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Impacts assessment of open field burning of agricultural residues in Mexico

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ABSTRACT

This research estimates the number of agricultural residues burned in open field, their pollutant emissions and the energy lost in the 2,476 municipalities that make up Mexico. The emissions of Particulate Matter 10 (PM10) and 2.5 (PM2.5), Black Carbon (BC), Carbon Dioxide (CO2) and Methane Gas (CH4) at the municipal level were estimated. The bioenergy loss was also estimated, in terms of anhydrous ethanol. In addition, the economic value lost was estimated, as well as the amount of gasoline that could have been oxygenated at 6 % volume and the percentage of participation in the national gasoline demand. The results, aggregated at the national level, show that Mexico annually incinerates 4.1 million tons of corn stover which emits 13,662 tons of PM10, 11,178 tons of PM2.5, 787 tons of BC, 7.2 million tons of CO2 and 8,653 tons of CH4 to the atmosphere. If this amount of biomass were used to produce anhydrous ethanol, a volume of 1,106 million liters, worth US$840 million, could be produced, which might also be used to oxygenate 18,425 million liters of gasoline, covering approximately 100 % of the national demand for this biofuel. The results provide empirical evidence on open burning of agricultural residues in Mexico and can be used to design public policies to reduce the country's share of global pollutant emissions.

1. Introduction

Open-field burning of agricultural residues (OFBAR) is a widely practiced method of agricultural residue disposal with substantial environmental, economic, and public health consequences. Although global studies have documented its effects on atmospheric pollution, soil fertility, and human health (Aghaei et al., 2022; Cherubin et al., 2018; Yevich and Logan, 2003). The amount of empirical research on this issue varies significantly by region. For example, comprehensive studies exist for South Asia (Lin and Begho, 2022), notably India (Singh, 2024; Urban Cordeiro et al., 2024; Deshpande et al., 2023; Singh et al., 2022; Lan et al., 2022; Porichha et al., 2021; Mithun et al., 2019; Kumar et al., 2015; Vadrevu et al., 2013), as well as the United States (Pouliot et al., 2017; Holder et al., 2017; McCarty, 2011), Thailand (Wangwongwatana, 2020; Johnston et al., 2019), and other countries, but data focused on Mexico remains limited and fragmented.

OFBAR persists globally as an expedient and inexpensive method to clear agricultural fields, particularly in regions with intense agricultural activity. This practice contributes significantly to greenhouse gas (GHG) emissions (e.g., carbon dioxide (CO2) and methane (CH4)), particulate matter (PM10 and PM2.5), and polycyclic aromatic hydrocarbons (PAHs), along with impacts on soil quality, including the loss of organic carbon and essential nutrients such as nitrogen (Singh et al., 2022; Kumar et al., 2015).

Globally, approximately 20 % of agricultural residues in developing nations are disposed of through open-air combustion, with notable regional variation: 28 % of residues in Africa, 18 % in Asia, and 23 % in Latin America are burned in fields (Lasko and Vadrevu, 2018; Streets et al., 2003; Singh et al., 2021). Countries such as India, China, and Brazil are identified as major contributors to open-field burning (Aghaei et al., 2022; Wang et al., 2025; Yadav, 2025), driven by logistical challenges and the urgent need to replant crops after harvest.

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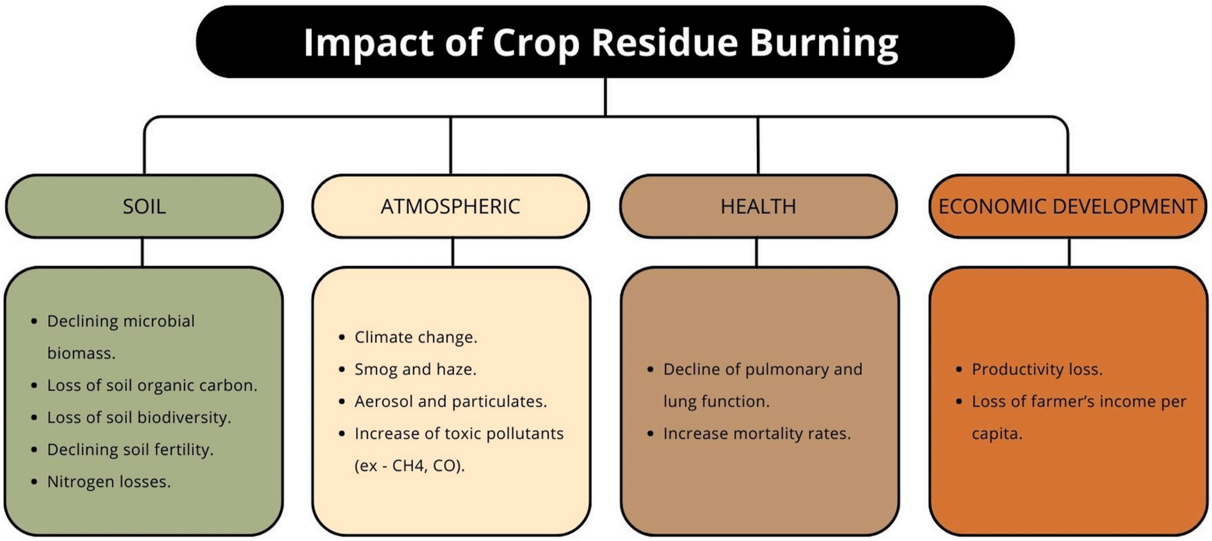

Fig. 1. Classification of impacts from open field burning of agricultural residues (OFBAR).
Source: Adapted from (Singh et al., 2022; Kumar et al., 2015).

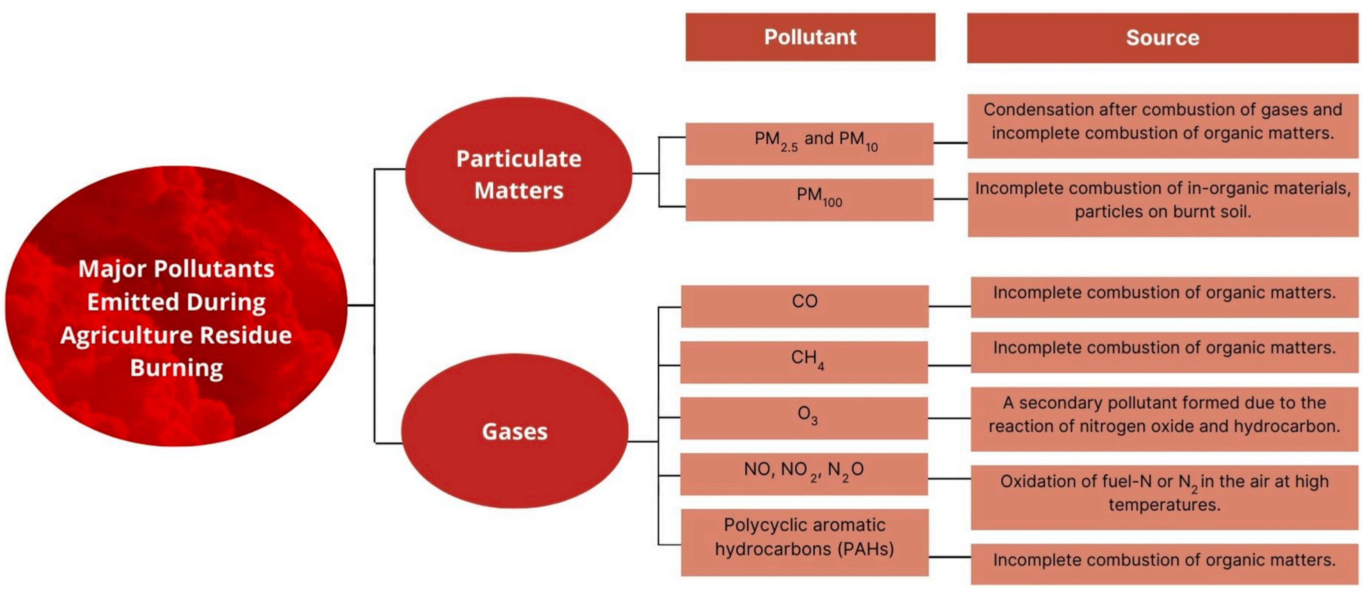

Fig. 2. Major pollutants emitted during open field burning of agricultural residues.
Source: Adapted from (Porichha et al., 2021; Kumar et al., 2015; Singh et al., 2008).

Collectively, these regions account for a significant proportion of the 5000 million tons of global agricultural residues generated annually, of which the majority is produced by cereals (3,600 million tons), sugar crops (630 million tons), legumes (380 million tons), oil crops (280 million tons), and tubers (120 million tons) (Ribeiro and Junior, 2023; Becker-Reshef et al., 2023).

China stands out as the largest global producer of agricultural residues, accounting for 17.3 % of the world total. Ranking first in rice and wheat production, second in corn, and third in sugarcane, China annually disposes of substantial residues through burning during the summer-autumn period, driven by economic and time-saving considerations (Chen et al., 2017; Bi et al., 2010). India, the second-largest producer of rice, wheat, and sugarcane, generates approximately 501.7 million tons of residues annually, of which 92.8 million tons (18.5 %) are burned in northern states such as Punjab, Haryana, and Uttar Pradesh (Singh et al., 2022). His process, particularly for rice and wheat residues, not only accelerates field clearing but also contributes to severe air pollution, with particulate matter exposure causing between 44,000 and 98,000 premature deaths annually between 2003 and 2019 (Lan et al., 2022). Satellite-based studies conducted by Deshpande et al. (2023) further reveal that CO2-equivalent emissions from OFBAR in India increased by 75 % from 2011 to 2020, largely attributable to the burning of rice and wheat residues.

In contrast, agricultural residue combustion in the United States is comparatively limited, with less than 1 % of the total cultivated area burned (Pouliot et al., 2017). However, certain regions, such as the

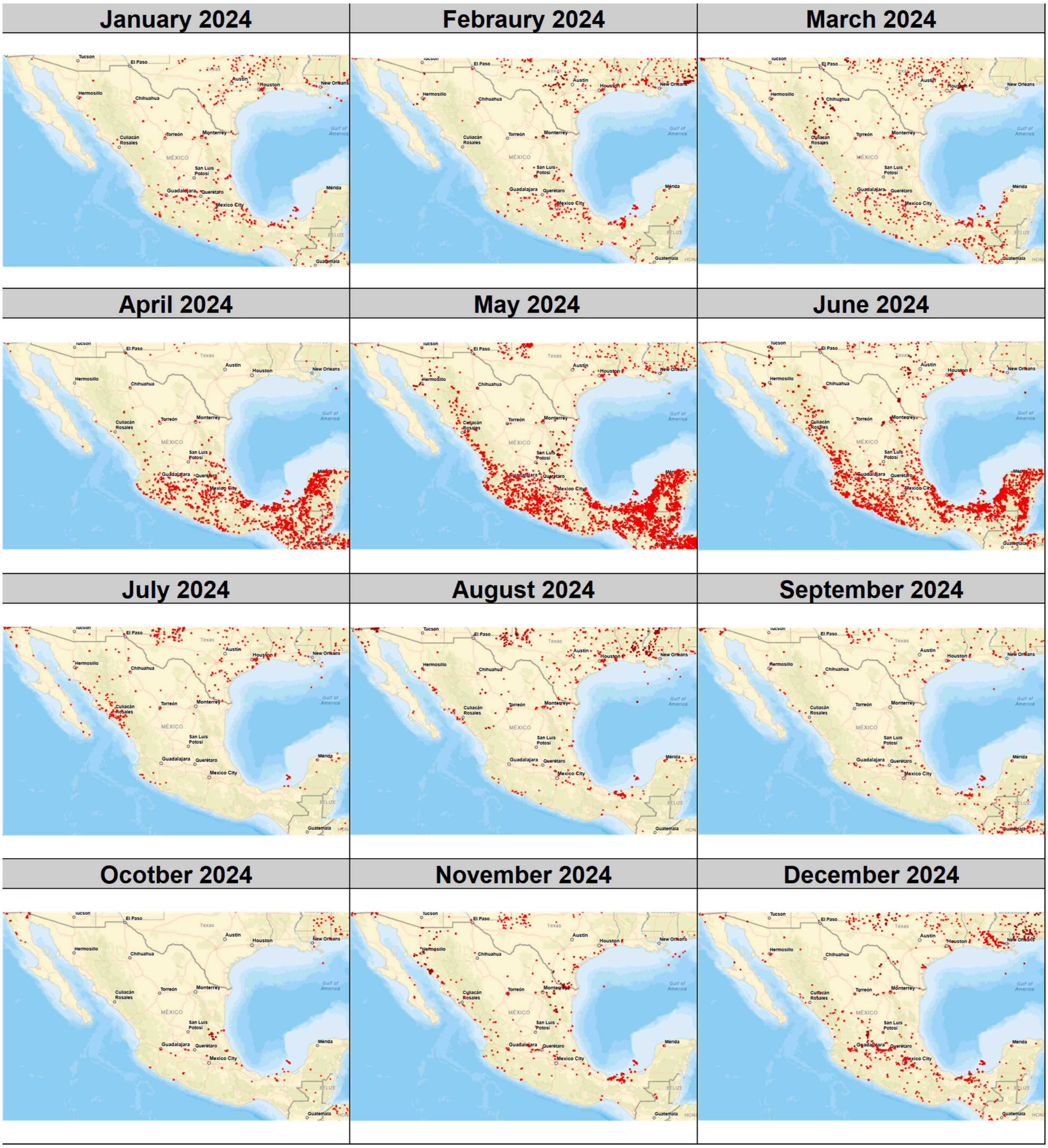

Fig. 3. Active Fire/Thermal Anomalies in Mexico in 2024 (last day of each month).
Source: (Earthdata, 2024).

