Southeast and South regions, where air quality monitoring and improvements are often neglected.[50] In the northern region of Brazil, the Institute of Energy and Environment (IEMA), has stated that "there is no official monitoring, only what we call low-cost monitoring."[51] In order to improve this, experts say that greater public pressure is necessary to compel authorities to take meaningful action and demand results from policymakers.[52,53]

The implementation of Brazil's National Air Quality Policy (PNQAr) in 2024 marks an important moment for the country, offering clarity and direction in the nation's approach to air quality management.[54] Worth noting is the inclusion of VigiAr Panel in PNQAr. This panel is a collaboration with Brazil's Ministries of Health and Environment and Climate Change and will use remote sensing data to monitor PM2.5 levels and provide user-friendly information on air pollution effects across Brazilian municipalities.[55]

In a report by Ronan Adler Tavella, "coordinator of the Working Group on Air Pollution" and Flavio Manoel Rodrigues da Silva Júnior, "president of the Brazilian Society of Ecotoxicology," they share that although this is a big step forward in air quality improvement for Brazil, Brazilian citizens must be proactive in ensuring this policy is effectively enforced and not just symbolic.[56,57,58] Beyond it being a national policy, Tavella and Silva state that "this policy should be regarded as a state policy, independent of political orientation of future governments, serving as a guiding framework for sustainable development, wellbeing, and the quality of life for all Brazilians."[59]

A goal of this paper is to examine how ethanol policies and political priorities have potentially influenced air quality policies in Brazil. Air quality is often not a primary

consideration when increasing biofuel mandates.[60] Decisions to increase the ethanol blend are often based on economic aspects, without adequate study of the air quality impacts.[61] Policies promoting ethanol use to reduce greenhouse gas (GHG) emissions may conflict with efforts to improve air quality.[62] A focus on carbon dioxide decreases through biofuel policies to meet global GHG emissions reduction goals can overshadow concerns about VOCs and their impact on ozone levels.

Economic Factors

A major challenge to air quality policy implementation and monitoring in Brazil, is the lack of sufficient funding and investment from both authorities and Brazilian companies.[63] Budget constraints further limit the government's ability to enforce and expand necessary environmental programs.[64,65] In an interview with Lucia Guardani, an expert in the air quality division at CETESB, she highlighted that effective programs for controlling emissions, both from fixed sources (industries) and vehicles, depend on funding and goodwill.[66] Despite São Paulo being a wealthy state, there are challenges due to limited public funding, which affects staff availability and the replacement of equipment.[67] These economic constraints make the implementation and maintenance of monitoring programs complicated.

An important economic factor to consider, is the economic losses that have been caused and will be caused by an absence of proper air quality management. Poor air quality leads to substantial economic losses due to the reduction in productive years of life caused by premature deaths.[68] Paulo Saldiva, "a pathologist and professor at the University of São Paulo (USP) School of Medicine," has estimated that the annual economic loss from air pollution in Brazil stands at $1 billion and could rise to $3 billion when considering the broader harmful effects of pollution.[69,70] In response to these findings and current state of air quality policies, David Tsai from IEMA has stated that investing in air quality management can yield significant savings by preventing respiratory illnesses and other health-related costs.[71] IEMA has estimated that investing in air quality monitoring stations will "cost between R$16 million and R$49 million," a "shockingly low [cost] compared to other public investments in Brazil," says Tsai.[72]

Social Factors

One major issue that arose in both interviews and media articles was the general lack of awareness and knowledge about air quality among both policymakers outside of environmental sectors and the public.[73] Tsai explains that air pollution is often

perceived as an "invisible issue," leading to limited pressure for action.[74]

As mentioned in the economic factors section, the health impacts of air pollution are severe and contribute to premature deaths and diseases such as respiratory and cardiovascular conditions, as well as lung cancer.[75] Globally, the WHO estimates that "7 million premature deaths annually are linked to air pollution."[76] In Brazil alone, "The WHO further estimates that air pollution leads to more than 50,000 deaths."[77]

Guardani of CETESB explained that currently the population doesn't necessarily know the air that they are breathing. Given these risks, effective public communication is essential. Informing the population about air quality issues and enabling them to take preventive measures through better dissemination of information can help drive both awareness and policy change.[78] Addressing these social challenges is key to fostering a more informed and engaged public that can demand stronger air quality policies in Brazil.

Carlos Ibsen Vianna Lacava, Manager of the Mobile Emission Sources Department at CETESB, explained in an interview that, from an ethanol perspective on air quality, the public tends to view ethanol as more environmentally friendly than gasoline.[79] This perception doesn't fully consider the potential contributions of ethanol to ozone formation.[80]

Technological Factors

Many states lack sufficient air quality monitoring stations, limiting the ability to produce reliable data. As mentioned in a previous section, the northern region of Brazil has "no official monitoring, only what we call low-cost monitoring."[81] Beyond a geographical issue, states that do have monitoring systems still lack a complete emissions inventory.[82] It is important to highlight that the new PNQAr policy has "principles and guidelines to address the issue. The law imposes obligations such as defining atmospheric pollutants and creating emission inventories. These documents would allow the mapping of emission sources from various economic activities or companies and the quantification, monitoring, and recording of emissions."[83] In an article with Paulo Saldiva, from USP's School of Medicine, he highlights "that Brazil still lacks a consistent state policy to improve air quality."[84] "It's not just an environmental issue; it's about citizenship and people's fundamental rights," he stated.[85]

There has been a pressing need for advancements in evaporative emission control technologies within both the industrial and transportation sectors. Unlike some countries like the United States, Brazil historically has lacked vapor recovery systems at gas stations.[86,87] This means that when vehicles are refueled, the vapors that escape are not captured, leading to significant evaporative emissions.[88] A study conducted in China, which analyzed the impact of a nationwide 10% ethanol blend in gasoline on evaporative emissions, found that this change would account for "40% of total vehicular VOCs in China."[89] While there's been progress with initiatives like the PROCONVE program's new L8 phase targeting these types of emissions, challenges remain in fully implementing planned actions.[90] To reduce evaporative emissions, Onboard Refueling Vapor Recovery (ORVR) systems have been mandated to be installed in new vehicles.[91] Even with this new technology being implemented, studies in Brazil have shown that "despite ORVR controlling diurnal and refueling emissions, this system would take a timespan longer than 2031 to efficiently decrease evaporative emissions and consequently reduce ozone concentrations."[92] Additionally, Professor Andrade of the University of São Paulo shared that PROCONVE regulations should address evaporative emissions not only from vehicles but also from stationary sources like gas stations.[93]

While progress has been made in the automotive industry through the PROCONVE program, further adoption of emission-reducing technologies is necessary. Lacava notes Brazil's potential for clean energy and renewable fuels to advance decarbonization in transport and other sectors.[94] EVs have emerged as a promising solution for reducing urban air pollution and mitigating GHG emissions globally.[95] Brazil, with its unique energy landscape and established automotive industry, stands to benefit from the adoption of EVs. However, current technological barriers and political landscapes are hindering the successful implementation of EVs in Brazil.[96] A detailed analysis on EV adoption in Brazil can be found in a following section.

Environmental Factors

Beyond emissions from ethanol combustion, deforestation and fires are major sources of air pollution in Brazil.[97] These fires generate unhealthy air conditions, often blanketing cities with smoke.[98] Extreme droughts, perpetuated by climate change, also further worsen air quality.[99]

As stated in the introduction and context section of this paper, although ethanol is often promoted as a cleaner fuel alternative, its combustion can contribute to the

formation of ozone precursors, and concerns remain regarding emissions from its production process.[100] These initial standards became outdated "due to population, industrial and vehicular growth."[101]

Legal Factors

Since the 1970s, Brazil's environmental policies have been influenced by a focus on economic development, often prioritizing growth over ecological considerations.[102] Even though Decree-Law 3030/1967 attempted to address environmental concerns, it was later withdrawn due to a lack of means for compliance.[103] It wasn't until the 1980s and 1990s that clear mechanisms for quantifying pollutants were developed in Brazil through the creation of CONAMA and PRONAR.[104] Only in 2018 did Brazil adopt the 2005 WHO guidelines years after their recommendation.[105] Just in 2024, The National Air Quality Policy (PNQAr) was established by Law 14.850/2024.[106]

The Brazilian Institute of Climate and Society highlights that PNQAr mandates the creation of the MonitorAr system to standardize air quality monitoring and publicly share real-time data based on state reports.[107] The new policy also mandates pollutant emission surveys by subnational entities within three years to define regional pollution parameters, followed by a national survey within a year.[108] This is something that has been missing from past air quality related policies in Brazil. PNQAr also provides tax incentives and funding for research, technological advancements, and pollution control initiatives.[109] It also promotes programs for vehicle inspection, fleet renewal, and emission reduction while granting states and municipalities the authority to impose emission-based traffic restrictions.[110] Within the PNQAr regulation framework, the objectives of the policy are related to the public and their health including:

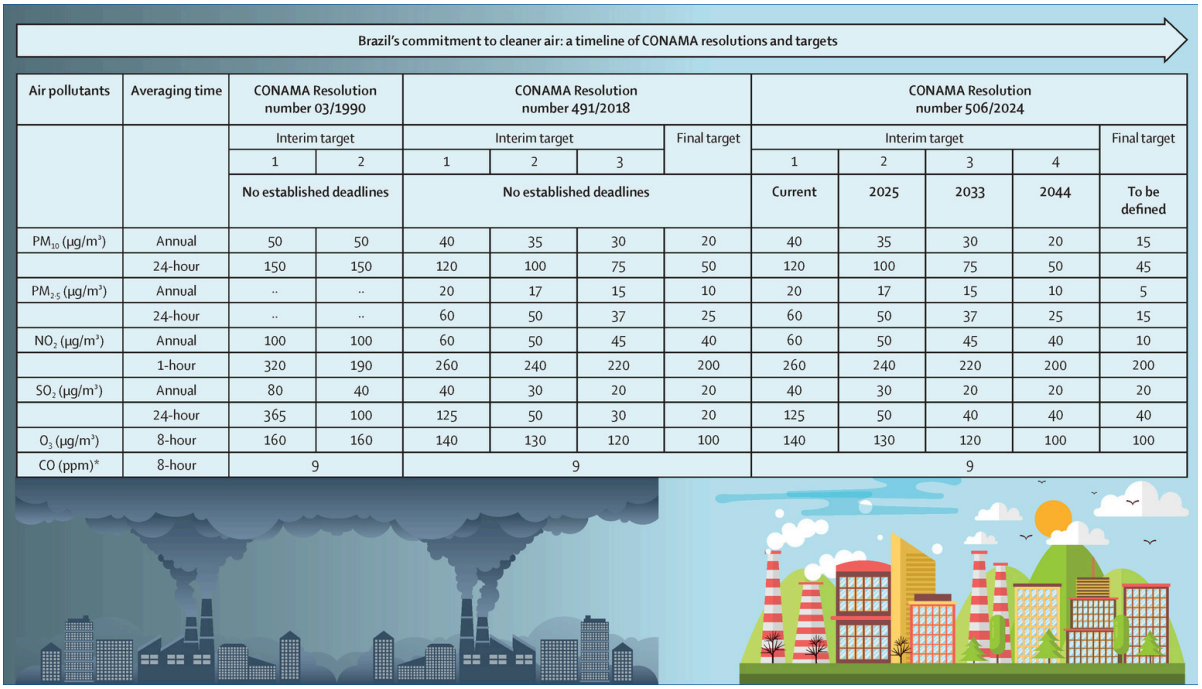
Article 1.3: "atmospheric pollutant: any form of matter in quantity, concentration, time or other characteristics that makes or may make the air unfit or harmful to health, inconvenient to public well-being, harmful to materials, fauna and flora or detrimental to safety, the use and enjoyment of property or the normal activities of the community"[111]

Article 4.1: "ensure the preservation of public health, well-being and environmental quality for present and future generations"[112]

Article 4.5: "propose and encourage the adoption, development and improvement of clean technologies, with a view to protecting health and improving air quality"[113]

Article 4.7: "ensure broad access to updated public data and information on air quality monitoring and management"[114]

Despite these efforts, David Tsai notes that the law is still "far from full compliance [and] explains that most states lack sufficient monitoring stations to produce reliable data."[115] It has yet to be seen whether the mandates and requirements of the law will be fulfilled. Enforcement and compliance remain key obstacles, as states and municipalities struggle to fully implement air quality policies due to legal and administrative challenges.[116]



Air pollutants	Averaging time	CONAMA Resolution number 03/1990		CONAMA Resolution number 491/2018				CONAMA Resolution number 506/2024				
		Interim target		Interim target			Final target	Interim target				Final target
		1	2	1	2	3		1	2	3	4	
		No established deadlines		No established deadlines				Current	2025	2033	2044	To be defined
PM_{10} (µg/m³)	Annual	50	50	40	35	30	20	40	35	30	20	15
	24-hour	150	150	120	100	75	50	120	100	75	50	45
$PM_{2.5}$ (µg/m³)	Annual	..	..	20	17	15	10	20	17	15	10	5
	24-hour	..	..	60	50	37	25	60	50	37	25	15
NO_2 (µg/m³)	Annual	100	100	60	50	45	40	60	50	45	40	10
	1-hour	320	190	260	240	220	200	260	240	220	200	200
SO_2 (µg/m³)	Annual	80	40	40	30	20	20	40	30	20	20	20
	24-hour	365	100	125	50	30	20	125	50	40	40	40
O_3 (µg/m³)	8-hour	160	160	140	130	120	100	140	130	120	100	100
CO (ppm)*	8-hour	9		9				9				

Figure 3 Evolution of Brazil's Air Quality Standards[117]

Worth also noting is CONAMA who is responsible for setting air quality monitoring standards for the states. Figure #3, displays the evolution of air quality standards in Brazil. In July 2024, The CONAMA Resolution No. 506/2024 passed.[118] This resolution sets deadlines for improving air quality in stages. The first goal will be in place until the end of 2024, with the next steps planned for 2025, 2033, and 2044.[119] The final goal follows the 2021 WHO guidelines.[120]

While these efforts are a step in the right direction, there is still room for improvement. Since 2044 is 19 years away, new WHO guidelines will likely be introduced before then. Tavella, "coordinator of the Working Group on Air Pollution," and Flavio Manoel Rodrigues da Silva Júnior, "president of the Brazilian Society of Ecotoxicology," believe that new WHO guidelines will make the current targets outdated.[121] Although the final air quality goal seems strong and ambitious, the long wait to reach these goals is concerning.[122] Ideally, Brazil should aim for faster progress to become a leader in air quality standards.

Another aspect of the Resolution requires the MMA and local environmental agencies to "update and publish the Technical Guide for Monitoring and Evaluating Air Quality within 18 months of the Resolution" taking effect.[123] "The guide will contain, among other points, the systematization of the calculation of the Air Quality Index (IQAr in Portuguese), which will be the value used for communicating the concentrations of monitored pollutants to the population."[124] This IQAr will be available to the public in real time.[125] IQAr has yet to be established, but the MMA and local agencies still have time before they exceed the 18 month deadline.

Beyond the air-quality related sources that are being addressed in PNQAr, Helen Sousa, a researcher at IEMA, has voiced concern regarding industry licensing.[126] Sousa states that "air quality is not properly assessed or considered during the licensing process for new industries. It's often not taken into account that the area may already be saturated with high concentrations of pollutants."[127] Licensing issues coupled with a lack of monitoring could exacerbate air quality issues until PNQAr mandates are truly implemented.

It is important to briefly discuss the legal aspects of RenovaBio, Brazil's ethanol policy, and its implementation timeline relative to other environmental policies. The approval times for ethanol laws in Brazil have varied, but RenovaBio was notably fast, taking only 28 days of legislative processing.[128] Lazaro and Thomaz share that the speed with which RenovaBio was approved, "can bring into question the effectiveness of the civil society and private sector participation."[129] Small time frames like this can limit the scope of stakeholder participation. It was identified in this stakeholder study that during RenovaBio's formulation there was a "lack of participation by other stakeholders such as environmental NGOs or representatives of other sectors even

though the impact of the policies regarding production and use of bioenergy may occur in a context where water scarcity, soil degradation and food security are relevant issues."[130] In addition to these environmental issues, it can be inferred that the true extent of air quality issues was also not considered.

STAKEHOLDER ANALYSIS

A structured stakeholder analysis was used to identify and evaluate the roles, interests, and influence of key actors in Brazil's air quality, biofuel, and electrification landscape. Information was gathered from interviews, policy documents, and existing research to map stakeholder priorities and alignments. Although EDF has already collaborated with the Ministry of Environment and Climate Change (MMA), Rio de Janeiro's Municipal Secretariat of Environment, and the São Paulo State Environmental Agency (CETESB) to enhance air quality and implement Air Tracker, EDF's tool that consolidates publicly available air quality data into a single interface for communities, a stakeholder analysis was still conducted.[131] This analysis aimed to highlight the significance of these partnerships while identifying opportunities for EDF to expand discussions and establish new collaborations.

The analysis below was split into the following categories: Key stakeholders and Primary and Secondary stakeholders. A summary table of the stakeholders can be found in appendix E.

KEY STAKEHOLDERS

The Ministry of the Environment and Climate Change & CONAMA

EDF's current collaboration with the MMA has brought exciting advancements to air quality monitoring the states of Rio de Janeiro and São Paulo through their Air Tracker implementation. In addition to expanding the Air Tracker projects, EDF has assisted the MMA in refining Brazil's air quality management strategy to align the country's standards with the WHO guidelines.[132] This collaboration is part of EDF's regional initiative with the United Nations Environment Program (UNEP) to promote clean air efforts across Latin America and the Caribbean (LAC).[133]

Continued partnership with MMA is essential for EDF to continue working to improve air quality in Latin America. In a report on the State of Global Air Quality Funding, Adalberto Maluf, the National Secretary of Urban Environment and Environmental

Quality at MMA, shared that Brazil has recently set new timelines to meet the World Health Organization's air quality standards.[134] Brazil's efforts to reduce air pollution are key to fostering a stronger economy, improving public health, achieving better social outcomes, and promoting more sustainable growth.[135]

The MMA plays a key role in implementing and coordinating national environmental policies influenced by PNQAr. In addition to PNQAr, the MMA is part of collaborative efforts like the VigiAr Panel, working with the Ministry of Health to monitor air pollution and its health effects.[136]

The MMA, specifically CONAMA within the ministry, is responsible for setting air quality monitoring standards for the states. EDF can collaborate with CONAMA to assess whether states are meeting targets using existing monitors, push for expanding air quality monitoring, advocate for stronger policies and monitoring requirements when new WHO guidelines are introduced, and support data analysis and recommended actions once the Air Quality Index is in place. EDF can potentially work with the MMA to increase public awareness of the health impacts of air pollution and the role of different emission sources.

State Environmental Agencies (CETESB, etc.) & State Secretariats for the Environment (e.g., SMAC, SEMAD, SEMA, SIMA)

State-level agencies and secretariats play an essential role in implementing and enforcing air quality policies. Organizations like CETESB monitor air pollution, manage pollution control programs, and enforce environmental licensing at the state level.[137] These agencies have high power within their jurisdictions and are crucial in ensuring that air quality regulations are followed effectively.[138] They possess scientific and technical expertise in air quality monitoring, pollution control, and environmental management—provided the state prioritizes and invests in air quality monitoring. As highlighted in the PESTLE analysis above, many "states lack sufficient monitoring stations to produce reliable air quality data."[139]

EDF has partnered with Rio de Janeiro's Municipal Secretariat of Environment (SMAC) and São Paulo's State Environmental Agency (CETESB) to implement Air Tracker and focus on air quality improvements in their states.[140] With PNQAr established into law, these state agencies and secretariats will have high interest in implementation and regulation because they are directly responsible for achieving air quality goals and

maintaining environmental standards.[141] EDF has the opportunity to take their findings from AirTracker, such as pollution hotspots, to not only continue to help with regulation enforcement, but to also increase public awareness of emission issues through promotional campaigns.[142]

With these partnerships already demonstrating significant progress and PNQAr inspiring other states to enhance their air quality monitoring and assessments, EDF can further strengthen monitoring networks. In addition to expanding and improving air quality monitoring systems, EDF can focus on identifying and prioritizing critical areas in need of air quality improvements across the country.

Ministry of Mines (MME), National Agency of Petroleum, Natural Gas, and Biofuels (ANP) and The Brazilian Sugarcane Industry Association (UNICA).

Since ethanol is a key focus of this research, analyzing stakeholders in the ethanol industry was considered significant in understanding Brazil's air quality policies, as well as related policies, such as EV implementation. These efforts could ultimately contribute to EDF's strategy in understanding and addressing emissions concerns.

The MME is responsible for overseeing the energy sector, including biofuel policies such as RenovaBio, and ensuring energy security.[143] Ethanol policies are seen to achieve energy security and reduce reliance on oil imports.[144] The National Agency of Petroleum, Natural Gas, and Biofuels (ANP), regulates and certifies biofuel production, including the criteria, procedures, suspension and renewal of the Certificate of Efficient Production of Biofuels.[145,146] The ANP is also responsible for defining mandatory individual targets for reducing greenhouse gas emissions for fuel distributors.[147] In order to fund research for knowledge development, the ANP ensure the availability of funds for R&D projects in companies in the energy sector by collecting one percent of "oil and gas exploration companies' revenues."[148]

The Brazilian Sugarcane Industry Association (UNICA) "is the representative body of a wide group of companies that produce sugar, ethanol and bioelectricity in the Center-South region of Brazil."[149] UNICA has positioned itself as a strong advocate for ethanol as a sustainable fuel, with a primary focus on GHG emissions reductions.[150] Their efforts have been instrumental in demonstrating the environmental benefits of sugarcane

ethanol, particularly in comparison to gasoline.[151] In its engagement with the U.S. Environmental Protection Agency (EPA), UNICA has provided substantial scientifically credible evidence supporting the claim that sugarcane ethanol reduces GHG emissions by 73-82% compared to gasoline.[152] This substantial reduction, which includes considerations of indirect emissions, has reinforced the competitive advantage of Brazilian ethanol in global markets.[153] However, while UNICA has made significant strides in addressing GHG emissions, its focus has not been as prominent in other air quality aspects of ethanol production and usage. The emphasis has largely remained on carbon footprint reduction rather than broader environmental considerations such as PM emissions, ozone formation, or other pollutants associated with ethanol combustion and production.