Pacific Northwest, employ burning as a standard method for managing residues such as wheat, barley, and grass seed (Holder et al., 2017). The potential bioenergy value of agricultural residues in the United States is significant, with an estimated 18.38 billion liters of ethanol derivable from corn residues alone, capable of reducing 42 million tons of CO2-equivalent annually (Aghaei et al., 2022; Koundinya, 2022).

OFBAR is a practice with both short-term benefits and far-reaching disadvantages. While its advantages include rapid pest, weed, and pathogen control, reduced tillage costs, and mineral recycling through biomass ash, its drawbacks are substantial. These include severe air and soil pollution, the emission of carcinogenic pollutants, loss of soil biodiversity, and severe public health impacts. The health risks associated with OFBAR pollutants, particularly PM and PAHs, include respiratory diseases such as asthma, chronic bronchitis, and lung cancer, as well as increased rates of cardiovascular diseases and premature mortality. These burdens are particularly pronounced in low-income areas,

Fig. 4. Graphic evidence of OFBAR. Photographs taken in the central region of the state of Sinaloa, May 2024[1].
Source: own photographs.

[1] MXN stands for Mexican Pesos.

where reliance on biomass combustion is highest, compounding vulnerability to air quality hazards (Johnston et al., 2019; Chen et al., 2017; Becerra-Pérez et al., 2024; Phairuang et al., 2024).

The objective of this study is to analyse the environmental and economic impacts of open-field burning of corn stover across all 2,476 municipalities in Mexico. Primary data was collected directly from an agricultural region through surveys and subsequently generalized to estimate the nationwide impacts of this practice. Utilizing a methodology that integrates this survey data with emission factors from SEMARNAT-INECC and IPCC guidelines, as well as municipal-level spatial analysis, the study quantifies emissions of key pollutants, including carbon dioxide (CO_2), methane (CH_4), particulate matter (PM), and black carbon (BC). It also evaluates the unrealized bioenergy potential from these residues, expressed as the volume of anhydrous ethanol that could otherwise be produced. The analysis includes the production of detailed, spatially resolved maps to illustrate the distribution of these impacts, providing a comprehensive overview of the environmental and economic implications at the municipal level.

2. The problem in Mexico

In Mexico, corn represents the most significant source of agricultural residues, followed by sugarcane, sorghum, wheat, and beans. Among these, the states producing the largest quantities of residual biomass include Sinaloa, Jalisco, Michoacán, Veracruz, and Chiapas. Annual outputs from corn cultivation alone reach approximately 29.2 million tons of dry biomass, corresponding to an energy potential of 450 petajoules (PJ) per year, while other cereal crops collectively produce 18.2 million tons (280 PJ). Sugarcane cultivation contributes an annual 3.2 million tons of dry biomass, generating an estimated energy yield of 55 PJ (SENER-CFE and Atlas Nacional de Biomasa, 2018).

Other studies determine that three crops produce more than 87 % of agricultural residues: corn (43 %), sorghum (26 %) and sugarcane (18 %), highlighting the regions of Sinaloa, Tamaulipas and Veracruz, respectively (Honorato-Salazar and Sadhukhan, 2020; Becerra-Pérez et al., 2021). Regarding regional importance, Sinaloa leads for corn production, Tamaulipas excels in sorghum, and Veracruz dominates sugarcane cultivation. A proportion of agricultural residues is utilized in agro-industrial facilities, such as sugar mills, sawmills, and

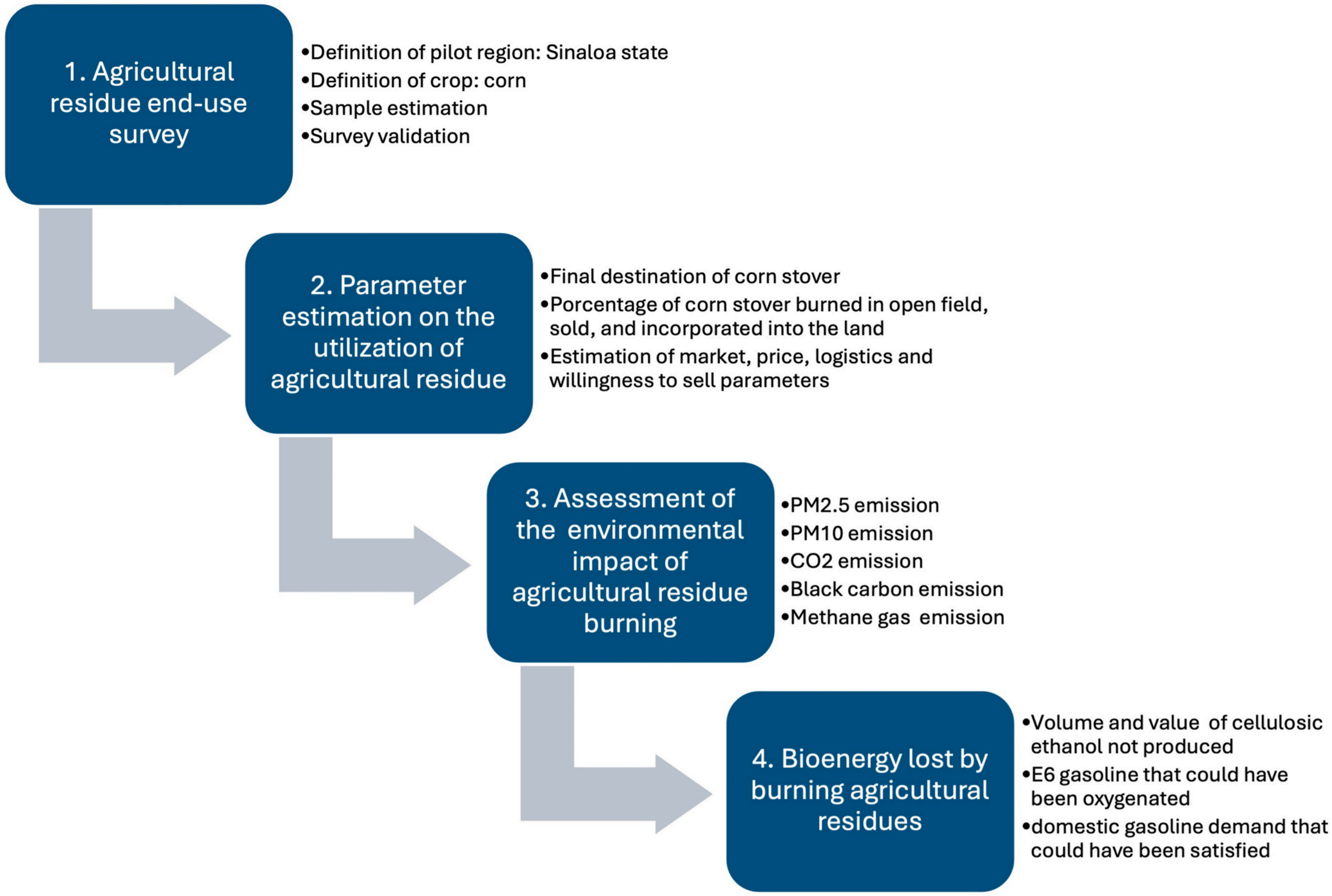

Fig. 5. General outline of the methodology used in the research.

fruit-packaging plants, due to their low logistics and transport costs, facilitating alternative uses (Becerra-Pérez et al., 2022). However, challenges persist in residue management. Excessive extraction or neglectful disposal compromises soil nutrients, creating long-term risks like erosion and reduced fertility. Conversely, retaining higher volumes of residues can hinder proper seed placement and introduce weed management problems, particularly in irrigated systems (Johnson et al., 2010).

Figures corroborate the legal and environmental complexities in managing such residues. Although open-field burning of biomass is outlawed under Article 139, Section II, of the "Ley Ambiental para el Desarrollo Sustentable del Estado de Sinaloa" (Congreso Estado de Sinaloa, 2018), significant portions of corn residues in the state are incinerated. Specifically, recent surveys indicate that only 13 % of corn stover is reserved for animal feed in Sinaloa; 16 % is burned on-site, while more than 70 % is unutilized and remains in the field (Becerra-Pérez et al., 2021). National patterns echo this inefficiency, with roughly 15 %–25 % of agricultural residues utilized for animal feed and large amounts left unattended or subjected to burning (Borja-Bravo et al., 2013).

In Mexico, the burning of agricultural residues, particularly from sugarcane and other major crops, persists as a cost-saving measure during harvest (UNC and Estadísticas de la Agroindustria de la Caña de Azúcar, 2010–2019, 2023), For instance, 90 % of Mexico's sugarcane is still harvested using the traditional method, which relies on a pre-harvest burning of dry leaves at the lower part of the plant, to facilitate manual cutting and deter dangerous animals (UNC and Estadísticas de la Agroindustria de la Caña de Azúcar, 2010–2019, 2023; Manzini Poli et al., 2022) This approach leaves soot on the ground and releases more than 70 hazardous substances, like polycyclic aromatic hydrocarbons (PAHs) recognized carcinogens and mutagens responsible for DNA damage and chromosomal alterations (Manzini Poli et al., 2022; Shikwambana et al., 2021; Aguiar et al., 2021). In addition, Sugarcane burning is a principal source of levoglucosan, a well-known molecular marker for biomass combustion, which along with incomplete combustion gases such as CO and CH_4, drives the formation of secondary organic aerosols and elevates PM2.5 and PM10 levels in affected areas (Wu et al., 2021; Salma et al., 2017). Exposure to these particles has been linked to acute and chronic respiratory and cardiovascular diseases, as well as cognitive deficits (Manrique et al., 2025; Paraiso and Gouveia, 2015) (see Figs. 1 and 2).

Fig. 3 displays images capturing active fires and thermal anomalies across Mexico, acquired through NASA's FIRMS (Fire Information for Resource Management System) utilizing data from the Aqua and Terra satellites (Earthdata, 2024). These images encompass various sources of thermal anomalies, including natural, forest, agricultural, and other types of fires. While it cannot be definitively concluded that all detected incidents are related to open-field burning of agricultural residues (OFBAR), the timing and geographic distribution of these fires align closely with the April-to-June harvest season for key crops. Additionally, crops grown using irrigation systems, known for their higher productivity, tend to generate larger volumes of residual biomass. This, in turn, increases the pressure on farmers to rapidly clear stover due to the compressed timeframe before the next planting cycle.

The use of fire for managing crop residues and preparing fields for subsequent planting remains a regionally variable yet persistent practice in Mexico (Eastmond and Faust, 2006; Korontzi et al., 2006). The smoke released during this process degrades air quality and poses significant risks to human health. Efforts to mitigate OFBAR are centered on promoting alternative residue management approaches, such as soil

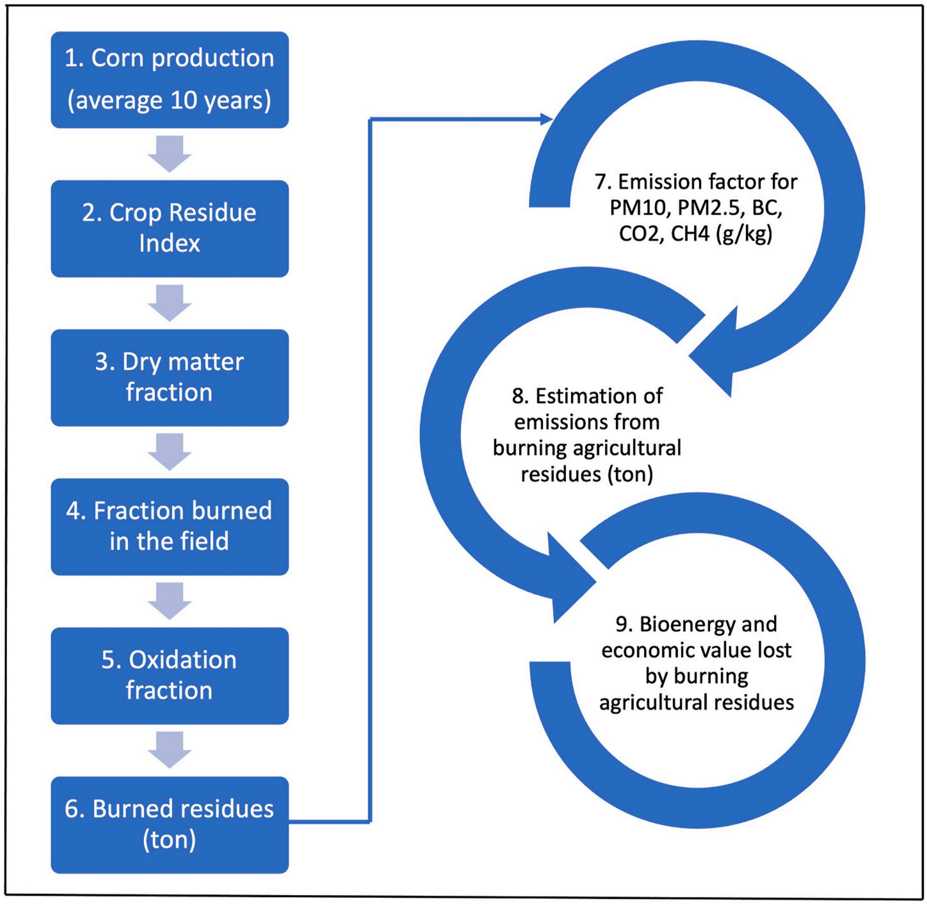

Fig. 6. Processes to estimate pollutant emissions from OFBAR from corn stover and calculate bioenergy lost in terms of anhydrous ethanol and monetary value.

incorporation, which can enhance soil quality over time (Bhuvaneshwari et al., 2019). However, the transition to such practices is hindered by challenges including the need to demonstrate clear benefits, the provision of public resources, the development of supportive legal frameworks, and the availability of viable alternative uses for agricultural residues. Resolving this complex issue will require coordinated efforts from the agricultural sector, government entities, and broader societal engagement.