MME, ANP, and UNICA have significant power in influencing policies related to the ethanol industry due to their strong relationships with policymakers, technical expertise, and economic importance. EDF can focus on fostering collaboration between these stakeholders and environmental agencies, researchers, and other stakeholders to develop integrated solutions that address both climate change and air pollution.

PRIMARY & SECONDARY STAKEHOLDERS

Academic and Research Institutions

Universities such as the University of São Paulo, UNICAMP, and the Federal University of Rio de Janeiro contribute significantly to advancing knowledge on air quality and ethanol's environmental impact. These institutions provide scientific data and collaborate with government and industry, influencing policy decisions. While they hold moderate power, their high interest in scientific research makes them key contributors to evidence-based policymaking.

Highlighted in the United Nations Technology Executive Committees report on Bioethanol activities in Brazil, the ethanol Technology Innovation System (TIS) in Brazil brought together multiple stakeholders, which includes Universities. TIS emerged from a prolonged interaction between grassroots experimentation efforts and top-down government policies in the ethanol industry.[154] Universities that have been a part of TIS include UNICAMP, Federal University of Rio de Janeiro, and the University of Brasilia. Because of TIS "different ethanol technologies have been developed and supported, with priorities changing on the basis of available knowledge and evolving societal

concerns related to, for example, deforestation, GHG emission reduction in the transport sector, food security and municipal governance impacts."[155]

Beyond TIS and ethanol related research, universities also conduct research on air quality. Academic and research institutions in Brazil possess skilled researchers and scientific knowledge, some of which are highlighted in interviews that were conducted for this study or found in literature.

Beyond what universities are already doing, the new PNQAr policy contains a provision in article 4.3 that states that one of the policy's objectives is to "promote scientific research applied to technology and innovation."[156] EDF should continue to engage and seek new relationships with academic stakeholders. EDF can work jointly with researchers to investigate the impacts of ethanol policies on air quality, especially regarding ozone formation and VOCs. In a later section of this paper, a preliminary analysis of air quality related gaps in current LCA of sugarcane-based ethanol is provided. Information like this, obtained or researched by EDF, can be valuable for co-designing research projects at the university level in Brazil.

Flex-Fuel Vehicle (FFV) Owners & General Public

FFV owners benefit from being able to choose between ethanol and gasoline based on price, taking advantage of cheaper fuel options.[157] In an interview with Carlos Lacava, Manager of the Mobile Emission Sources Department at CETESB, FFV owners may be influenced by the perception that ethanol is more environmentally friendly than gasoline, though this perception may not be fully accurate when considering ozone formation.[158] As residents of urban areas, they are directly impacted by air quality, with vehicle emissions being a major contributor to air pollution. Changes in policies related to ethanol blends, fuel subsidies, and emission standards can directly affect FFV owners. FFV owners collectively influence fuel demand through their purchasing decisions, impacting the ethanol and gasoline markets.[159]

Both FFV owners and the Brazilian public are directly affected by air pollution. Air pollution directly impacts public health, leading to premature deaths and increased healthcare costs.[160] While individuals may have limited power, public support can drive the adoption and enforcement of stricter air quality regulations that are seen in the PNQAr provisions (See Legal section of PESTEL Analysis).[161] As noted in multiple

interviews and media articles, without sufficient awareness, the general public remains unaware of the risks they face daily.[162] This lack of awareness prevents them from taking preventive measures or demanding policy changes to ensure they have clean air to breathe. As Tsai notes, air quality is an "invisible issue."[163]

Effective public communication is essential to increase awareness and engagement. Providing clear and accessible information about air quality issues, risks, and preventive measures can empower the public to demand stronger policies. EDF's support for tools like Air Tracker can play a crucial role in disseminating information and enabling citizen monitoring. Addressing the social challenge of limited awareness and knowledge is critical for EDF's work to succeed. By fostering a more informed and engaged public, EDF can help drive both awareness and policy change, leading to more effective air quality policies and a healthier environment in Brazil.

Environmental NGOs and International Organizations

Nonprofits such as the International Council on Clean Transportation (ICCT) and the World Resources Institute (WRI) advocate for stricter environmental regulations and sustainable practices. The Environmental Defense Fund has partnered with other international organizations, including the UNEP Climate & Clean Air Coalition. These organizations influence global environmental policies and collaborate with local stakeholders in Brazil. These groups have moderate power but high interest in promoting sustainable air quality initiatives.

Other partnerships to consider, if they have not already been established, are the Brazilian Society of Ecotoxicology (ECOTOX Brasil; Contact: Flavio Manoel Rodrigues da Silva Junior), the Working Group on Air Pollution (Grupo de Trabalho em Poluição do Ar; Contact: Ronan Adler Tavella), and The Institute for Energy and Environment (IEMA).[164] ECOTOX focuses on early detection and prevention of environmental pollution, promotes research and discussions on environmental issues, and collaborates with the government and congress to carry out studies and air in solutions to environmental issues.[165]

KEY TAKEAWAYS FROM STAKEHOLDER ANALYSIS

Brazil's air quality challenges and ethanol policies involve a complex network of stakeholders with varying degrees of power and interest. Government agencies play

a crucial role in setting and enforcing regulations, while industry groups and researchers contribute expertise and economic influence. The interplay between these stakeholders determines the effectiveness of air quality policies and the sustainable future of Brazil's ethanol sector. Moving forward, collaboration among government, industry, and research institutions will be essential to balancing economic growth, energy security, and environmental sustainability.

LIFE CYCLE ASSESSMENT RESULTS & ANALYSIS

LCA is a well-established method for analyzing the environmental effects of a product or service across part or all of its life cycle.[166] LCAs help pinpoint which stages of a product's life cycle contribute most to its environmental footprint.[167] LCAs can be used to enable "vehicle designers and manufacturers, fuel producers and distributors, as well as, policy makers, to make informed decisions regarding the environmental consequences in the entire production and supply chain."[168] LCAs can be helpful in assessing and improving air quality, specifically through the selection of air-quality related impact categories. Impact categories are the different environmental effects considered when evaluating a product's life cycle.[169] Some examples of impact categories used are "global warming potential (GWP), cumulative energy demand (CED), eutrophication, acidification, photochemical ozone creation potential, ozone depletion potential, human toxicity potential, ecotoxicity potential, land use and water use."[170] A complete list of impact categories and their definitions used in the study is provided in Appendix G.

CURRENT RESEARCH & GAPS

This analysis was done for EDF to find gaps in current literature on the LCA of sugarcane-based ethanol in Brazil. By having a baseline understanding of what LCA studies in this area look like, EDF can conduct their own LCA study, investigating air quality impact categories more thoroughly. A total of fourteen studies related to this process in Brazil were analyzed in NVivo, a qualitative software program. Appendix F and H contain a list of the selected literature/authors, the coding schema that was developed to examine these studies, and additional NVivo results.

The NVivo LCA Analysis has helped answer the following questions:

From an LCA perspective, what impact categories, endpoint indicators, and assessment measures are absent or lacking in these sources regarding air quality, emissions, and ground-level ozone in sugarcane LCAs?

Were impact categories and assessment measures related to PM2.5, ground-level ozone, NOx, VOCs, etc., analyzed? If so, to what extent?

DATA SOURCES IN LIFE CYCLE ASSESSMENT OF BIOFUELS

The accuracy and reliability of LCA results are highly dependent on the quality and representativeness of the data used, however they can be used for fair comparisons between products or help identify environmental hotspots.[171] This section details the diverse range of data sources employed in LCA studies of biofuels, with a particular emphasis on those utilized in the assessment of sugarcane ethanol production in Brazil.

In eight studies, primary data was referenced to be used. Primary data is often gathered directly from the studied systems, such as agricultural fields, industrial facilities, and transportation processes. Although many studies referenced primary data to be a part of their methodology, it is important to note that due to the complexity and resource-intensive nature of primary data collection, it was seen that LCA practitioners frequently rely on secondary data sources to supplement or, in some cases, replace primary data. These secondary sources provide valuable information on various aspects of the life cycle, including:

Several databases and models are frequently cited in the sources as valuable sources of secondary data for LCA. Literature, experimental lab data, and other public documents were also used for secondary data.

Based on the sources, the following secondary sources and types were used:

- **Databases:**
  - Ecoinvent. Versions used include v2.2
  - European Reference Life Cycle Database (ELCD)
  - Economic Input-Output-Based Life-Cycle Assessment (EIO-LCA)
  - Agri-footprint
  - OpenLCA nexus database

- **Models & Software:**
  - SimaPro. Versions used include 7, 7.0.1, and 7.3
  - GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model)
  - AspenPlus™
  - OpenLCA®
- **Reports & Statistics:**
  - IPCC (Intergovernmental Panel on Climate Change)
  - FAOSTAT (Food and Agriculture Organization of the United Nations)
  - International Fertilizer Association (IFA) statistics
- **Literature:**
  - Published documents (books, papers, manuals, other databases, etc.)
- **Other**
  - Emission factors from various sources
  - Simulated data through software
  - Estimates based on scientific articles
  - Lab results
  - Industry and agriculture activities

The selection of appropriate secondary data sources is a critical step in LCA, as it directly impacts the accuracy and reliability of the results.[172] Researchers should carefully evaluate the data quality, representativeness, and geographic and temporal relevance of secondary data before incorporating it into their LCA models. In cases where significant data gaps or uncertainties exist, sensitivity analyses should be conducted to assess the potential influence on the LCA outcomes.

RELATIVE FREQUENCY OF IMPACT CATEGORIES RELATING TO AIR QUALITY

LCA can be an important tool for evaluating the environmental impacts of biofuel production. However, a review of the literature reveals that certain air quality-related impact categories receive less attention than others. This analysis highlights the relative scarcity of studies focusing on specific air quality impacts, particularly those related to ground-level ozone formation and respiratory health. Figure 4 illustrates the frequency with which these impact categories appeared in sugarcane ethanol-related studies.

Figure 4: Impact Category Type & Hierarchy of Number of Times Referenced in Studies

While Global Warming Potential (GWP), Eutrophication, and Land Use (LU) are frequently assessed, other air quality-related impact categories appear less often in the reviewed studies. Based on a qualitative analysis in Nvivo, the number of uses of different air quality related impact categories includes:

- **Photochemical Ozone Formation (POCP):** Used in 5 sources
- **Ozone Layer Depletion Potential (ODP):** Used in 5 sources
- **Acidification:** Used in 6 sources
- **Human Toxicity:** Used in 6 sources
- **Particulate Matter:** Used in 1 source

The observed differences in the number of studies that consider each impact category could be attributed to several factors, including data availability, methodological challenges, and regional priorities.

The observed differences in the number of studies that consider each impact category could be attributed to several factors, including data availability, methodological challenges, and regional priorities.

DISCREPANCIES IN OZONE IMPACT CATEGORIES

It is important to distinguish between ozone layer depletion (ODP) and photochemical ozone formation (POCP), since they address distinct environmental problems. ODP measures the degradation of the stratospheric ozone layer, which protects Earth and humans from damaging ultraviolet (UV) radiation.[173] POCP, on the other hand, relates to the formation of ground-level ozone (smog) through reactions between nitrogen oxides (NOx), VOCs, and sunlight.[174] While both involve ozone, they have vastly different environmental and health consequences.

Several studies highlight the importance of VOCs and NOx in photochemical ozone creation.[175] Although not all studies focused on this impact category, those that did found that ethanol production significantly contributes to photochemical ozone formation.[176]

UNDER-REPRESENTATION OF PARTICULATE MATTER

The limited number of studies addressing PM specifically PM2.5, is a significant gap, given the well-established link between PM exposure and respiratory illness.[177] It is important for Brazil to have a national tracking system for PM2.5 to establish baseline emissions and identify strategies for further reductions. Increased attention to PM emissions from biofuel production and use is essential for a comprehensive assessment of air quality impacts.

REGIONAL SPECIFICITY

Many LCA studies rely on generic or international datasets, which may not accurately reflect the specific conditions in Brazil. Emission factors, agricultural practices, and energy mixes vary regionally, impacting air quality outcomes.

IMPLICATIONS FOR POLICY AND RESEARCH

The unequal consideration of air quality impact categories in LCA studies of biofuels has implications for both policy and future research. Policymakers need comprehensive

LCA data to make informed decisions about biofuel policies. The under-representation of certain air quality impacts may lead to an incomplete understanding of the trade-offs associated with different biofuel pathways. LCAs should strive for a more holistic assessment of environmental impacts, including a broader range of air quality indicators. This may involve incorporating more detailed emission inventories, improved characterization factors, and spatially resolved modeling to capture regional variations in air quality impacts. Further research is needed to address data gaps and methodological challenges in assessing air quality impacts, particularly those related to PM and ground-level ozone formation. This may involve primary data collection, development of region-specific emission factors, and refinement of impact assessment methods.

EV LITERATURE REVIEW & COMPARATIVE ANALYSIS

The electric vehicle (EV) market in Brazil faces a unique set of challenges and opportunities, influenced by governmental policies, a strong ethanol industry, and specific consumer perceptions. While the transition to EVs is seen globally as a sustainable way to decrease emissions, its progress in Brazil is complex. This analysis expands upon the introduction section, examining current challenges, policy influences, the impact of ethanol, and potential strategies for market growth, drawing upon recent research and data from a literature review.

EV IMPLEMENTATION IN BRAZIL

EV adoption in Brazil is still in an early stage.[178] As of January 2023, there were approximately 126,000 EVs compared to 60 million internal combustion engine vehicles (ICEVs), with new EV sales accounting for less than 2% of the total vehicle market.[179,180] ,While there are signs of market growth, with a projected CAGR of approximately 17% from 2022 to 2028, Brazil's share of the global EV market is quite small.[181] Despite current growth and projections, some automotive industry consultants believe large-scale production of EVs in Brazil is not expected due to industrial plants most likely being located in the USA, Europe, and China.[182]

Geographically, EV diffusion is mostly concentrated in Southeastern Brazil.[183] "This is consistent with economic aspects, since Southeastern region is responsible for around 70% of the industry's production and for more than 50% of the country's vehicle fleet."[184]

POLICIES RELATED TO ELECTRIC VEHICLES IN BRAZIL

While Brazil has made some progress with policies related to EVs, it still falls behind other countries in offering incentives to promote EV adoption.[185] Policies like Normative Resolution No. 819 in 2018, implemented by the Brazilian Electricity Regulatory Agency (ANEEL), have reduced uncertainties for entrepreneurs wishing to invest in recharging infrastructure, but a lack of consistent and substantial support remains a significant barrier.[186] Additionally, Brazil's National Traffic Council (CONTRAN) established Normative Resolution nº 749 in 2018.[187] This resolution outlined safety requirements for EVs in the country. Both resolutions bring greater security for Brazilian consumers.[188] In addition to resolutions established by ANEEL and CONTRAN, the Brazilian Federal Government in the past has created economic incentives exempting importation taxes for EVs in 2016, but this ended in 2024.[189] In January 2024, EV and HEV imports began being subject to a 10-15% tax, increasing to 35% by 2026.[190]

STRUGGLES AND BARRIERS TO EV ADOPTION IN BRAZIL

Lack of Public Policies and Incentives

A lack of broad and specific federal policies encouraging EVs is a major barrier to implementation in Brazil.[191] In a 2019 study by Rietmann and Lieven, they "indicated that Brazil was the least successful case in EV acceptance" among 20 countries analyzed regarding the impact of government incentives and charging infrastructure.[192] According to Ruoso et al., "reduced taxation on the purchase of EVs and parts, reduced motor-vehicle tax, special transit permits for EVs, facilities for implementation of charging stations, and reduced vehicular electricity tariffs" could significantly promote EV adoption in Brazil.[193] Beyond this, governmental actions at the municipal level, including regulatory changes and the electrification of public transportation fleets, can also drive demand and visibility for EVs. Establishing regulatory benchmarks for performance specifications and sales quotas can further stimulate the local EV industry.[194]

Government policies aimed at expanding charging infrastructure, as seen in markets like China and the Netherlands, highlight the potential for similar initiatives in Brazil.[195] Even within Latin America, countries like Colombia, Panama, and Ecuador have clearer plans for vehicle electrification than Brazil.[196] Argentina and Mexico, with stronger automotive industries, are also taking significant steps in electrification, while Brazil's direction is less certain.[197]

High Cost and Limited Charging Infrastructure

High initial costs are a significant barrier, driven by substantial taxes and a lack of economies of scale.[198] The expensive price point makes EVs inaccessible to a large segment of the population, hindering broader adoption.[199] The limited availability of charging infrastructure contributes to range anxiety, discouraging potential buyers who fear being stranded without a charging point.[200,201] The absence of a robust national incentive plan exacerbates these challenges, leaving the EV market without the necessary support to overcome these initial hurdles.[202]

Consumer Awareness and Perception

Public awareness campaigns are essential for addressing consumer anxieties and misconceptions about EVs.[203] For EV adoption in Brazil, a key social aspect is changing consumer behavior and perceptions regarding EV limitations, particularly range anxiety and charging infrastructure concerns. Ruoso et al. explains that consumers "are skeptical before their first experience, reluctant because of the inability to drive long distances, and uncomfortable with the limited charging options."[204] To help facilitate this transition, awareness campaigns highlighting EV benefits and the importance of decarbonization are crucial. Government policies should provide incentives and recognition programs while conducting consumer surveys to identify barriers.[205] The vehicular industry should also enhance visibility of existing charging infrastructure and promote hands-on experiences through test drives, carsharing, taxi fleets, and educational programs.[206] Ruoso et al. suggest that policymakers in Brazil should prioritize consumer education over extensive public charging networks to accelerate adoption.[207]

Beyond these points, the price consumers pay for ethanol also influences their consumer behavior habits. The consumer's choice between fuels or vehicle type is also likely influenced by their relative prices and perceived benefits. Ethanol's more affordable price relative to gasoline is a significant factor for consumers. According to the president of Unica (Sugarcane and Bioenergy Industry Union), Evandro Gussi, unlike electric cars, the ethanol network is already established and delivers decarbonization without cost to Brazilian society, implying that its price to consumers is already integrated within the existing system.[208] Changing consumer habits may present difficulties considering these factors.

Competition with Biofuels

Some argue that low implementation of EVs and EV policies in Brazil are tied to

government hesitancy because of the high dependence on the fuel sector and the consolidated production and distribution infrastructure for ethanol.[209]

HYBRID VEHCILES VS. FULL EV IMPLEMENTAION IN BRAZIL

Currently, HEVs, especially flex-fuel HEVs, hold a larger share of the "electrified" vehicle market in Brazil compared to pure BEVs.[210] In 2022, pure BEVs represented only about 0.4% of total light vehicle sales in the domestic market, while HEVs had a significant share.[211] Flex-fuel HEVs, which can run on both ethanol and electricity, accounted for 48% of the Brazilian EV market in 2022.[212] This prevalence can be attributed to several factors:

Using Existing Infrastructure and Expertise: Brazil has a well-established infrastructure for the production and distribution of biofuels like ethanol.[213] Major automakers in Brazil, such as Toyota, Volkswagen, and Stellantis, are actively working on developing hybrid vehicles that combine ethanol and electrification, aiming to capitalize on this existing ecosystem.[214] Some believe that partial electrification through hybridization can "take advantage of the current production and business structure."[215]

Addressing Range Anxiety and Charging Infrastructure Limitations: As stated in the previous section, a major concern regarding full BEVs in Brazil is the lack of a widespread and reliable charging station network.[216] HEVs mitigate this concern as they are fueled at traditional gas stations and do not rely solely on charging infrastructure.[217] The batteries in these vehicles are charged by the internal combustion engine or through regenerative braking.[218]

Gradual Transition and Lower Technological Shift: For the Brazilian automotive industry, a move towards hybridization might represent a less radical transformation compared to a full-scale shift to BEV production.[219] It allows them to utilize their existing manufacturing capabilities and supply chains to a greater extent in the short term. Some experts argue that without government investment, the "transfer of knowledge for full EV technology may only occur after it is consolidated internationally."[220]

However, despite the current dominance of HEVs in the small EV market, it is important to compare the impacts of HEVs and BEVs.

Environmental Benefits Comparison: BEVs have the potential for significantly lower greenhouse gas (GHG) emissions, especially in Brazil where over 83% of the electricity matrix comes from renewable sources.[221] Studies indicate that even considering thermoelectric generation during water crises, "the CO2 emissions of EVs are at least 10 times lower than conventional vehicles (CVs)."[222] While HEVs using biofuels can also reduce emissions compared to gasoline-only vehicles, research suggests that flex PHEVs and HEVs have lower GHG emission mitigation potential than BEVs.[223]

The choice between prioritizing full EV implementation or focusing on hybrid technologies in Brazil is complex. Some argue that Brazil needs to decide whether to pursue full electrification, like many other adopting countries, or partial electrification via hybridization.[224] A total shift to electric power demands an overhaul of the entire supply chain, calling for funding in battery production, mining for essential materials, and retraining employees, all of which could disrupt conventional sectors.[225] Phasing in electrification may allow businesses to utilize existing infrastructure while capitalizing on Brazil's biofuel expertise.[226]

Ultimately, a successful strategy for sustainable mobility in Brazil likely involves a combination of approaches. Hybrid vehicles, particularly those utilizing Brazil's biofuel resources, can serve as a transitional solution, reducing emissions while the infrastructure and market for BEVs mature.[227] However, to achieve significant decarbonization in the long term and align with global trends, a clear federal policy supporting the adoption and production of full BEVs, along with investments in charging infrastructure and battery technology, will be essential.

RECOMMENDATIONS

Informed by the research findings and analysis of Brazil's air quality and urban mobility landscape, this section presents several key recommendations to address the intricate challenges at the nexus of decarbonization and air quality. These recommendations, derived from PESTLE analysis, stakeholder analysis, academic literature, expert interviews, and the analysis of LCA studies, aim to provide pathways for EDF to help Brazil mitigate air pollution while advancing its climate goals.