To validate the prevalence of the issue, field visits were conducted in agricultural regions during the 2024 corn post-harvest period, confirming the continued practice of open-field burning of agricultural residues despite existing legal prohibitions. Evidence of this activity was documented through images presented in Fig. 4, highlighting that a segment of farmers persists in burning residues due to economic or logistical pressures.

3. Methods

3.1. Research stages

This study is quantitative in nature and was carried out in four structured stages (Fig. 5). First, a survey was conducted among corn farmers in the pilot region of Sinaloa to collect information on the management practices and logistical handling of agricultural residues. Second, the final destination of the corn stover was analyzed to assess residue utilization or disposal methods. Third, the environmental impacts of open-field burning of agricultural residues (OFBAR) were evaluated by estimating emissions of PM2.5, PM10, CO_2, black carbon (BC), and methane (CH_4) using established emission factors. Finally, the bioenergy loss associated with OFBAR was quantified by calculating the potential anhydrous ethanol yield from the burned biomass, along with its monetary value. Furthermore, the share of domestic gasoline demand that could be met by blending ethanol at 6 % by volume (E6) was estimated. This blend percentage was selected based on Mexican regulatory limits for ethanol in gasoline (Diario Oficial de la Federación, 2016), which prohibit the use of anhydrous ethanol in major metropolitan zones, including Mexico City, Guadalajara, and Monterrey.

3.2. Agricultural residue end-use survey

3.2.1. Study area

The geographic area of the study was at two levels: a) the 32 federal entities; b) the 2,476 municipalities that make up Mexico. The smallest area of analysis was the municipality because it is the political-administrative delimitation for which there are comparable and reliable data, then the states, and finally the data were aggregated at the national level for the entire country. The State of Sinaloa was selected as a pilot region to estimate the OFBAR parameters, which were applied to the rest of the country. Although corn growing conditions are not homogeneous throughout Mexico, it would be very difficult, as well as costly, to estimate these parameters for all 2,476 municipalities. Field research is very important because there is little information about the

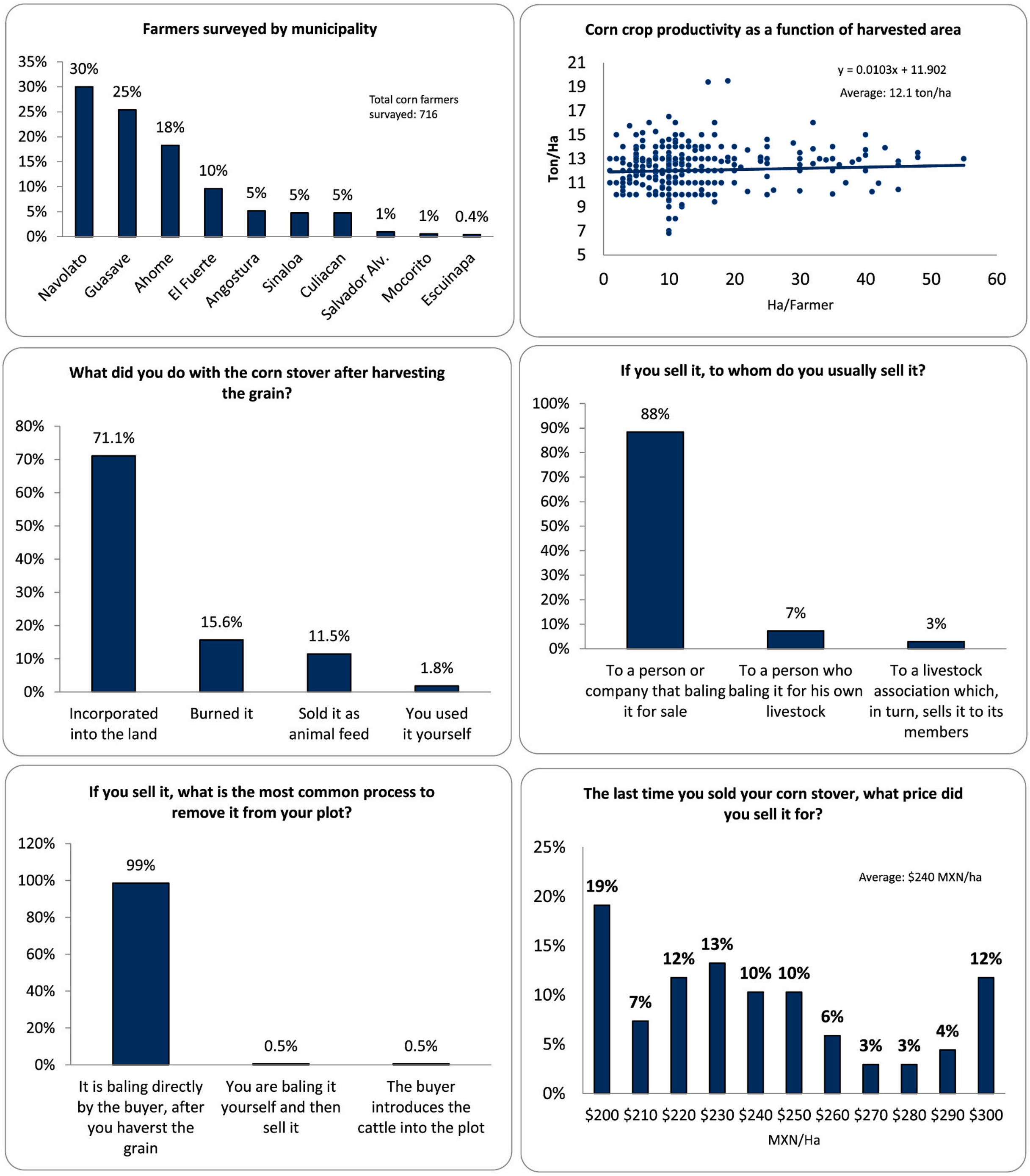

Fig. 7 (a). Results of the survey of corn producers showing the destination of agricultural residues, logistics and quantity removed, portion incinerated, actual selling price, willingness to sell, asking price, among other characteristics.

logistics of agricultural residues, their destination, commercialization, and very little awareness of the impact of OFBAR on the environment and human health.

3.2.2. Sample estimation at pilot region

According to the register of beneficiaries with some type of agricultural subsidy (SADER, 2023), the number of corn farmers in the State of Sinaloa is 25,093 people, who harvest white corn mainly for human consumption. A 16-item survey was designed using a *Likert-type* scale to learn about the logistics followed by producers in the management of their agricultural residues and their destination. The questionnaire was pre-validated in the field through a pilot test of 10 interviews, which was used to fine-tune the questions for the final survey. To determine the number of surveys, the simple random sampling method was used (Palella and Martins, 2012):

$$n = \frac{N^{*} Z^{2*} p^{*} q}{(N-1)^{*} e^{2} + Z^{2*} p^{*} q}$$

where:

n = sample size.

N = population size.

Z = confidence level.

e = margin of error.

p = population proportion (+).

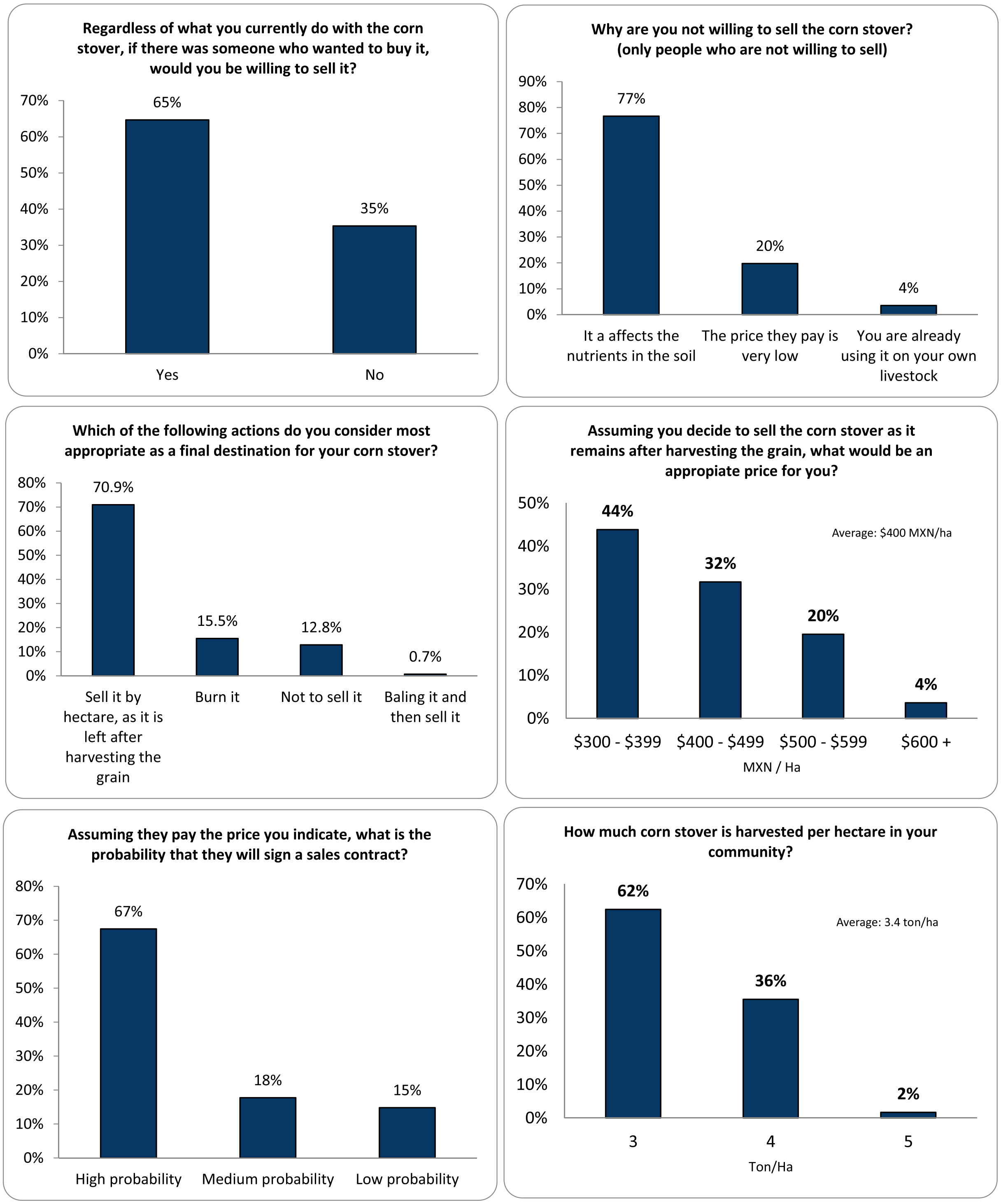

Fig. 7 (b). Results of the survey of corn producers showing the destination of agricultural residues, logistics and quantity removed, portion incinerated, actual selling price, willingness to sell, asking price, among other characteristics.

q = (1-p).

Based on the aforementioned formula, with the defined farmer population (25,093), a confidence level of 99 %, a margin of error of 5 %, and a positive population proportion of 0.5, a sample size of 716 surveys was determined.

The survey was applied directly in the field in the municipalities of Culiacan, Navolato, Angostura, Guasave and Ahome in the State of Sinaloa, during the months of May, June and July 2023. Subsequently, the surveys were computed in SPSS software and the *Cronbach's alpha* test was applied, with a result of 0.72, which means, according to the scale of Palella and Martins (2012), a high reliability coefficient in the questionnaire. In addition, the data were cleaned and plotted in Microsoft Excel.

3.3. Environmental impact and bioenergy potential loss of OFBAR

To evaluate the environmental impact of OFBAR, the volume of emissions of five pollutants were estimated: PM_{10}, $PM_{2.5}$, BC, CO_2, and

Table 1
Corn stover production in Mexico by provincial State.

Ranking	State	Corn-grain	Corn stover	Individual share
		Average 2013–2022, tons		
1	Sinaloa	5,469,325	6,684,730	20.8 %
2	Jalisco	3,732,589	4,562,052	14.2 %
3	México State	1,975,700	2,414,744	7.5 %
4	Michoacán	1,921,791	2,348,856	7.3 %
5	Guanajuato	1,686,153	2,060,854	6.4 %
6	Chihuahua	1,404,454	1,716,555	5.3 %
7	Guerrero	1,292,424	1,579,629	4.9 %
8	Chiapas	1,271,346	1,553,867	4.8 %
9	Veracruz	1,248,915	1,526,452	4.8 %
10	Puebla	994,708	1,215,754	3.8 %
11	Tamaulipas	731,031	893,483	2.8 %
12	Oaxaca	694,155	848,411	2.6 %
13	Hidalgo	663,415	810,841	2.5 %
14	Campeche	447,672	547,155	1.7 %
15	Zacatecas	406,342	496,640	1.5 %
16	Sonora	367,079	448,653	1.4 %
17	Tlaxcala	351,111	429,136	1.3 %
18	Durango	315,198	385,242	1.2 %
19	Querétaro	260,836	318,800	1.0 %
20	San Luis Potosí	167,174	204,324	0.6 %
21	Tabasco	147,636	180,444	0.6 %
22	Nayarit	137,343	167,863	0.5 %
23	Morelos	126,578	154,706	0.5 %
24	Yucatán	116,597	142,508	0.4 %
25	Aguascalientes	70,164	85,757	0.3 %
26	Nuevo León	63,254	77,310	0.2 %
27	Quintana Roo	55,240	67,515	0.2 %
28	Colima	47,754	58,366	0.2 %
29	Baja California Sur	42,662	52,143	0.2 %
30	Coahuila	28,926	35,354	0.1 %
31	Baja California	10,009	12,233	0.0 %
32	Ciudad de México	4756	5812	0.0 %
	National	26,252,341	32,086,188	100.0 %

CH_4. The IPCC methodology was followed, specifically the guidelines for estimating national inventories of GHG from agriculture, forestry and other land uses (Eggleston et al., 2006).