Strengthening stakeholder engagement and collaborative frameworks is paramount for effective policy implementation. It is recommended that EDF expand its collaborative work with a diverse range of stakeholders, including new local governments, automakers, environmental NGOs like IEMA and ICCT, and academia. Facilitating multi-stakeholder dialogues focused on air quality policy reforms can foster more comprehensive and widely accepted policy outcomes. EDF has already established collaborations with entities such as the MMA and CETESB. Building upon this foundation and engaging new stakeholders in the ethanol industry alongside environmental agencies and researchers can lead to integrated solutions addressing both climate change and air pollution.

Raising public awareness regarding air quality and clean transportation is crucial for garnering public support for policy changes. It is recommended to educate both policymakers and the public on the specific impacts of ethanol on ozone pollution and respiratory health, thereby addressing the common perception of ethanol as an inherently clean fuel. Public perception studies conducted by EDF on EV, consumer behavior, and otherscould help expand knowledge on barriers to EV implementation in the country. In addition to this, public engagement campaigns could also highlight the benefits of EV and HEV adoption and the direct link to improved air quality. Collaborating with organizations like the MMA and groups like Brazil's Working Group on Air Pollution to increase public understanding of the health consequences of air pollution and the contributions of various emission sources is also essential.

Advocating for more robust emissions regulations is a key step towards cleaner air. This includes pushing for updates to the PROCONVE program to incorporate stricter emission limits for ethanol-related pollutants such as VOCs, ozone, and PM2.5. Promoting transparent emissions reporting across the vehicle and biofuel production sectors will enhance accountability and facilitate more informed policymaking. As highlighted in the stakeholder analysis, government agencies like CONAMA play a crucial role in defining air quality standards. It is important for EDF to begin conversations with CONAMA to advocate for strong policies and monitoring frameworks that align with evolving scientific understanding, such as the introduction of new WHO guidelines. Furthermore, exploring the inclusion of evaporative emissions and VOC control measures within biofuel policies like RenovaBio is a critical consideration. Investigating and potentially advocating in regulating emissions from the ethanol production process itself, particularly concerning the use of bagasse, is also recommended.

Expanding air quality monitoring and research Initiatives is fundamental to establishing a comprehensive understanding of the current situation and the effectiveness of interventions. This necessitates supporting enhanced tracking of VOCs, NOx, and PM2.5, coupled with comprehensive LCAs to accurately evaluate the air quality impacts of ethanol.

Continued collaboration between federal and state level government agencies (MMA, CETESB) and universities is vital for improving data collection efforts. Leveraging tools like EDF's Air Tracker to extend monitoring beyond major urban centers is crucial, as air quality data remains limited in many regions of Brazil. Targeted monitoring and research should be supported to deepen the understanding of the health impacts associated with ethanol-related pollutants throughout the entire fuel lifecycle. Joint research endeavors between EDF and academic stakeholders to investigate the impacts of ethanol policies on air quality, especially concerning ozone formation and VOCs, should be prioritized. Increasing primary data collection from ethanol production and vehicle use is also necessary to refine emission estimates used in LCA studies and to better reflect local variations through expanded regional air quality monitoring.

Incorporating full spectrum air quality metrics in LCA Studies is essential for a holistic environmental assessment. It is recommended to ensure that ozone, PM2.5, and NOx emissions are consistently and thoroughly analyzed in ethanol-related LCAs, moving beyond a primary focus on greenhouse gas emissions. Current LCA studies show a gap in the analysis of these crucial air quality impact categories.

Aligning policy with a holistic environmental impact perspective is vital for sustainable development. Policies such as PROCONVE and RenovaBio should integrate air quality impacts as a central consideration, rather than solely focusing on CO_2 reductions. Encouraging multi-pollutant impact assessments in environmental policymaking will provide a more comprehensive understanding of the trade-offs between different fuel pathways.

EDF should play a role in raising public awareness regarding the benefits of EV and HEV adoption and their direct link to improved air quality. This includes educating both policymakers and the public on the advantages of cleaner transportation options. Furthermore, EDF should facilitate discussions and pilot projects exploring the integration of ethanol policies with EV promotion strategies, potentially considering hybrid ethanol-EV solutions as a transitional pathway.

This approach acknowledges Brazil's existing biofuel infrastructure while looking towards greater electrification. Expanding EDF's stakeholder outreach and engaging with the ethanol industry and the automotive sector to invest in hybrid ethanol-EV solutions could also be a means to bridge the transition to full electrification. Finally, public perception studies conducted by EDF on EV consumer behavior could help expand knowledge on barriers to EVimplementation in the country. Ultimately, a successful long-term approach likely involves a combination of strategies, with hybrid vehicles playing a significant role in the medium term while policies and infrastructure to support full Battery Electric Vehicle (BEV) adoption are further developed in Brazil.

IMPLEMENTATION PLAN

Phase 1: Foundation Building and Collaborative Frameworks

Formalize and Expand Stakeholder Engagement:

- Proactively maintain relationships and reach out to new key stakeholders identified in the stakeholder analysis, such as the Ministry of Environment and Climate Change (MMA), CONAMA, state environmental agencies (CETESB, etc.), automakers, and relevant NGOs (IEMA, ICCT).
- Organize initial multi-stakeholder workshops and dialogues focused on the air quality impacts of urban mobility, including ethanol and the potential of EV/HEV adoption. These dialogues can aim to identify common goals and areas for collaboration.
- Establish Memorandums of Understanding (MOUs) with key government agencies and universities to formalize collaborative efforts on air quality monitoring and policy development, building on existing partnerships.
- Engage with the ethanol industry (UNICA, ANP, MME) to discuss pathways for cleaner ethanol production and potential integration with FFHEV strategies.
- Foster relationships with new academic institutions (Federal, state, and private) to co-design research projects focusing on air quality impacts and solutions.

Enhance Public Awareness Initiatives:

- Develop targeted educational materials for policymakers and the public on the health impacts of air pollution, specifically addressing the nuances of ethanol's contribution to ozone formation despite its lower carbon emissions.
- Collaborate with media outlets and social media platforms to launch public awareness campaigns highlighting the benefits of clean transportation options, including EVs & HEVs, and the importance of demanding stronger air quality policies.

- Support initiatives led by organizations like the MMA to disseminate information on air quality using tools like the VigiAr Panel and EDFs Air Tracker.

Phase 2: Evidence Generation and Policy Advocacy

Continue to Expand Air Quality Monitoring and Research:

- Continue and expand collaboration with federal, state, and local government agencies to expand the coverage of air quality monitoring networks, particularly in regions currently lacking sufficient data, potentially leveraging EDF's Air Tracker tool.
- Support research initiatives focused on improving VOC, NOx, and PM2.5 tracking related to ethanol production and use, including primary data collection from ethanol vehicles.
- Fund and conduct comprehensive LCA studies of ethanol that fully incorporate ozone, PM2.5, and NOx emissions, ensuring regional specificity and utilizing robust data sources.
- Investigate emissions from ethanol production processes, particularly the use of bagasse, and assess the feasibility of incorporating emission standards at the production level.
- Work with researchers to model the potential air quality impacts of different ethanol blend levels (e.g., increase to E30) to inform future policy decisions.

Advocate for Stronger Emissions Regulations:

- Present research findings and LCA results to policymakers to advocate for stricter ethanol emissions limits (VOCs, ozone, PM2.5) in PROCONVE updates.
- Push for policies that mandate transparent emissions reporting for vehicles and biofuel production.
- Engage with CONAMA to advocate for the incorporation of more stringent air quality standards aligned with WHO guidelines into national regulations.
- Explore avenues to include the control of evaporative emissions and VOCs within biofuel policies like RenovaBio.
- Advocate for the effective enforcement of existing and new air quality regulations (PNQAr), addressing legal and administrative challenges at the state and municipal levels.

Phase 3: Policy Integration and Sustainable Solutions

Promote Holistic Policy Alignment:

- Work with policymakers to ensure that PROCONVE and RenovaBio policies fully integrate air quality impacts alongside carbon dioxide reduction goals.
- Advocate for the adoption of multi-pollutant impact assessments in environmental policymaking related to the transportation sector.
- Facilitate discussions and pilot projects exploring the integration of ethanol policies with EV promotion strategies, potentially considering hybrid ethanol-EV solutions as a transitional pathway.

Support Long-Term Monitoring and Evaluation:

- Continue to support and expand air quality monitoring efforts to track progress and the effectiveness of implemented policies.
- Regularly evaluate the air quality impacts of ethanol use and EV adoption based on monitoring data and updated research.
- Foster ongoing dialogue and collaboration among stakeholders to adapt policies and strategies as needed to achieve long-term decarbonization and clean air goals.

CONCLUSION

Drawing upon the research and analysis presented, this paper concludes that while ethanol has played a significant role in Brazil's energy independence and greenhouse gas emissions reduction efforts, its widespread use presents notable air quality challenges, particularly concerning the formation of tropospheric ozone. The study highlights that despite the lower carbon footprint of ethanol compared to fossil fuels, its VOC emissions contribute to ozone formation, an impact often under examined in policy decisions. Furthermore, the analysis of LCA studies reveals significant gaps in the comprehensive evaluation of air quality impacts, with many studies underrepresenting or omitting key pollutants like PM2.5, NOx, and VOCs. The heavy reliance on secondary data in many LCAs further underscores the need for more regionally specific primary data collection to accurately assess these impacts.

The research also underscores the complex interplay of political, economic, social, technological, environmental, and legal factors influencing Brazil's urban mobility

landscape. The strong historical and political support for ethanol, exemplified by programs like Proálcool and RenovaBio, has contributed to a slower adoption of EVs compared to other regions. However, the recent enactment of the National Air Quality Policy (PNQAr) signals a potential shift towards greater attention to air quality management.

To address the identified challenges and move towards cleaner air and reduced emissions in Brazil's urban mobility sector, a holistic approach that integrates both climate and air quality considerations in policymaking is essential

EDF is uniquely positioned to play a crucial role in facilitating this transition. Building upon its existing collaborations with the MMA and state environmental agencies through initiatives like Air Tracker, as well as fostering new stakeholder relationships can help EDF continue to support the expansion and enhancement of air quality monitoring networks across Brazil.

Ultimately, Brazil's path towards sustainable urban mobility requires a nuanced strategy that acknowledges the complexities of its energy landscape. While ethanol will likely continue to be a significant part of the energy mix, a greater emphasis on integrating air quality considerations into biofuel policies and actively promoting the adoption of EVs is crucial for achieving both climate goals and cleaner, healthier urban environments for the Brazilian people. EDF's continued engagement and strategic interventions can be instrumental in guiding Brazil towards this more sustainable future.

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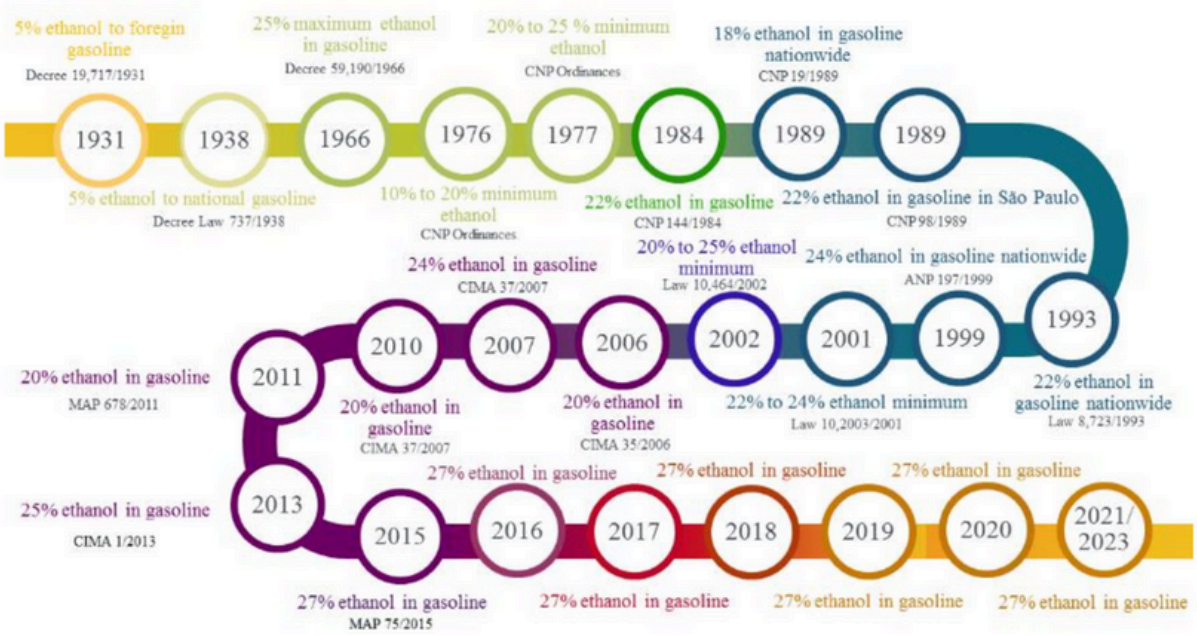
APPENDICES

APPENDIX A:

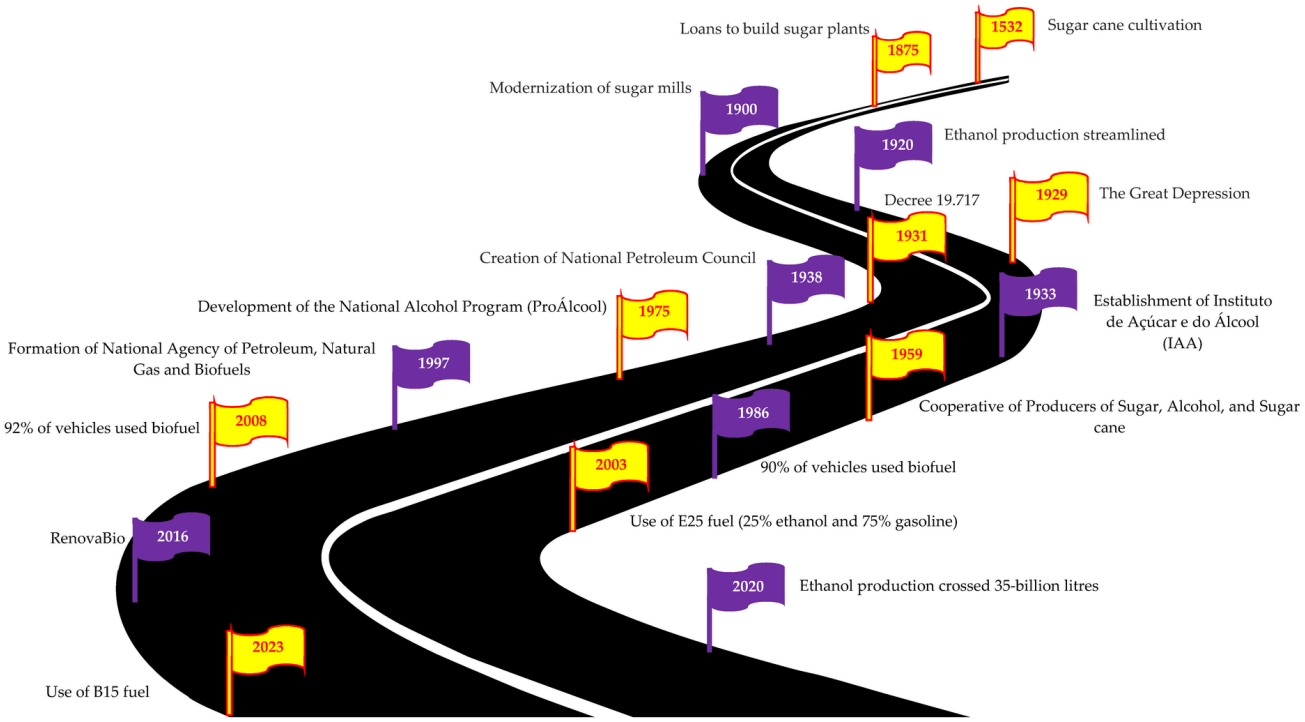
Historical ethanol blending mandate in Brazil



Source: Assessment of successes and lessons learned for biofuels deployment [228]

APPENDIX B:

Historical trajectory curve of major biofuel policies and developments in Brazil



Source: Historical Analysis of the Role of Governance Systems in the Sustainable Development of Biofuels in Brazil and the United States of America (USA)[229]

APPENDIX C:

Interviewee & Expert Profiles/Information Referenced in the Paper

Name	Affiliates With	Source
Elliot Campbell	University of California, Merced	Email Interview
Fatima Andrade	University of São Paulo	Interview in Portuguese
Carlos Ibsen Viana Lacava	CETESB	Email Interview in Portuguese
Marcos Rangel	Duke University	Interview
Lucia Guardani	CETESB	Interview in Portuguese
Paulo Saldiva	University of São Paulo Medical School;Harvard's Public Health Scientific Committee;WHO Air Quality Committee; Council member for the city of São Paulo	Media Article Interview
Flavio Manoel Rodrigues da Silva Junior	President of ECOTOX BRASIL	Literature
Ronan Adler Tavella	Coordinator of the Air Pollution Working Group	Literature
David Tsai	Instituto de Energia e Meio AmbientelEMA	Media Article Interview

Expert Interview Questions and Interview Summary

Below is a list of interview questions for each conducted interview as well as a summary. The questions include both pre-prepared ones and those formulated during the interview to enhance understanding or seek clarification.

PROFESSOR FATIMA ANDRADE INTERVIEW

About: Maria de Fátima Andrade is a physicist and a full professor at the Institute of Astronomy, Geophysics, and Atmospheric Sciences at USP. She is a member of the Brazilian Academy of Sciences and conducts research in air pollution. Professor Andrade has worked on WRI Brazil papers relating to air quality.

Professor Andrade had highlighted findings from a long-term study on ozone formation, emphasizing ethanol's high potential for ozone creation. We discussed challenges such as economic barriers to implementing air quality policies and the limited capacity for monitoring air pollution effectively. The conversation had also touched on the critical need to control evaporative emissions from gas stations and vehicles, the potential health implications of higher ethanol blends, and the importance of crafting air quality regulations that addressed both climate and public health concerns comprehensively.

High level summary

Discussion on Ozone Formation and Ethanol

- Professor Andrade discussed her long-term research on ozone formation and the role of VOCs.
- Professor Andrade explained the challenges in maintaining detailed emissions inventories and the importance of ambient experiments to analyze VOCs.
- Professor Andrade highlighted the high ozone potential of ethanol compared to gasoline, contributing to stagnant ozone levels.
- Professor Andrade noted the decrease in primary pollutants like CO2 and NOx despite stable PM2.5 and Ozone levels.

Collaboration with Environmental Agencies

- Professor Andrade described informal and formal collaborations with environmental agencies on ozone studies and air quality monitoring.
- Professor Andrade mentioned the federal level's role in establishing air quality standards and the need for state-level monitoring.
- Professor Andrade emphasized the importance of including air quality monitoring in federal policies to address health and climate concerns.
- Professor Andrade highlighted the challenges in implementing air quality standards due to economic and technological constraints.

Policy Implementation and Economic Challenges

- Professor Andrade attributed delays in PRONAR implementation to economic factors and political influence.
- Professor Andrade provided examples of delayed regulations, such as the sulfur content in diesel and the transition to electric buses in São Paulo
- Professor Andrade discussed the economic challenges faced by the environmental sector in implementing regulations.

Air Quality Monitoring and Federal Funding

- Professor Andrade explained the responsibility of states in establishing air quality monitoring stations and the challenges in securing funding.
- Professor Andrade mentioned the use of local sensors and the need for reference air quality stations in regions like the Amazon.
- Professor Andrade highlighted the lack of dialogue and funding as barriers to implementing air quality monitoring.

Emissions from Ethanol Production

- Professor Andrade discussed the use of bagasse in ethanol production and its potential as a source of pollution.
- Professor Andrade noted the lack of studies on pollutant emissions from ethanol production compared to CO2 emissions.
- Professor Andrade suggested that the use of bagasse should be regulated to control pollutant emissions.
- Balancing Climate and Air Quality Policies
- Professor Andrade emphasized the need for air quality monitoring in urban areas to address health issues.

- Professor Andrade mentioned ongoing efforts to measure CO2 emissions in São Paulo and the challenges in attributing local emissions to CO2 levels.
- Professor Andrade discussed the benefits of transitioning to cleaner energy sources like electric buses for improving air quality.
- Ethanol Blend Policies and Public Health
- Professor Andrade explained that policies focus on economic aspects rather than air quality, ignoring potential public health impacts.
- Professor Andrade highlighted the delays in implementing regulations due to economic constraints and the lack of consideration for air quality.
- Professor Andrade emphasized the need for a balanced approach that considers both economic and health aspects in policy-making.

Fatima Andrade Interview Questions:

1. The study highlights the PROCONVE program aimed at reducing vehicle emissions.
2. .How effective has PROCONVE been in controlling emissions from ethanol-fueled vehicles?
3. What specific aspects of PROCONVE directly address ethanol-related emissions? In the policy, we see NOx, but another precursor to ozone is volatile organic compounds. Are these regulated?
4. What are the main barriers to implementing science-based policy changes in Brazil?
5. .How receptive are policymakers to scientific evidence when making decisions related to air quality?
6. .Are there gaps between the goals of different policies/laws (such as Pronar, PROCONVE, PNQAr) and their implementation? What are the main political, economic, and institutional barriers hindering the effective implementation of Pronar's air quality goals?
7. How readily available and accessible are air quality data in Brazil, and how can data collection and sharing be improved to support evidence-based policymaking?
8. How can a more integrated approach to air quality management—beyond just environmental ministries—incorporate sectors such as health and urban planning?

9.How can Brazil effectively integrate its ethanol policies with broader strategies for climate change mitigation while ensuring air quality improvements?
10.Are there any other experts or contacts you recommend I speak with on this topic?
11.Are economic factors currently hindering the ability to meet air quality and emissions goals?
12.With increasing collaboration between scientists and federal ministries, is there growing interest in funding air quality improvements, particularly expanding monitoring outside major urban areas?
13.Have you investigated emissions from ethanol production itself, and should there be additional emissions standards or tracking at the production level?
14.From an economic perspective, is carbon dioxide prioritized over other air pollutants due to its prominence in international climate agendas? Could leveraging CO2 discussions help justify better air quality monitoring?
15.When considering increasing ethanol blends (e.g., E30), do you think air quality impacts will be a major factor in decision-making?