The pollutant emission calculation was made from the average corn production of a 10-year period (2013–2022) and the information was extracted from the Mexican government's agricultural database (SIACON-NG et al., 2023). The Crop Residue Index (1.22) was obtained from Becerra-Pérez et al. (2022); the fraction burned by farmers (0.156) comes from an own survey (described in the previous section); dry matter fraction (0.919), oxidation fraction (0.9), and factor emission PM_{10} (3.3), $PM_{2.5}$ (2.7), BC (0.19), CO_2 (1747.8), CH_4 (2.09), all in g/kg of residue, come from SEMARNAT-INECC (2016).

The conversion process assumes a lignocellulosic biomass yield of 297 L of ethanol/dry metric ton of biomass and an efficiency factor of 90 %; ethanol indifference price of 0.76 USD/liter is assumed from Becerra-Pérez et al. (2023). The gasoline demand in Mexico was assumed to reach approximately 26,000 million of liters, 30 % of which corresponds to the three main metropolitan areas (SENER and Base de Datos, 2022). Note that the Mexican legal framework prohibits the use of anhydrous ethanol in major metropolitan areas (Diario Oficial de la Federación, 2016), so that gasoline demand from these urban areas was eliminated with the idea of adjusting estimates to current regulations.

The approach used to estimate pollutant emissions and bioenergy losses resulting from OFBAR is outlined in Fig. 6. The calculation began by multiplying indices 1 through 5 to determine the total mass of residues burned in the field per year (indicator 6, measured in tons). This value was then multiplied by pollutant-specific emission factors, expressed (indicator 7, measured in grams per kilogram of residue), to estimate the annual emissions attributable to OFBAR in each municipality (indicator 8, measured in ton of PM10, PM2.5, BC, CO2 and CH4). Appropriate unit conversions were made to ensure consistency between tons of residue and emission factors given in grams per kilogram. Next,

Table 2
Estimation of OFBAR-corn stover in Mexico.

State	Burned Residues, average 2013–2022 (ton/year)	Emissions by burned residues (ton)				
		PM10	PM2.5	BC	CO2	CH4
Sinaloa	862,515	2846	2329	164	1,507,503	1803
Jalisco	588,631	1942	1589	112	1,028,809	1230
México	311,569	1028	841	59	544,560	651
Michoacán	303,067	1000	818	58	529,701	633
Guanajuato	265,907	877	718	51	464,752	556
Chihuahua	221,483	731	598	42	387,108	463
Guerrero	203,816	673	550	39	356,229	426
Chiapas	200,492	662	541	38	350,420	419
Veracruz	196,955	650	532	37	344,237	412
Puebla	156,866	518	424	30	274,170	328
Tamaulipas	115,284	380	311	22	201,493	241
Oaxaca	109,469	361	296	21	191,329	229
Hidalgo	104,621	345	282	20	182,856	219
Campeche	70,598	233	191	13	123,391	148
Zacatecas	64,080	211	173	12	112,000	134
Sonora	57,889	191	156	11	101,178	121
Tlaxcala	55,370	183	150	11	96,776	116
Durango	49,707	164	134	9	86,878	104
Querétaro	41,134	136	111	8	71,894	86
San Luis Potosí	26,364	87	71	5	46,078	55
Tabasco	23,282	77	63	4	40,693	49
Nayarit	21,659	71	58	4	37,856	45
Morelos	19,961	66	54	4	34,889	42
Yucatán	18,387	61	50	3	32,138	38
Aguascalientes	11,065	37	30	2	19,339	23
Nuevo León	9975	33	27	2	17,435	21
Quintana Roo	8711	29	24	2	15,226	18
Colima	7531	25	20	1	13,163	16
Baja California Sur	6728	22	18	1	11,759	14
Coahuila	4562	15	12	1	7973	10
Baja California	1578	5	4	0	2759	3
Ciudad de México	750	2	2	0	1311	2
National	4,140,004	13,662	11,178	787	7,235,900	8653

Note: The national amount may not match the total due to rounding.

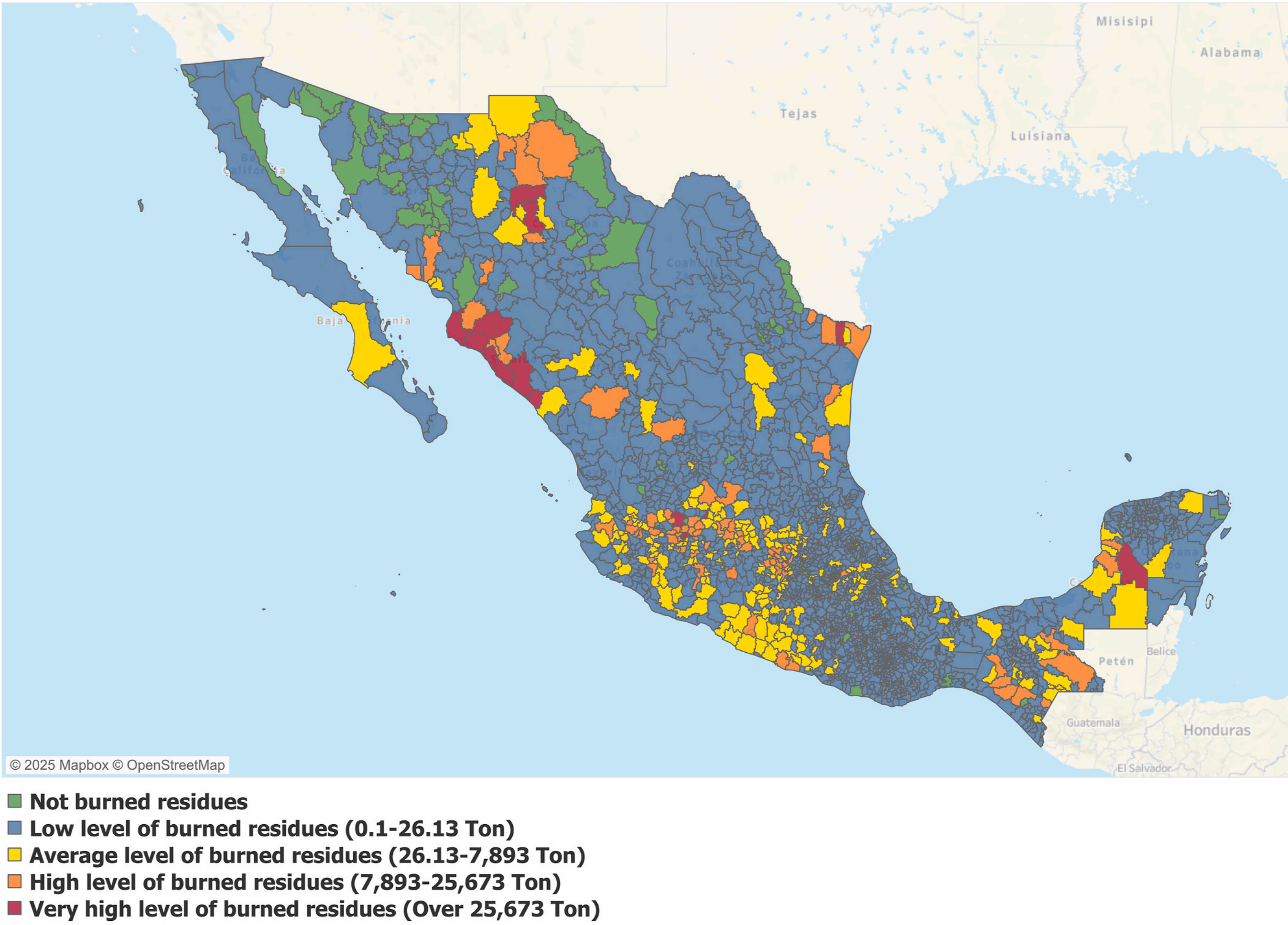

Fig. 8. Open field burning of agricultural residues of corn in Mexico by municipality.

the quantity of OFBAR was combined with a standard cellulosic ethanol yield per metric ton and an assumed biorefinery plant utilization rate of 90 %, to estimate the amount of bioenergy (as anhydrous ethanol) not produced due to burning (indicator 9). Additionally, the monetary value of this unproduced ethanol, it was estimated the corresponding volume of gasoline that could have been oxygenated, and the proportion of national E6 ethanol-blended gasoline demand that could have been satisfied, were calculated according to prevailing regulatory limits.

Given the large amount of data and the calculations required for the analysis at the municipal level (2,476), a database was built and cleaned in Microsoft Excel; subsequently, a quartile segmentation was carried out for each variable using Google Cloud's Big Query tool. An algorithm was also built in Python (ver. 7.0.8 Jupiter Notebook, and ver. 3.11.5 Phyton by Anaconda) to calculate the sub-totals by state and the national total for each pollutant and to standardize the formats of the final tables. The information was then loaded into Tableau software (Professional edition 2024.1.2), cross-referencing the data with information on geographic coordinates obtained from INEGI, finally generating the 10 municipal maps of emissions and bioenergy loss.

3.4. Limitations

Finally, the development of this study brought certain limitations which must be acknowledged to contextualize the obtained results. Data collection was restricted to Sinaloa, with only 2.9 % of the region's corn producers surveyed. While this focus provides valuable regional data, it limits the generalizability of results to Mexico's 2,476 municipalities, given the diversity of agricultural and environmental conditions. Additionally, the study relied on widely accepted global datasets, such as SEMARNAT-INECC and IPCC emission factors, rather than direct, localized measurements, which may introduce uncertainties when applying generalized values to Mexico's specific agricultural systems. Collecting such site-specific data was outside the logistical and resource scope of this research. Seasonal variations in residue burning, which heavily influence emissions, were not analyzed since this study centered on annual averages to simplify interpretation within time constraints. Socioeconomic factors, such as the enforcement of residue-burning laws and logistical obstacles (e.g., transport and storage), were equally critical but excluded, as their exploration extended beyond the environmental focus of this paper. Lastly, the effects of residue management practices on soil health and nutrient cycles were not assessed, as the primary emphasis was on emissions and bioenergy potential.

4. Results and discussion

4.1. Survey of farmers

The results of the survey on the current destination of agricultural

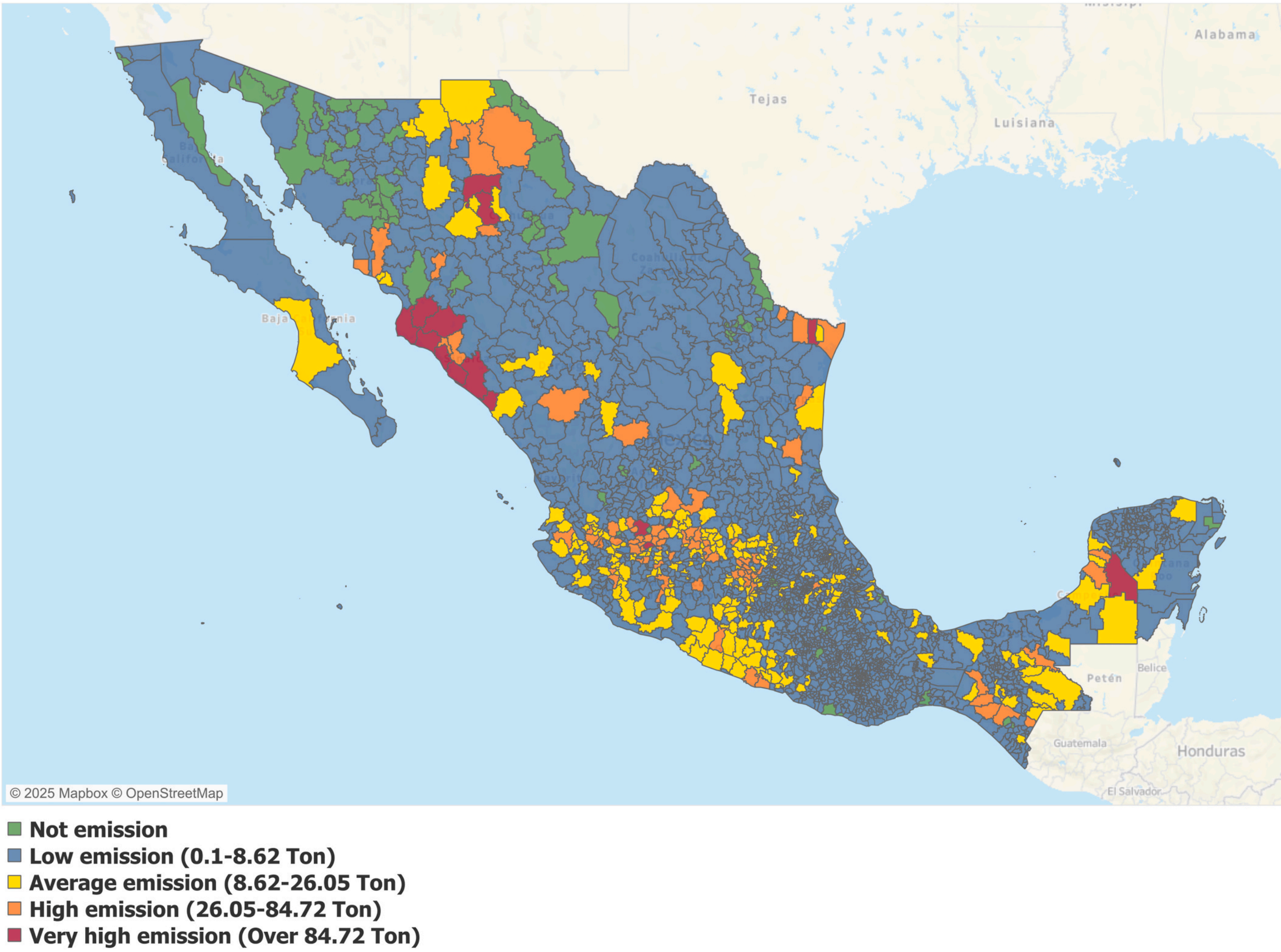

Fig. 9. PM_{10} emission of OFBAR from corn by municipality.

residues are presented in Fig. 7(a) and (b). The survey recorded an average corn yield of 12.10 tons per hectare, aligning closely with the governmental registry value of 12.18 tons per hectare for the same region under irrigation systems (SIAP and Database, 2024). At the national level, however, the average yield under similar conditions is 8.94 tons per hectare, reflecting a positive differential of over 3 tons per hectare. This highlights the degree of specialization in the region studied.