Maria Lucia Goncalves Guardani Interview:

About: Maria Lucia Goncalves Guardani is a chemist and the manager of the Air Quality Division at CETESB (São Paulo State Environmental Agency). With over 30 years of experience in air quality monitoring and regulation, she oversees São Paulo's extensive public air monitoring network, the largest in Brazil. Her work focuses on bridging gaps between scientific research, policy implementation, and public communication.

Key Discussion Points

Effectiveness of Vehicle Emission Programs

- PROCONVE has been effective since the 1980s at reducing inhalable particles (MP10) through phased regulations on vehicles and fuel quality
- New challenges emerged as the program reached its limits - current measures can't achieve WHO standards
- PM2.5 monitoring only began in 2014 and remains limited, presenting new regulatory challenges

Ozone Pollution Challenges

- Ozone levels fluctuate unpredictably and frequently exceed standards
- Unlike particulate matter, ozone saw increases during pandemic restrictions
- VOC recovery programs (like during refueling) exist but ozone remains difficult to control

Implementation Barriers

- Lack of monitoring networks nationwide prevents problem identification and policy development
- Public communication is critical but challenging due to pollution's "invisible" nature
- Funding and staffing limitations affect even São Paulo's advanced monitoring network

Ethanol Policy Considerations

- Ethanol reduces particulate emissions but contributes to ozone formation through VOCs
- Flex-fuel vehicles are positive but consumer choices favor cheaper fossil fuels
- Land use trade-offs exist between food production and sugarcane for ethanol

Recommendations for Further Interviews

- CETESB vehicle emissions experts for technical details on PROCONVE implementation
- Agricultural policy experts to discuss food vs. fuel land use considerations

Questions

1. What effectiveness has PROCONVE had in controlling emissions from ethanol-powered vehicles in Brazil? In your opinion, how will this phase be implemented in São Paulo?
2. Are you already seeing PM2.5 or not, only PM10 in the program?
3. Do you also have information about ozone?
4. In your opinion, what are the main barriers to implementing science-based changes in air quality policy in Brazil?
5. Do you think there are discrepancies between the objectives of various policies and laws and their implementation in the city or in Brazil as a whole? In your opinion, what are the main political and economic challenges that hinder the effective achievement of air quality goals in Brazil?

6. With that, do you think this communication and campaigns to improve in Brazil, be done at the federal level to help the public understand? Or do you think each state should be responsible for this?
7. How can Brazil effectively deliver its ethanol policies with broader strategies for medicating climate change, guaranteed, but at the same time, improvements in air quality?
8. Also wanted to ask if you have anyone in mind with whom I should talk about this topic.

CARLOS IBSEN VIANNA LACAVA INTERVIEW:

About: Carlos Ibsen Vianna Lacava is an emissions expert at CETESB (São Paulo State Environmental Agency), specializing in vehicle emissions regulations and air quality policy.

Key Discussion Points

PROCONVE L7 & L8 Implementation

- Phases L7 (2022) and L8 (2025) implemented simultaneously with technology-neutral standards
- Key innovations:
  - NMOG parameter adoption (mirroring U.S. standards)
  - ORVR vapor recovery systems requirement
  - Corporate average limits for pollutants
- Flex-fuel vehicles (85% of light vehicles) must meet same standards regardless of fuel used

Ethanol's Ozone Formation Challenges

- Specialists recognize ethanol's VOC emissions contribute to ozone formation
- General public perceives ethanol as environmentally superior despite ozone impacts
- Policy response: NMOG parameter accounts for different fuels' ozone formation potential

Urban Air Quality Concerns

- Vehicles remain primary urban air polluters (ozone and particulate matter)
- No current studies specifically quantifying ethanol's ozone contribution
- Policy approach: uniform limits regardless of fuel technology

Policy Implementation Challenges

- PROCONVE progresses well but complementary programs lag (e.g., vehicle inspections)
- Difficulty coordinating federal guidelines with state/municipal realities
- New national policy initiative may improve integration

Climate-Air Quality Integration

- Brazil's strong biofuel potential supports decarbonization
- Opportunity to increase ethanol use in flex-fuel fleet (currently underutilized)
- Urban centers need clean public transport alongside fleet renewal

Recommendations for Further Interviews

- Federal policymakers on PROCONVE implementation challenges
- Urban transportation planners on clean public transit solutions
- Fuel technology researchers on next-generation biofuel developments

Interview Questions Asked

1. What specific strategies are being implemented in the PROCONVE L-8 phase to address evaporative emissions from ethanol-powered vehicles, and how do they compare to global best practices?
2. To what extent are policymakers, industry representatives, and the public aware of the role ethanol use plays in contributing to emissions of ozone precursors, such as VOCs and nitrogen oxides (NOx)?
3. Are ozone precursors from ethanol-powered vehicles recognized as a significant concern for air quality in Brazil, particularly in urban areas with high vehicle density?
4. Are there ongoing studies or monitoring programs to quantify the contribution of ethanol use and production to ozone levels in Brazil's environment?
5. Are there discrepancies between the objectives of various policies and laws (such as Pronar, PROCONVE, PNQAr, etc.) and their implementation? In your opinion, what are the main political, economic, and institutional challenges hindering the effective achievement of air quality goals?
6. How can Brazil effectively integrate its ethanol policies with broader climate change mitigation strategies while ensuring improvements in air quality?

APPENDIX D:

PESTEL Analysis Summary Table

PESTEL COMPONENTS	
POLITICAL FACTORS	❖ Fragmented enforcement on federal vs. state level for air quality ❖ Strong political support for ethanol through RenovaBio and National Energy Plan 2050.
ECONOMIC FACTORS	❖ Funding challenges, cost-benefit of air pollution control ❖ New 2024 National Air Quality Policy (PNQAr) aims to expand monitoring but lacks clear funding mechanisms.
SOCIAL FACTORS	❖ Public perceives ethanol as clean but lacks awareness of ozone impacts. ❖ Brazilians support ethanol due to its affordability ❖ No widespread air quality education campaigns.
TECHNOLOGICAL FACTORS	❖ EV infrastructure challenges ➢ Flex-fuel vehicles (FFVs) dominate the passenger car market. ❖ Lack of Onboard Refueling Vapor Recovery (ORVR) systems ❖ Few monitoring stations outside major cities.
ENVIRONMENTAL FACTORS	❖ Deforestation for sugarcane expansion ❖ Ethanol's role in ozone formation.
LEGAL FACTORS	❖ Weak enforcement of air quality regulations (e.g., Proconve gaps, annual vehicle inspections, etc.). ❖ Lack of penalties for non-compliance with emissions limits.

APPENDIX E:

Stakeholder Analysis

STAKEHOLDER	TYPE	STAKES & INTERESTS	INFLUENCE & POWER
Ministry of Environment & Climate Change (MMA)	Government	Improving air quality, aligning policies with WHO standards, enforcing PNQAr.	**Very High** – Regulates environmental policies but faces enforcement challenges.
National Environment Council (CONAMA)	Government	Defines air quality standards, regulates industrial activities affecting air pollution.	**Moderate** – Sets regulations but effectiveness is limited by enforcement gaps.
State Environmental Agencies (CETESB, etc.)	Government	Monitor pollution levels, implement policies at the state level.	**High** – Strong regional authority over environmental management.
Ethanol Industry (UNICA, ANP, MME)	Industry	Promote ethanol as a clean fuel, protect market share, influence policies.	**High** – Strong lobbying power, rapid policy approvals (e.g., RenovaBio approved in just 28 days).
Automotive Industry	Industry	Developing both ethanol-compatible and electric vehicles (EVs).	**Moderate**– Investing in EVs but constrained by high costs & infrastructure limits.
Environmental NGOs (EDF, ICCT, IEMA, WRI)	NGO	Advocate for stricter emission standards & EV adoption.	**Moderate** – Influence through research, policy recommendations, and advocacy .
Public & Consumers (FFV	Public	Demand clean air, make fuel choices based on price & perception.	**Low-Moderate** – Influence through public pressure & voting

APPENDIX F:

LCA Literature & Coding Schema

LCA Studies Used

Academic Paper Name	Author(s)
"Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods"[230]	Cavalett et al.
"Life Cycle Greenhouse Gas Emissions of Brazilian Sugarcane Ethanol Evaluated with the GREET Model Using Data Submitted to RenovaBio"[231]	Liu et al.
"Lifecycle assessment of fuel ethanol from sugarcane in Brazil"[232]	Roberto Ometto et al.
"Life Cycle Assessment of the Sugarcane Supply Chain in the Brazilian Midwest Region"[233]	Rodrigues and Machado
"Análise ambiental do ciclo de vida do etanol combustível"[234]	Silva and Zapparoli
"Potential of biofuels from algae: Comparison with fossil fuels, ethanol and biodiesel in Europe and Brazil through life cycle assessment (LCA)"[235]	Carneiro et al.
"Emissão de gases de efeito estufa no ciclo de vida do etanol: estimativa nas fases de agricultura e industrialização em Minas Gerais"[236]	Claros Garcia and Von Sperling
"Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil"[237]	de Souza et al.
"Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use"[238]	Joaquim E. A. Seabra et al.
"Life cycle assessment of battery electric vehicles and internal combustion vehicles using sugarcane ethanol in Brazil: A critical review"[239]	Lavrador and Teles
"Life cycle assessment and life cycle costing bioethanol from sugarcane in Brazil"[240]	Luo et al.
"Atmospheric impacts of the life cycle emissions of fuel ethanol in Brazil: based on chemical exergy"[241]	Ometto and Roma
"Life cycle assessment of sugarcane ethanol production in India in comparison to Brazil"[242]	Tsiropoulos et al.
"Economic and GHG emissions analyses for sugarcane ethanol in Brazil: Looking forward"[243]	Wang et al.