In terms of corn stover utilization, 71.1 % of farmers reported incorporating residues into the soil, while 15.6 % reported burning their residues in the open field, and 11.5 % reported selling them for animal feed. A smaller proportion (1.8 %) reported using the residues for other purposes, such as supporting their own livestock. Notably, the 15.6 % who engage in open-field burning contribute to environmental impacts, whereas the 11.5 % who sell residues represent the existing local stover market.

Farmers who sell their corn stover were asked about their buyers. Of these, 88 % reported selling to intermediaries who bale the residues and resell them, 7 % sold to individuals baling residues for their own livestock, and 3 % sold directly to livestock associations, which then distribute the residues to members. This identifies a structured value chain for agricultural residues, highlighting the role of wholesale traders serving as intermediaries between farmers, the original residue owners, and livestock farmers, the end users.

This information confirms the presence of a value chain for agricultural residues in Sinaloa, where a wholesale trader serves as an intermediary between farmers, who are the original owners of the residues, and livestock farmers, who constitute the primary market for these agricultural by-products.

The survey revealed that the most common logistical method for removing corn stover from fields, once the corn grain has been harvested, involves a baling process performed by wholesale traders, accounting for 99 % of cases. In this region, the collection of corn stover is carried out using large square bales, each weighing approximately 500 kg. These findings indicate that farmers do not sell their agricultural residues directly to the end users. Instead, an intermediary, typically a wholesale trader, handles the baling process and retains a portion of the value of the agricultural residues. Additionally, the survey reported that the price paid to farmers for their stover ranges between \$200 and \$300 MXN[1]/ha, which is significantly lower than the price at which the wholesale trader sells it on the final market.

In a previous works, the authors (Becerra-Pérez et al., 2022) identified that residue collection logistics in Mexico typically follow a three-pass method, which includes shredding, raking, and baling. While this method increases the cost of corn stover collection, it maximizes the amount of residues extracted from the field. Brechbill and Tyner (2008) estimated that using the three-pass method allows for the recovery of up

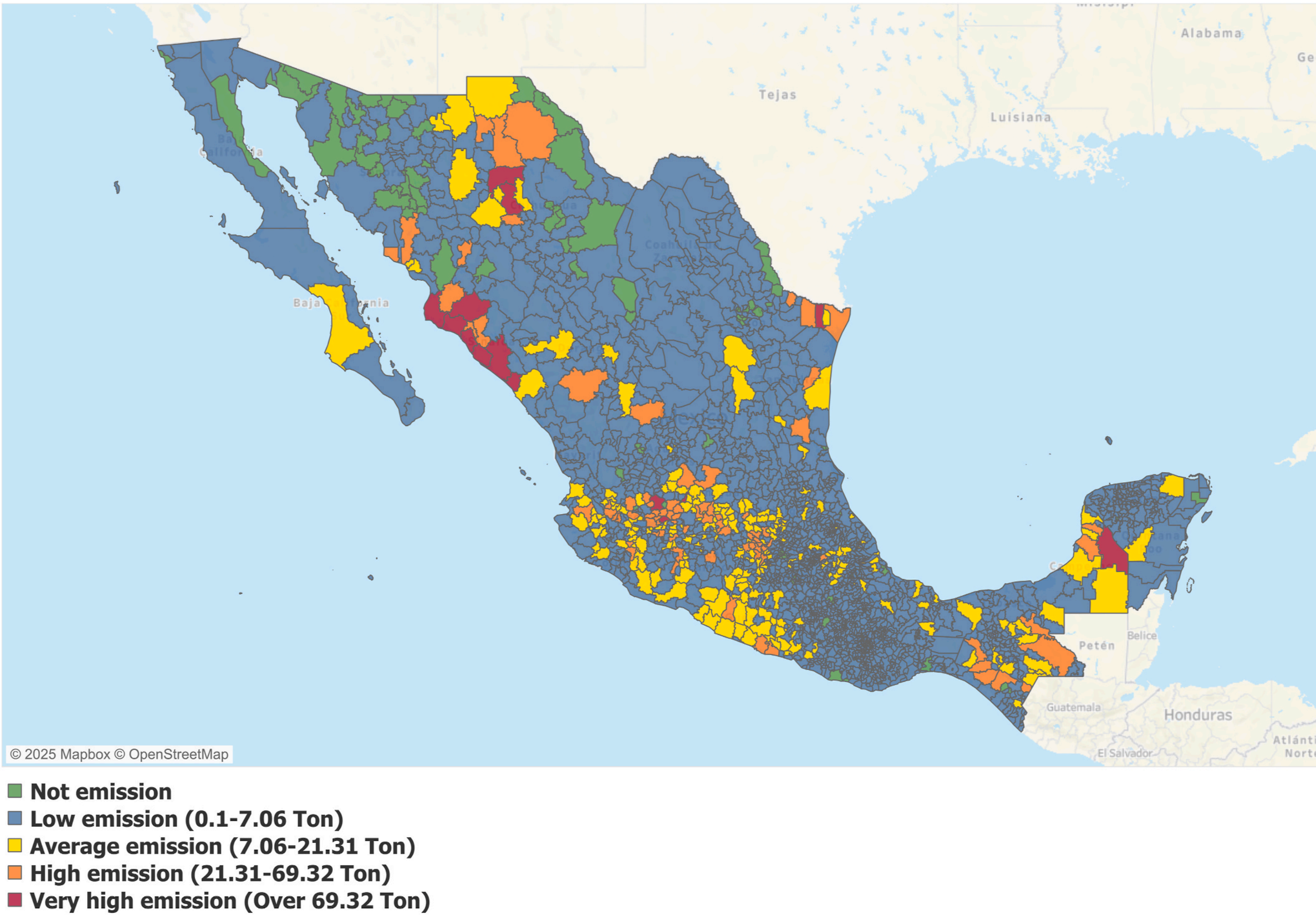

Fig. 10. $PM_{2.5}$ emission of OFBAR from corn by municipality.

to 70 % of the total corn stover produced. In contrast, the two-pass method, which involves raking and baling, recovers up to 52 %, while the one-pass method, limited to baling, recovers up to 38 %.

The presence of a wholesale trader in the value chain for agricultural residues in Mexico may contribute to excessive collection of corn stover, which could lead to nutrient depletion and soil erosion, creating conditions of unsustainability in agricultural practices. Studies suggest that agricultural residue remotion should be limited to 30–50 % of the total residue volume (Honorato-Salazar and Sadhukhan, 2020; Becerra-Pérez et al., 2022; Yepez-García et al., 2010; English et al., 2012; Blanco-Canqui and Lal, 2009; Blanco-Canqui, 2013; Hernández et al., 2019), to avoid the excessive use of machinery and transport to reduce soil compaction and thus control erosion by water runoff (Gupta et al., 1979; Wortmann et al., 2012)and force the replenishment of nutrients by the concept of agricultural residue remotion (Becerra-Pérez et al., 2022; Brechbill and Tyner, 2008).

The survey results indicate that 65 % of corn farmers are willing to sell their crop residues, while 35 % are not. Among those unwilling to sell, most cited concerns include soil nutrient depletion if residues are removed (77 %), followed by unacceptably low market prices (20 %), and current on-farm use of the residues. Notably, 20 % of the unwilling farmers constitute a subgroup that might reconsider if financial incentives improve. This equivalent to roughly 7 % of all respondents. Above findings suggest that the practical willingness to sell could potentially increase to 72 % under better market conditions. Regarding preferred management options for crop residues, 71 % of respondents favored selling the residues as-is after harvest to avoid additional expenses, 15.6 % reported incineration, 12.8 % opted not to sell, and only 0.7 % preferred baling stover for later sale. These responses highlight two key findings: first, approximately 71 % of farmers could directly supply corn stover to alternative uses; second, a significant minority (around 16 %) continue to burning their stover.

Above findings are interpreted with direct reference to the practical circumstances and decision-making processes that farmers encounter in managing their crop residues. In case a farmer chooses to sell their corn stover, there are generally two options: a) The farmer can sell the stover as it remains spread across the field after grain harvest, incurring no additional costs since no further action is taken. In this scenario, the buyer (often a third party) is responsible for harvesting and collecting the residue. b) the farmer can undertake the harvesting process themselves by baling the stover and then selling the bales. This approach involves additional labour and operational expenses for the farmer. Although, most farmers prefer the first option, as it involves minimal effort and no extra costs. It is also notable that, in regions characterized by intensive agriculture, a type of wholesale intermediary has emerged. This wholesaler is neither a farmer nor a final end-user of the stover. Instead, they specialize in purchasing the spread stover directly from farmers (following the first option), assume the costs associated with its collection, and subsequently sell the processed residue to end users. Naturally, these intermediaries derive substantial profit from this

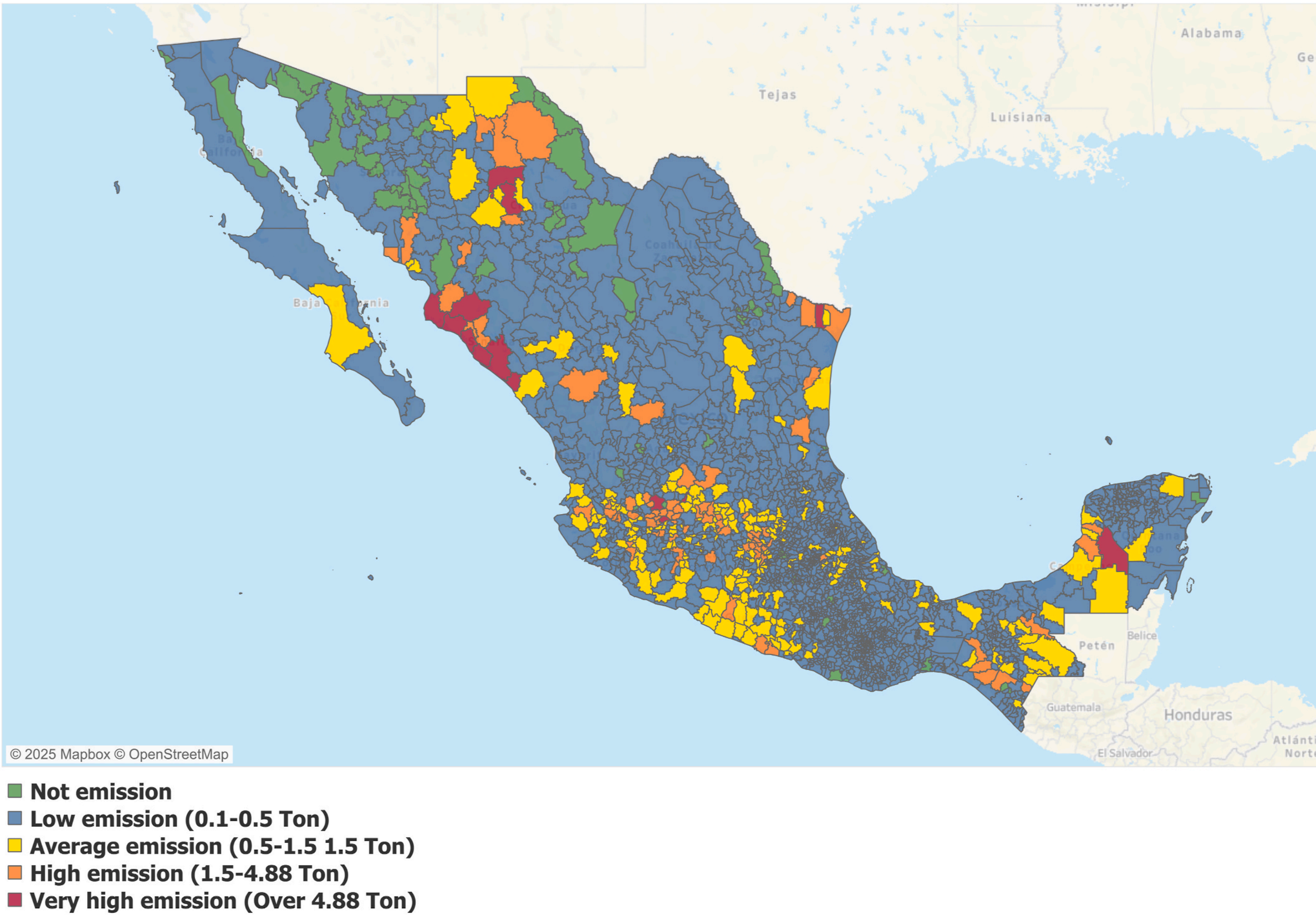

Fig. 11. Black Carbon emission of OFBAR from corn by municipality.

arrangement.

The survey revealed that the price requested by corn producers for corn stover is between $400 and $600 MXN/ha, which is double the current market price in the region. To promote the use of agricultural residues, public policies may need to focus on increasing demand through targeted projects, which could drive a rise in the price of corn stover and provide farmers with an additional source of income, thereby improving their overall profitability. Such measures may also discourage the open-field burning of stover, as selling the residues would become a more economically attractive alternative to incineration.

The survey further highlighted farmers' willingness to formalize the commercialization of stover through buy-sell contracts, contingent upon price improvements. Among respondents, 65 % expressed a high probability of signing such contracts under favorable pricing conditions, 18 % reported medium probability, and 15 % indicated low probability. Additionally, the average volume of corn stover extracted was reported to be 3.4 tons/ha.

4.2. *Current use of corn stover*

Corn cultivation in Mexico is concentrated in a limited number of regions. During the decade 2013–2022, the average annual corn production was 26.3 million tons, with 80 % of this volume generated in ten states: Sinaloa, Jalisco, State of Mexico, Michoacán, Guanajuato, Chihuahua, Guerrero, Chiapas, Veracruz, and Puebla. Notably, the top four states (Sinaloa, Jalisco, State of Mexico, and Michoacán) produced 50 % of the nation's corn, with Sinaloa alone contributing over one-fifth of total national production (see Table 1). Since the volume of agricultural residues correlates directly with the harvested grain, Sinaloa also generates the largest volume of corn stover. According to Becerra-Pérez et al. (2022), the Harvest Index (HI) for corn is 0.45, indicating that 45 % of the total aboveground biomass in corn crops consists of harvestable grain. To derive the volume of corn residues, the following formula is applied:

$$CRI = \left(\frac{1}{HI}\right) - 1$$

Where CRI = crop residue index, and HI = harvest index.

In the case under analysis, the Corn-to-Residue Index (CRI) is 1.22, indicating that 1.22 kg of residue is generated for every kilogram of corn grain harvested. Annual corn stover production in Mexico is estimated at 32.1 million tons, with the highest residues produced in the same ten states that lead in grain production. Two key aspects should be highlighted regarding this estimate: 1) it represents the gross volume of corn stover, which varies based on factors such as the proportion burned in open fields (OFBAR), the amount used for animal feed, the agricultural practices followed by farmers (traditional or conservation tillage), and sustainability criteria aimed at preventing soil nutrient depletion and erosion; and 2) it does not account for yield differences associated with irrigation versus rainfed systems. Nonetheless, this figure provides a

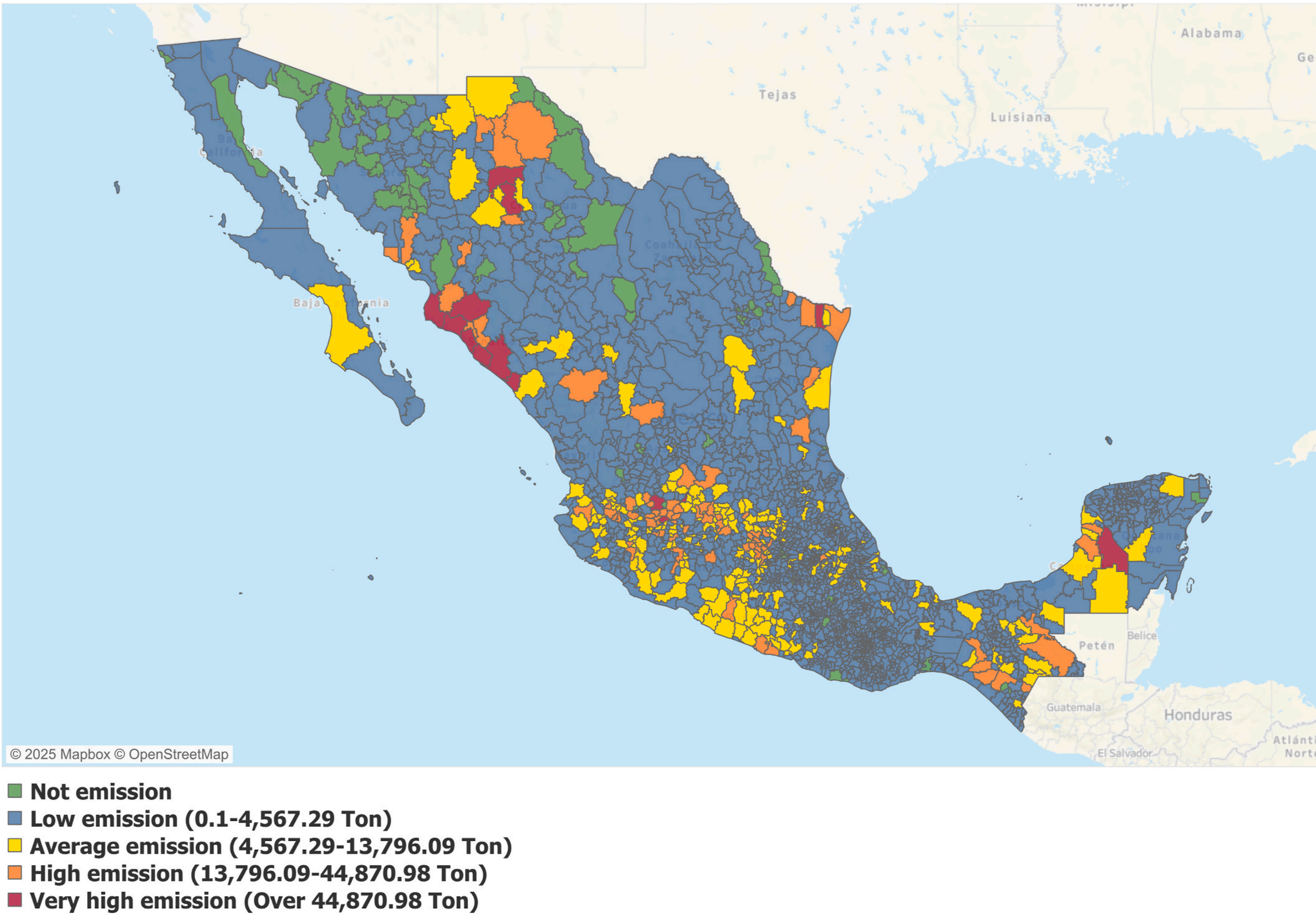

Fig. 12. CO_2 emission of OFBAR from corn by municipality.

useful approximation for determining the geographic distribution of crop residues in Mexico and facilitates interregional analyses at the municipal scale.

The analysis also reveals significant gaps in knowledge and infrastructure concerning agricultural residues in Mexico, including logistics, quantification, trading, open-field burning practices, pricing, geographic distribution, willingness to sell, and their impacts on environmental health. Moreover, their untapped potential for contributing to regional development remains underexplored.

4.3. Pollutant emissions from open fields burning corn stover

Following the methodology outlined in Section 3.3, along with emission factors provided by SEMARNAT-INECC (SEMARNAT-INECC, 2016) and IPCC guidelines (IPCC, 2006), the emissions resulting from OFBAR - corn stover at the municipal scale were calculated. The emissions of five key pollutants: PM10, PM2.5, BC, CO_2 and CH_4 were considered. Recognizing the uncertainties surrounding the management and utilization of agricultural residues in Mexico, a key objective of the conducted survey was to quantify the volume of OFBAR. The findings revealed that 15.6 % of corn farmers in the study area still resort to burning their residues. This practice persists largely due to cultural traditions or as a cost-saving measure for land preparation ahead of the subsequent planting season.

The results at the state level are presented in descending order, ranked from the largest to smallest contributors of open-field burning of corn stover. At municipal level, due to the extensive number of municipalities (2,476), results are grouped into ranges and illustrated through maps to facilitate interpretation. Table 2 shows OFBAR - corn stover volumes and the corresponding emissions across Mexico by state. Estimates indicate that eight states collectively account for over 70 % of all OFBAR - corn stover. The largest contributor is Sinaloa, with approximately 860,000 tons annually (21 %), followed by Jalisco with 590,000 tons (14 %), the State of Mexico with 310,000 tons (8 %), Michoacán with 300,000 tons (7 %), Guanajuato with 270,000 tons (6 %), Chihuahua with 220,000 tons (5 %), Guerrero with 200,000 tons (5 %), and Chiapas with 200,000 tons (5 %). These same states are also the highest contributors GHG emissions from corn stover and should therefore be prioritized in the development of regional policies aimed at reducing these emissions, which negatively impact both environmental quality and public health. For instance in Sinaloa, where agricultural residue burning is paradoxically prohibited by the state's law (Congreso Estado de Sinaloa, 2018), approximately 2,900 tons of PM10, 2,300 tons of PM2.5, 164 tons of BC, 1.5 million tons of CO_2, and 1800 tons of CH_4 are emitted into the atmosphere annually.

It is estimated that Mexico incinerates approximately 4.1 million tons of corn residues annually, releasing significant quantities of pollutants into the atmosphere. These include around 13,600 tons of PM10,

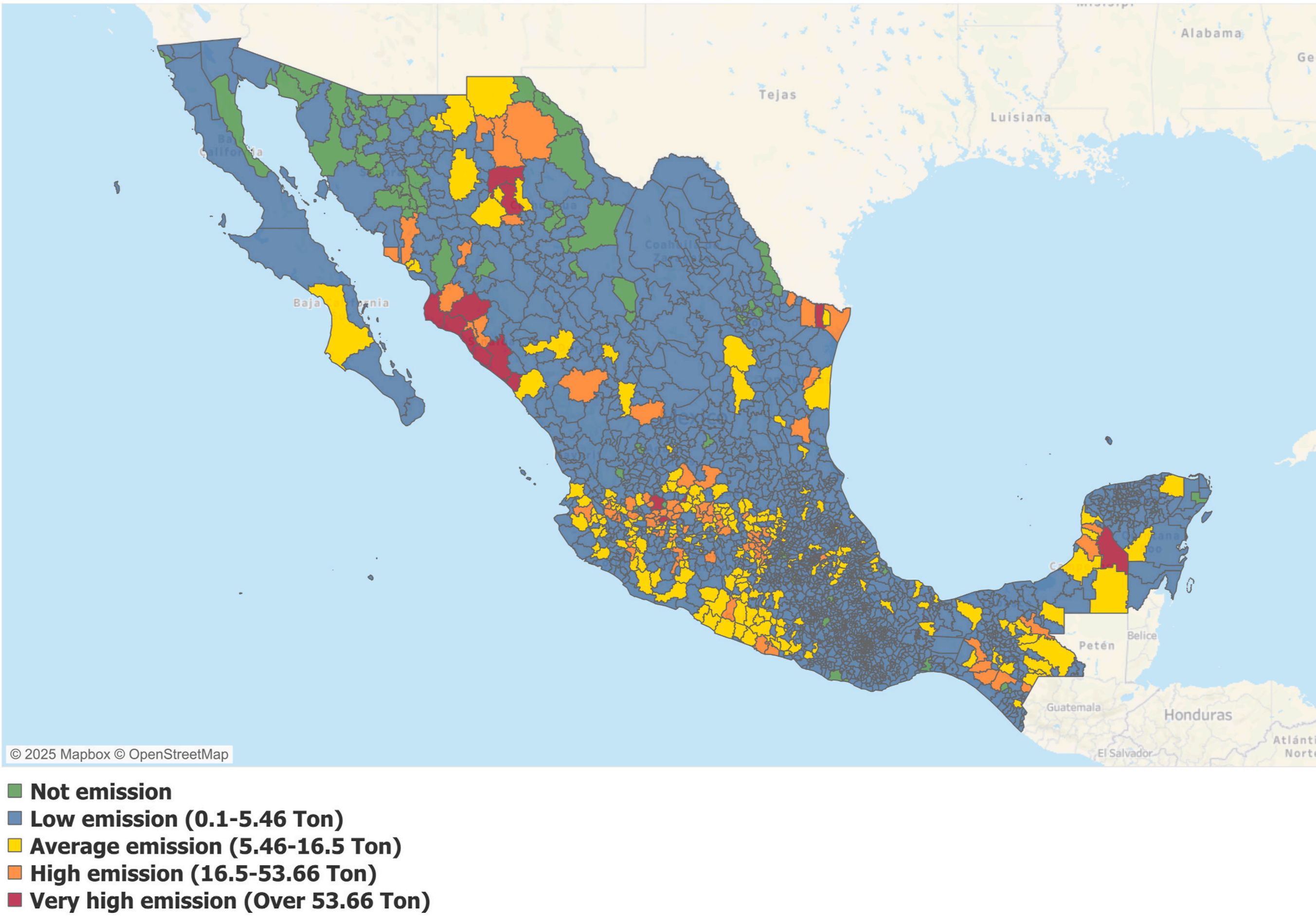

Fig. 13. CH_4 emission of OFBAR from corn by municipality.

11,200 tons of PM2.5, 800 tons of black carbon (BC), 7.2 million tons of CO_2, and 8700 tons of CH_4. This study focuses on corn, the country's most important agricultural crop, which produces just over 32 million tons of residues annually. The estimates represent an annual average from 2013 to 2022, encompassing planted areas under both irrigation and rainfed systems.

The municipal-level analysis of corn stover is illustrated in Fig. 8. Due to the large number of municipalities in Mexico (2,476), a classification scheme was developed, dividing municipalities into five groups.

1) **Not burned residues**: municipalities that do not produce corn and therefore do not engage in burning (77 municipalities).
2) **Low-level burned residues**: municipalities burning between 0.1 and 26.13 tons of corn residues (2075 municipalities).
3) **Average-level burned residues**: municipalities burning between 26.14 and 7893 tons (229 municipalities).
4) **High-level burned residues**: municipalities burning volumes between 7893 and 25,673 tons (81 municipalities).
5) **Very high-level burned residues**: municipalities where burning exceeds 25,674 tons (14 municipalities).

The estimated emissions for each pollutant are depicted in Fig. 9 through 13, with municipalities grouped into five categories: 1) No emissions, 2) Low emissions, 3) Average emissions, 4) High emissions, and 5) Very high emissions. Details of the emission ranges for each classification are included in the map legends.

The municipalities in the "very high-level burned residues" category are of particular interest due to the significant volume of biomass involved. This group includes 14 municipalities, with seven located in Sinaloa (Guasave, Ahome, Angostura, Culiacán, Elota, Navolato, and Sinaloa). The remaining municipalities are in Chihuahua (Cuauhtémoc and Namiquipa), Jalisco (La Barca and Tepatitlán de Morelos), Campeche (Hopelchén), Tamaulipas (Río Bravo), and Guanajuato (Purísima del Rincón). Notably, Sinaloa accounts for 50 % of the municipalities within this category, underscoring its importance in contributing to open-field burning emissions.