LCA Literature & Coding Schema

Coding Schema for LCA Literature Analysis

- Allocation Methods
  - Energy Allocation
  - Economic Allocation
  - Substitution Method
  - System Expansion
  - Other Methods
- Data Sources
  - Primary Data
  - Secondary Data
    - Ecoinvent
    - Other Databases
  - Software
    - SimaPro
    - Other Software
- Ethanol vs. Other Fuels
  - Comparison with Gasoline
  - Comparison with EVs
- Functional Unit Information
  - Functional Unit
    - Output-Related FU (e.g., 1 MJ of biofuel)
    - Input-Related FU (e.g., per unit of biomass)
  - Variability in FU Selection
- Impact Assessment Methods
  - Eco-Indicator 99
  - Ecological Scarcity 2006
  - IMPACT
  - ReCiPe
  - CML
  - EDIP
- Impact Categories & Endpoint Indicators
  - Endpoint Indicators
  - Endpoint Life Cycle Impact Assessment (LCIA)
  - Human Health Endpoint Indicator

    - Impact Category Selection
    - Impact Category Types
        - Abiotic Depletion
        - Fossil Fuel Depletion Potential
        - Acidification
        - Climate Change
        - Ecotoxicity
        - Eutrophication
        - Global Warming Potential (GWP)
        - Human Toxicity
        - Ozone Layer Depletion
        - Photochemical Ozone Formation
        - Resource Depletion
    - Natural Environment Endpoint Indicator
    - Natural Resources Endpoint Indicator
- LCA & LCIA Selection
- LCA Purpose
- LCA System Boundary
    - Well-to-Wheel (WtW)
    - Well-to-Tank (WtT)
    - Well-to-Gate (WtG)
- Recommendations & Improvements
    - Emission Scope Limitations (e.g., CO_2 focus, exclusion of air pollutants)
    - Uncertainties (e.g., sensitivity analysis)
    - Data Needs & Gaps (e.g., completeness, accuracy, geographic relevance)
    - Methodological Limitations
- Inventory Emissions
    - Greenhouse Gases (GHG)
        - CO_2
        - CH_4
        - N_2O
    - Air Pollutants
        - NOx
        - VOCs
        - Ozone (O_3)
        - CO

APPENDIX G:

Impact Categories Used in LCA Study

Impact Categories Used in LCA Study
Abiotic Depletion
Acidification
Climate Change
Ecosystem Quality
Ecotoxicity
Eutrophication
Fossil Fuels Abiotic Depletion Potential (FDP)
Global Warming Potential (GWP)
Greenhouse Gas Emissions
Human Health
Human Toxicity
Land Use
Natural Environment
Natural Resources
Non-renewable Energy Use
Nutrient Enrichment
Ozone Layer Depletion
Particulate Matter
Photochemical Ozone Formation
Resource Depletion
Water Use

APPENDIX H:

NVivo LCA Analysis Figures

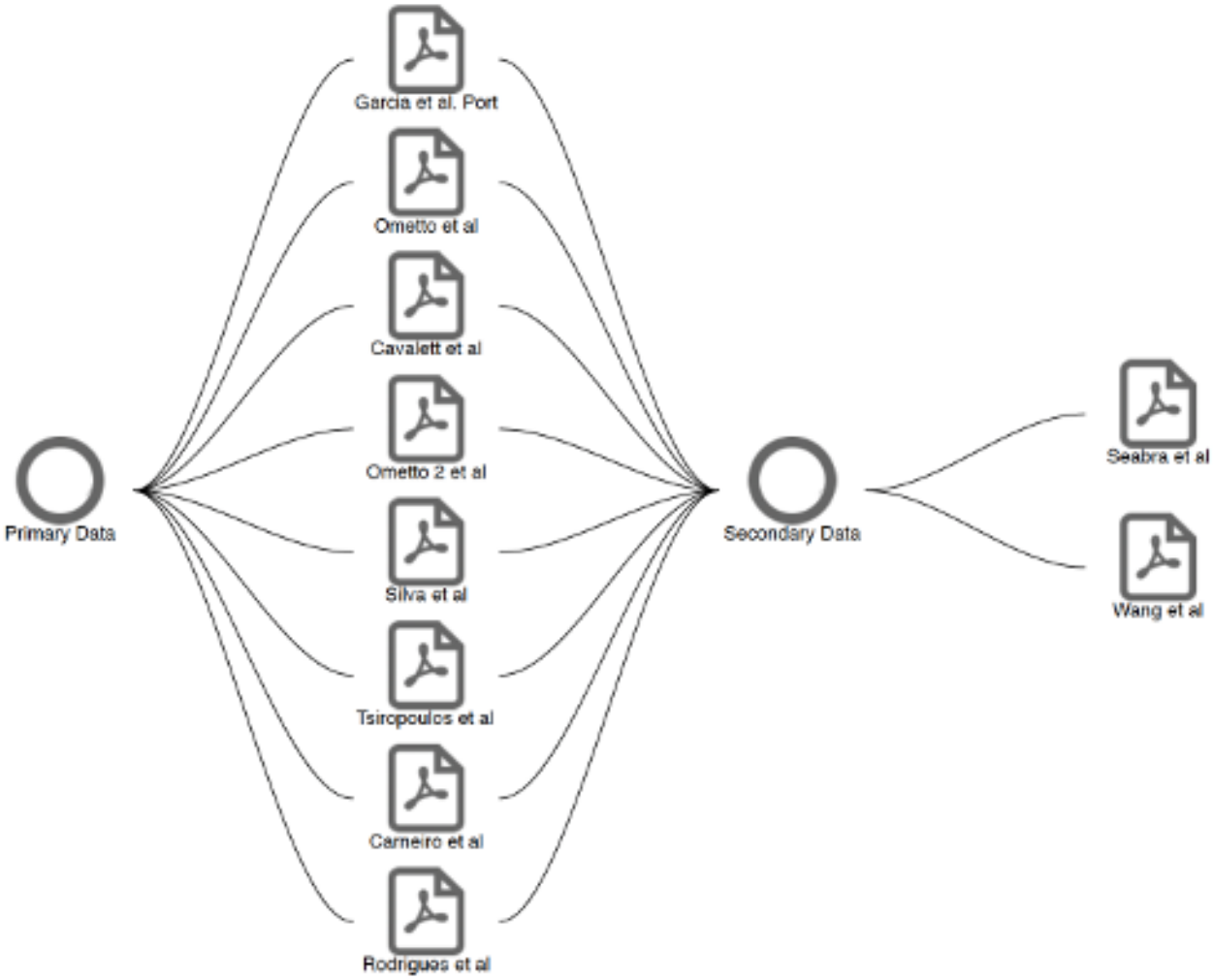


Figure 1: Papers using Secondary Vs. Primary Data

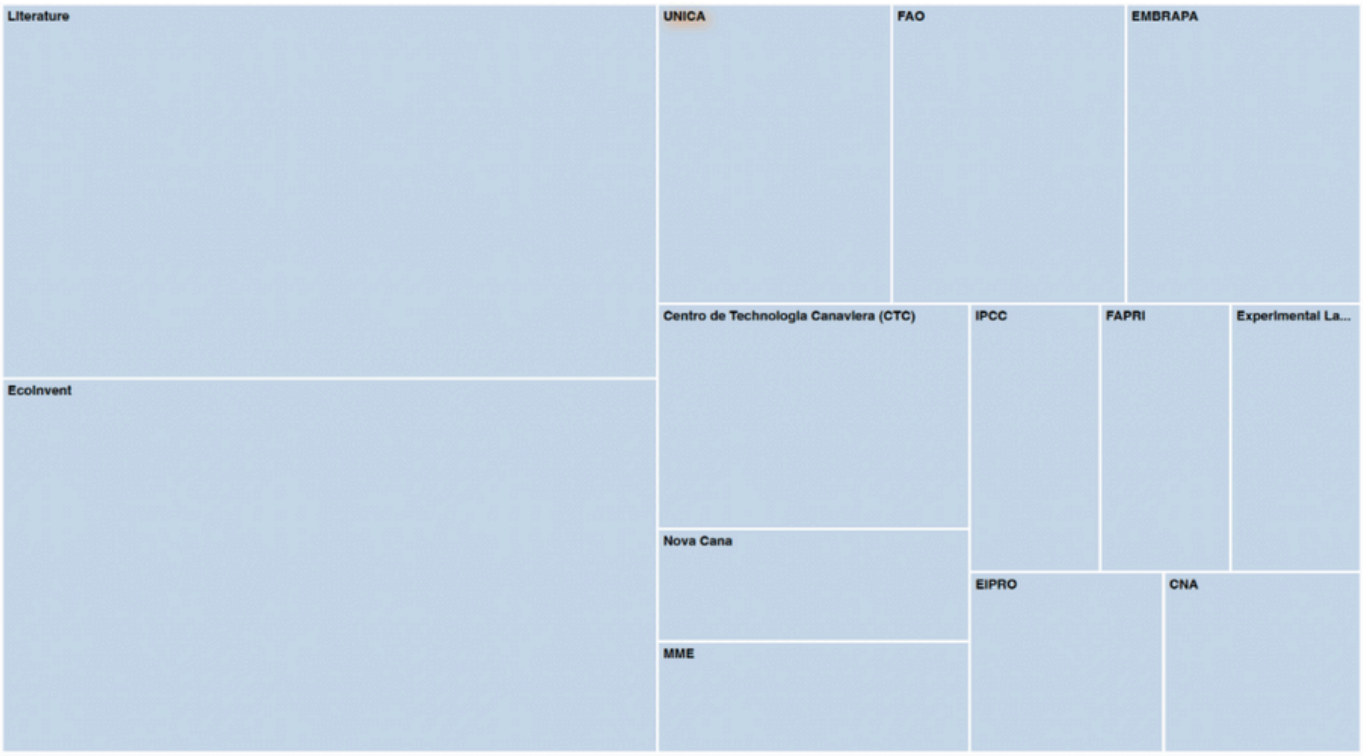


Figure 2: Types of Secondary Data Used in LCA Studies

APPENDIX I:

Key Terms

The meanings of the following terms are used in the context of this MP:

Bioenergy:
"Bioenergy is produced from organic material, known as biomass, which contains carbon absorbed by plants through photosynthesis. When this biomass is used to produce energy, the carbon is released during combustion and returns to the atmosphere."[244]

Ethanol:
"...a chemical compound that is produced through the fermentation of agricultural products like sugarcane and corn. It is commonly used as a high-octane fuel in vehicles due to its favorable properties such as lower evaporative emissions and reduced flammability compared to gasoline."[245]

Ground-Level Ozone:
"Ozone is a gas composed of three atoms of oxygen. Ozone occurs both in the Earth's upper atmosphere and at ground level. Ozone at ground level is a harmful air pollutant, because of its effects on people and the environment, and it is the main ingredient in "smog."[246]

Air Tracker:
"...web-based tool that allows users to plot the likely path of air pollution. Run on real-time, trusted scientific models and coupled with air pollution and weather data... Air Tracker is part of EDF's ongoing work to better understand local air pollution, its behavior and its impacts."[247]

Criteria Pollutants (PM2.5, SO2, CO, NOx):
"...pollutants that are ubiquitous in the United States and are known or strongly suspected to be harmful to public health and the environment. Currently, six pollutants are designated as criteria pollutants: particles with aerodynamic diameters under 10 and 2.5 lpm, ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and lead."[248]

Electrification (EVs & BEVs):
"...replacing technologies or processes that use fossil fuels, like internal combustion engines and gas boilers, with electrically powered equivalents, such as electric vehicles or heat pumps."[249]

Carbon Intensity:
"a measure of how clean our electricity is. It refers to how many grams of carbon dioxide (CO2) are released to produce a kilowatt hour (kWh) of electricity."[250]

Life-Cycle Assessment (LCA):
"a tool to assess the environmental impacts and resources used throughout a product's life cycle"[251]

Sustainable Development Goals (SDGs):
"17 goals and 169 targets that were created to end poverty, promote prosperity and well-being for all, and protect the planet."[252]

Flex-Fuel Vehicles (FFVs):
"Flex-fuel vehicles are vehicles that can operate with multiple fuels (or fuel blends) ... The main fuels used include gasoline and several alternative fuels, such as pure ethanol (already used in Brazil in automotive vehicles) and blends of ethanol and gasoline."[253]

PROCONVE:
Brazilian policy program created to "control vehicle emissions, its main goal being the reduction of atmospheric contamination by setting emission standards, thereby inducing technological improvements of manufacturing processes and verifying that vehicles and engines meet emission limits in standardized tests with a reference fuel."[254]

Proálcool Program:
"a strategic policy of the Brazilian government to replace petroleum-based fuels with alcohol (ethanol)"[255]

RenovaBio:
A Brazilian policy program that "aims at establishing a mechanism for the commercialization of decarbonization credits linked to the carbon intensity of several biofuels."[256]