The PM and BC are particularly concerning are widely acknowledged to have harmful effects on human health, not only in areas close to their emission sources but also in remote regions. Due to their small size and aerodynamic properties, these particles can travel long distances. For instance, Sapkota et al. (2005) observed PM from forest fires in Quebec, Canada, being detected in Baltimore, USA, approximately 1,200 km downwind. This underscores the broader spatial impact of biomass burning emissions on air quality and public health, extending well beyond the immediate point of origin.

Although the majority of anthropogenic PM emissions result from fossil fuel combustion, primarily in the transportation and electricity sectors, OFBAR also contributes significantly to PM levels. In addition, residential biomass use for heating in developed countries and biomass burning for cooking in developing regions further elevate particulate matter emissions (Borchers Arriagada et al., 2019). Evidence in the literature strongly links PM exposure to adverse human health effects

Table 3
Bioenergy and monetary value lost in Mexico due to the OFBAR-corn stover.

State	Bioenergy lost by burned residues (millions of liters of anhydrous ethanol)	Monetary value lost due to non-production of anhydrous ethanol (USD millions)	E6 gasoline that might have been oxygenated (millions of liters)	Share of domestic E6 demand in Mexico (2022) (%)
Sinaloa	230	$175.0	3839	20.9 %
Jalisco	157	$119.5	2620	14.3 %
México	83	$63.2	1387	7.6 %
Michoacán	81	$61.5	1349	7.4 %
Guanajuato	71	$54.0	1183	6.5 %
Chihuahua	59	$44.9	986	5.4 %
Guerrero	54	$41.4	907	4.9 %
Chiapas	54	$40.7	892	4.9 %
Veracruz	53	$40.0	877	4.8 %
Puebla	42	$31.8	698	3.8 %
Tamaulipas	31	$23.4	513	2.8 %
Oaxaca	29	$22.2	487	2.7 %
Hidalgo	28	$21.2	466	2.5 %
Campeche	19	$14.3	314	1.7 %
Zacatecas	17	$13.0	285	1.6 %
Sonora	15	$11.7	258	1.4 %
Tlaxcala	15	$11.2	246	1.3 %
Durango	13	$10.1	221	1.2 %
Querétaro	11	$8.3	183	1.0 %
San Luis Potosí	7	$5.4	117	0.6 %
Tabasco	6	$4.7	104	0.6 %
Nayarit	6	$4.4	96	0.5 %
Morelos	5	$4.1	89	0.5 %
Yucatán	5	$3.7	82	0.4 %
Aguascalientes	3	$2.2	49	0.3 %
Nuevo León	3	$2.0	44	0.2 %
Quintana Roo	2	$1.8	39	0.2 %
Colima	2	$1.5	34	0.2 %
Baja California Sur	2	$1.4	30	0.2 %
Coahuila	1	$0.9	20	0.1 %
Baja California	0	$0.3	7	0.0 %
Ciudad de México	0	$0.2	3	0.0 %
National	1106	$840.2	18,425	100 %

Note: The national amount may not match the total due to rounding.

(Becerra-Pérez et al., 2021). Documented health outcomes include stroke (Yuan et al., 2019), Alzheimer's disease and dementia (Tsai et al., 2019), asthma (Borchers Arriagada et al., 2019), atopic dermatitis and rhinitis (Hassoun et al., 2019), low birth weight (Tsoli et al., 2019), breast cancer (Zhang et al., 2019), melanogenesis (Peng et al., 2019), chronic obstructive pulmonary disease (Han et al., 2019), among others.

The World Health Organization (WHO) has set upper limits for PM2.5 concentrations at 15 μg/m^3 for the 24-h average and 5 μg/m^3 for the annual average load (WHO, 2021). In Mexico, as of 2023, the established upper limits were 33 μg/m^3 for the 24-h average and 10 μg/m^3 for the annual average load (Diario Oficial de la Federación, 2021). However, diverse authors indicates that many cities in both developed and developing countries exceed these thresholds, thereby exposing their populations to significant health risks. Ultrafine particles (PM0.1) and fine particles (PM2.5) are particularly dangerous as they penetrate the lungs through inhalation and are retained in the alveoli, where they may contribute to cardiorespiratory diseases and lung cancer. In this context, Johnston et al. (2019) in a study conducted for Thailand conclude that PM from agricultural biomass burning causes toxicity, like PM from the use of fossil fuels in transportation, causing the same problems on human health. In addition, PM can travel long distances, depending on wind speed and direction, so it is possible that OFBAR is impacting not only rural areas, but also urban areas. Research demonstrates that combustion-derived particulates constitute a primary driver of cardiopulmonary disease, with $PM_{2.5}$ particles penetrating deep into respiratory airways, compromising macrophage function, and initiating pathological processes ranging from obstructive pulmonary diseases to neoplastic transformations (Niu et al., 2023). Regional studies across Southeast Asia reveal distinct spatial and temporal patterns in exposure and health outcomes. In northern Thailand, satellite-monitored agricultural burning sequences—beginning with sugar-cane fields, followed by corn, forest areas, and rice paddies—directly correlate with reduced visibility and increased hospital admissions (Paluang et al., 2024). Beyond Thailand, Equatorial Asian peatland fires during El Niño events show strong associations with elevated community mortality rates (Yin, 2023). Detailed pollutant characterization studies demonstrate that ultrafine carbonaceous particles (<0.1 μm) reach concentrations of 20 μg m^{-3} during dry seasons in Chiang Mai and Tachileik, while vehicular emissions dominate during wet periods (Tial et al., 2024). A comprehensive decade-long review confirms persistent north-south gradients in $PM_{0.1}$ concentrations, attributing episodic peaks to both local combustion sources and transboundary transport mechanisms (Suriyawong et al., 2023).

In addition to its environmental and public health impacts OFBAR can also degrade soil properties and fertility. Incineration alters the soil structure, particularly the uppermost layer, disrupting oxygenation and allowing combustion residues to infiltrate the water table, thus contaminating groundwater. Moreover, when the soil is left exposed after burning, it becomes vulnerable to erosion from rainfall. The incineration process also eliminates beneficial soil organisms, including earthworms, actinomycetes, bacteria, and fungi, which are critical for the decomposition of organic matter and the natural release of nutrients (Costa Rica University, 2024). To counteract OFBAR, some local authorities have initiated campaigns to raise awareness about the

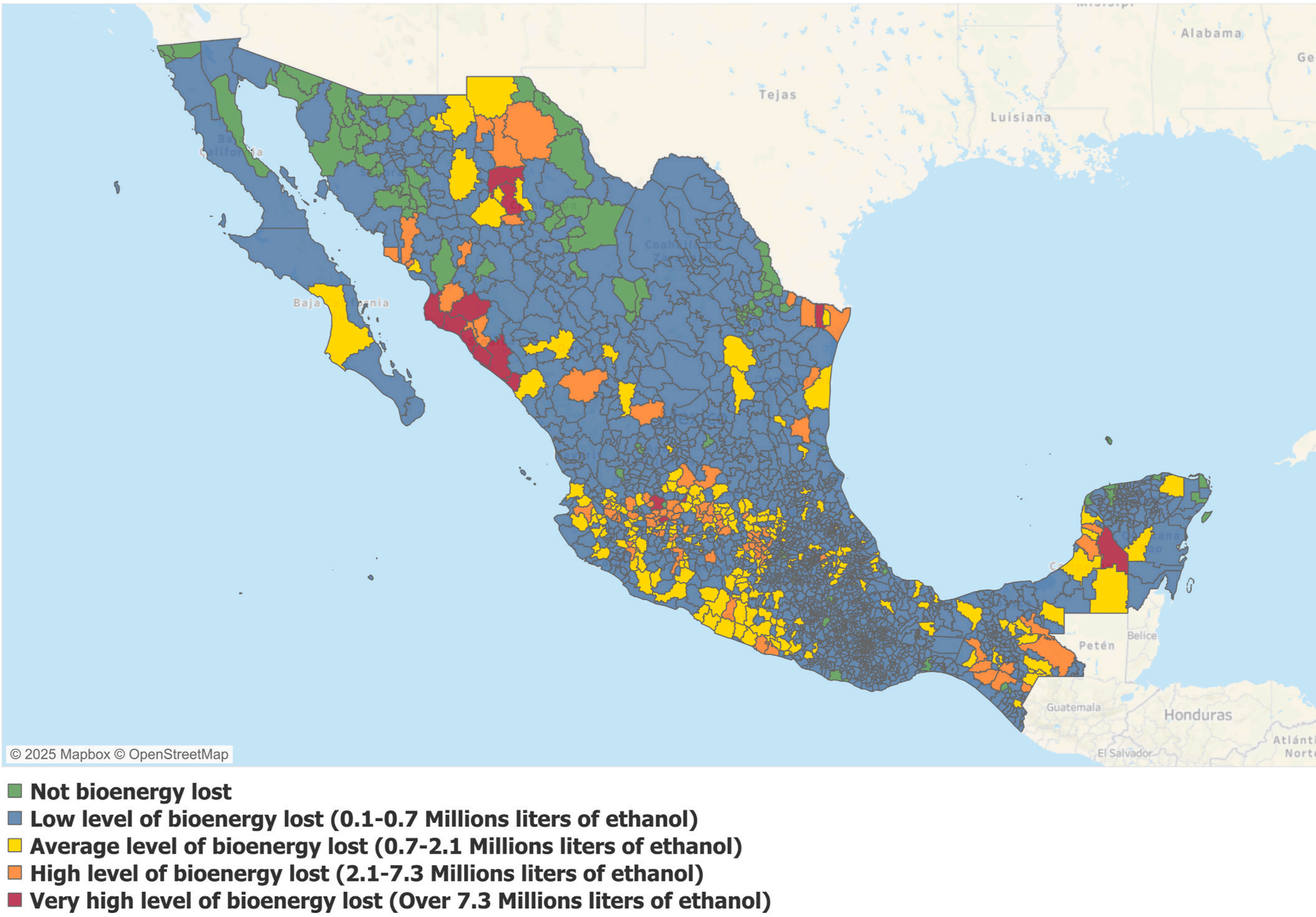

Fig. 14. Bioenergy loss of OFBAR from corn by municipality (millions of litters of ethanol anhydro).

advantages of incorporating agricultural residues back into the soil. In Sinaloa, Mexico, these efforts emphasize benefits such as improving soil pH, boosting microbial diversity, and increasing populations of specific beneficial microorganisms such as actinomycetes, Bacillus, Trichoderma spp., and nitrifying bacteria. Collectively, these measures aim to enhance soil fertility and productivity (CESAVESIN, 2016).

4.4. Potential impacts of bioenergy lost

To evaluate the economic impact of OFBAR, the bioenergy lost due to the residues not being utilized to obtain added value products was estimated. Utilizing global expertise in converting lignocellulosic biomass, such as corn stover, combined with widely available technologies and standard conversion parameters, the potential production of anhydrous ethanol (commonly used as a gasoline oxygenate) was calculated. The analysis revealed that the biofuel production forgone amounted to over 1100 million liters of anhydrous ethanol, with an estimated market value of US$ 840 million.

Another metric to assess the impact of OFBAR is the volume of gasoline that could have been oxygenated using the unrealized anhydrous ethanol, along with its contribution to national biofuel demand. According to Mexican Standard NOM-016-CRE-201 (Diario Oficial de la Federación, 2016), which allows up to 6 % ethanol blending by volume, approximately 18,500 million liters of gasoline could have been oxygenated. This volume corresponds to nearly 100 % of the national demand for ethanol-blended fuels, underscoring the considerable economic and energy potential lost due to OFBAR.

The state-level estimates of bioenergy potential as anhydrous ethanol and its corresponding monetary value, lost due to the burning of corn stover, are presented in Table 3. Across Mexico's 32 regions, eight states alone could produce approximately 790 million liters of anhydrous ethanol, with a market value of US$ 600 million, representing 72 % of the national demand for this biofuel. The anhydrous ethanol potential lost within these eight leading states includes 230 million liters in Sinaloa, 157 million liters in Jalisco, 83 million liters in the State of Mexico, 81 million liters in Michoacán, 71 million liters in Guanajuato, 59 million liters in Chihuahua, and 54 million liters each in Guerrero and Chiapas. This figures represent a substantial economic and social loss, as failing to utilize this biomass not only forfeits significant financial benefits but also perpetuates an environmental and public health issue in Mexico.

To estimate the economic impact of OFBAR at the municipal level, the bioenergy loss was calculated in terms of liters of anhydrous ethanol that could have been produced from the unused biomass, along with its corresponding economic value. Additionally, the potential volume of gasoline that could have been oxygenated at a 6 % ethanol blend (by volume) and the percentage this would represent relative to the national gasoline demand for fuel use were determined. Given the large number of municipalities in Mexico (2,476), the results are presented through maps in Figs. 14–17. Municipalities were categorized into five groups for each variable: 1) **No bioenergy loss**: No ethanol loss, monetary value loss, or contribution to domestic E6 demand. 2) **Low bioenergy loss**:

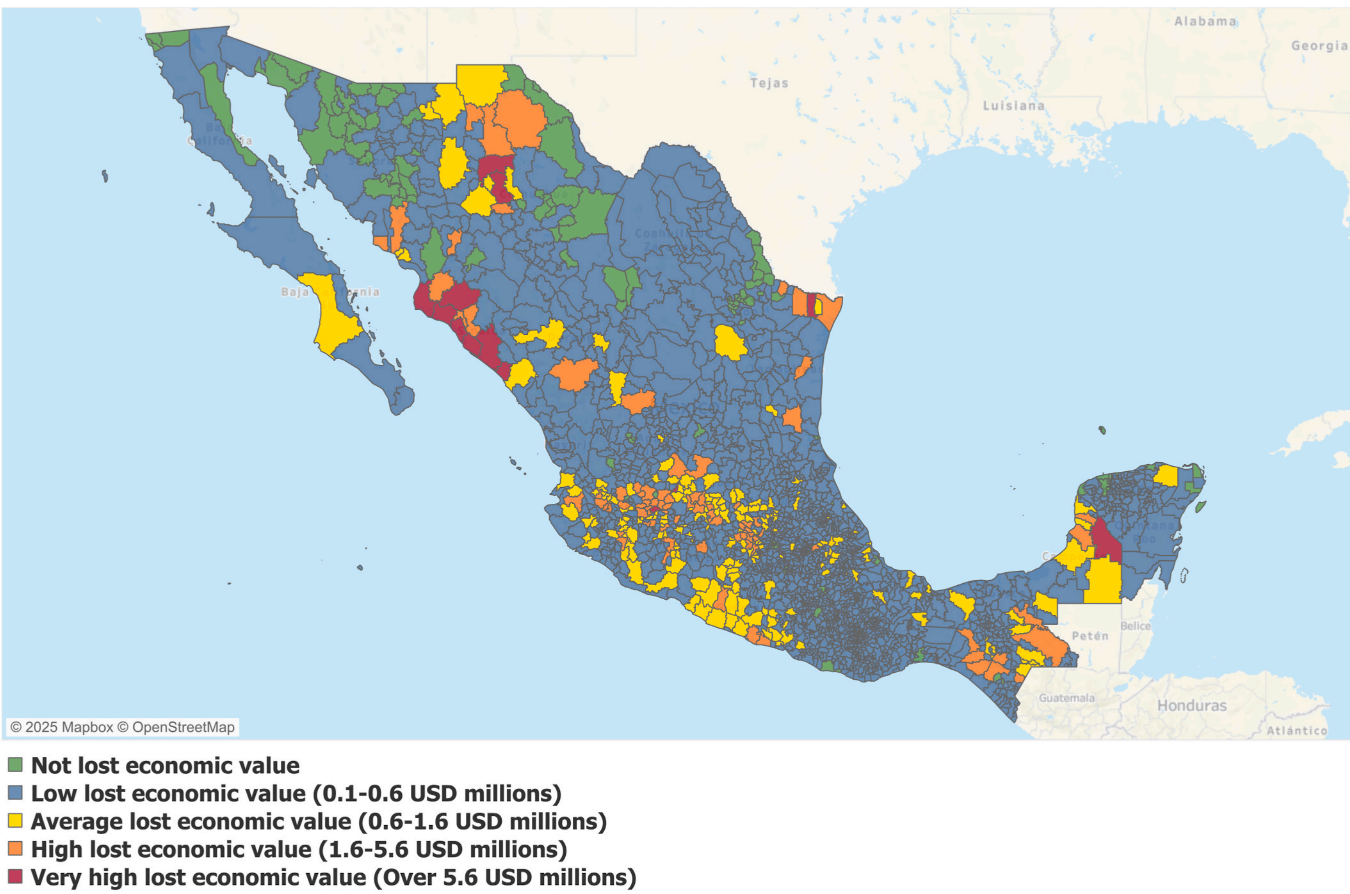

Fig. 15. Monetary value lost due to non-production of ethanol anhydro by municipality (USD millions).

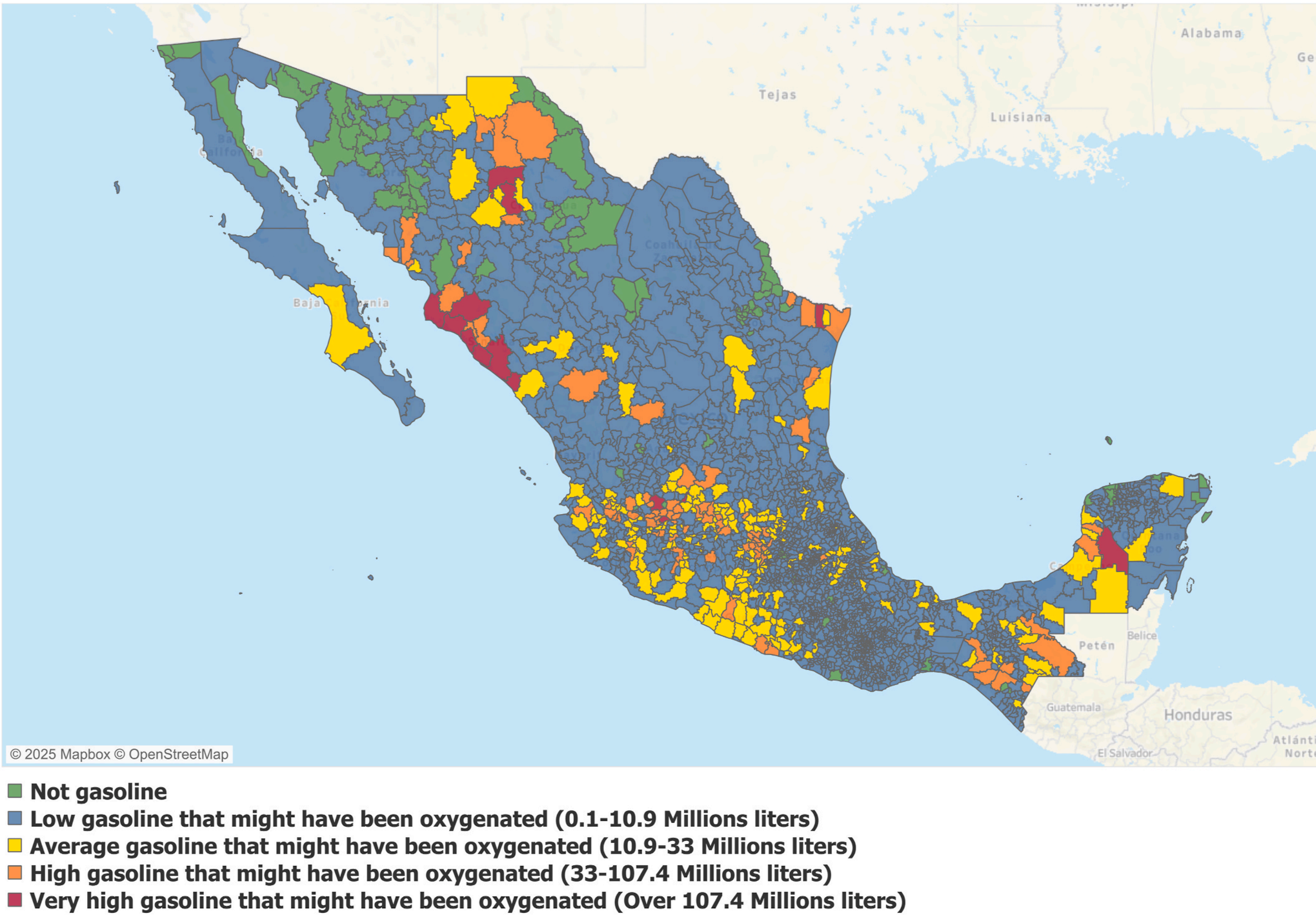

Fig. 16. E6 gasoline that might have been oxygenated by municipality (millions of liters).

Minimal ethanol loss, monetary value loss, or contribution to E6 demand. 3) **Average bioenergy loss**: Moderate ethanol loss, monetary value loss, and gasoline oxygenation potential relative to E6 demand. 4) **High bioenergy loss**: Significant losses in ethanol, monetary value, and E6 demand potential. 5) **Very high bioenergy loss**: Substantial ethanol losses, monetary value losses, and gasoline oxygenation potential. The ranges of estimated values for each group are detailed in the map legends. As with pollutant emissions, bioenergy losses are directly proportional to the volume of corn stover burned. Consequently, the same 14 municipalities identified as the largest contributors to OFBAR also incur the greatest economic losses. These regions, therefore, hold the highest potential for social and economic gains should this natural resource be redirected for productive use rather than being burned.

5. Conclusions

The open-field burning of agricultural residues (OFBAR) in Mexico represents a pressing issue for the country, with deep implications not only for public well-being but also for the environmental health of its inhabitants. This paper has shown how approximately 15.6 % of annual corn stover (about 4.1 million tons per year) is burned in the field. The emissions concentrated in 14 municipalities release approximately 13,600 tons of PM10, 11,200 tons of PM2.5, 800 tons of black carbon, 7.2 million tons of CO2, and 8,700 tons of CH4 annually, which severely impact air quality and can potentially increase the probabilities of respiratory illness, particularly for vulnerable populations. Most of the OFBAR related emissions are concentrated in eight states (Sinaloa, Jalisco, State of Mexico, Michoacán, Guanajuato, Chihuahua, Guerrero, and Chiapas) which are responsible for over 70 % of emissions.

This paper also demonstrates how the inefficient OFBAR results in substantial economic losses; the same biomass residues could potentially be converted into 1,100 million liters of anhydrous ethanol per year, which is valued at over $ 840 million. These anhydrous ethanol losses could potentially meet 100 % of Mexico's current demand for anhydrous ethanol (at an E6 ethanol blend with gasoline), presenting an alternative to fossil-fuel-derived additives such as MTBE. Eight key states, led by Sinaloa, collectively account for more than 70 % of residues burned and lost ethanol potential, making them critical targets for interventions. Consequently, the valorization of corn stover as an ethanol feedstock offers a dual advantage: significantly reducing pollutant emissions while driving the advancement of Mexico's ethanol industry.

The results from this paper reveal the urgent need for integrative strategies to address the harmful impacts of biomass burning, particularly on environmental health. Thus, regionally focused policies should be implemented prioritizing high-emission municipalities, employing strict regulatory enforcement, and comprehensive farmer education initiatives, while considering targeted financial incentives to encourage sustainable crop residue management practices among farmers. Moreover, the promotion of market-driven approaches, particularly through the expansion of biofuel infrastructure, has the potential to transform agricultural residues from an environmental problem into a valuable economic asset. Finally, the integration of localized interventions, considering national energy and environmental objectives, will allow Mexico to achieve meaningful reductions in greenhouse gas emissions, enhance air quality, and stimulate sustainable economic development in rural regions.

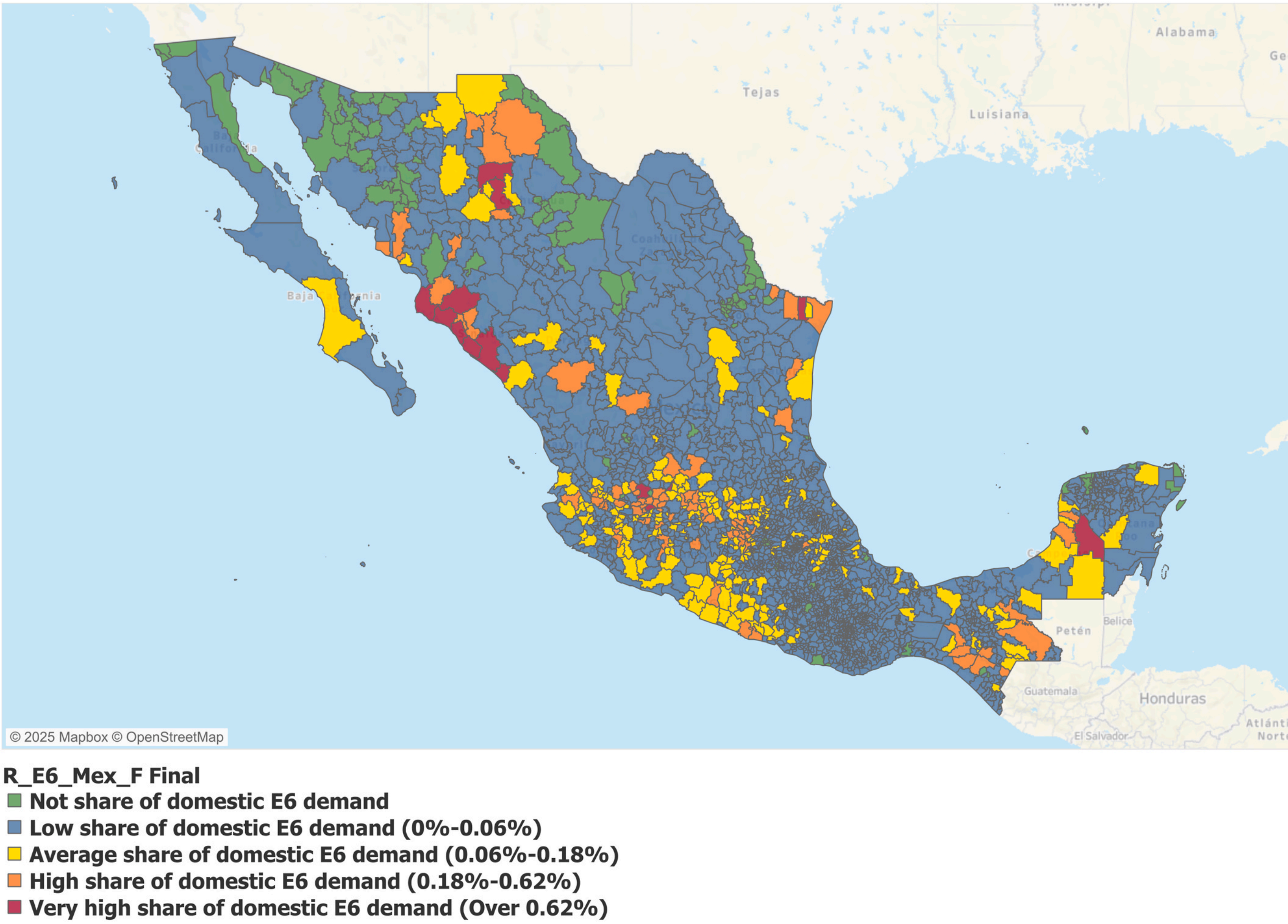

Fig. 17. Percentage of E6 demand that could have been met in Mexico per municipality (%).

CRediT authorship contribution statement

Luis Armando Becerra-Pérez: Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Luis E. Rincón:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Benjamín García-Páez:** Writing – review & editing, Validation, Methodology, Investigation. **John A. Posada-Duque:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Claude 4 Sonnet in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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