Variations of Atmospheric Emissions in the Biomass Burning of Tree Species as an Environmental Indicator

Variaciones de emisiones atmosféricas en la quema de biomasa de especies arbóreas como indicador ambiental

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Abstract

Biomass burning (BB) serves as both an energy source and an environmental indicator. This study examined how CO_2 and fine particle emissions vary during the combustion of biomass from three tree species to determine their contribution to environmental pollution. Leave and stem samples were taken from *A. farnesiana* (huizache) tree, *S. molle* (pirul), and *P. laevigata* (mesquite). The dry biomass was thermally processed in a muffle furnace at temperatures ranging from 50°C to 450°C. Emissions of CO_2, particles smaller than 2.5 microns ($PM_{2.5}$), particles smaller than 10 microns (PM_{10}), and total volatile organic compounds (TVOC) were measured. The highest emission levels occurred during the pyrolysis process between 250°C and 450°C in both leaves and stems. Among the leaves, the highest emissions of $PM_{2.5}$ and PM_{10} were found in huizache, while the highest values were found in mesquite stems. In terms of leaves, mesquite had the highest CO_2 emissions, followed by huizache and pirul. Regarding the stems, pirul had the highest atmospheric emissions of CO_2, followed by huizache and mesquite. In all cases, emission levels exceeded the limits established by Mexican and international environmental regulations, indicating a significant risk to the environment and public health.

Keywords
Carbon dioxide • fine particles • incineration temperature • permissible limits

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Resumen

La quema de biomasa (BB) sirve tanto como fuente de energía como indicador medioambiental. Este estudio examinó las variaciones de las emisiones de CO_2 y partículas finas durante la combustión de biomasa de tres especies de árboles para determinar su contribución a la contaminación medioambiental. Se tomaron muestras de hojas y tallos de *A. farnesiana* (huizache), *S. molle* (pirul) y *P. laevigata* (mezquite). La biomasa seca se procesó térmicamente en un horno de mufla a temperaturas que oscilaron entre 50°C y 450°C. Se midieron las emisiones de CO_2, partículas menores de 2,5 micras ($PM_{2.5}$), partículas menores de 10 micras (PM_{10}) y compuestos orgánicos volátiles totales (TVOC). Los niveles más altos de emisión se produjeron durante el proceso de pirólisis entre 250°C y 450°C, tanto en las hojas como en los tallos. Entre las hojas, las emisiones más altas de $PM_{2.5}$ y PM_{10} se encontraron en el huizache, mientras que los valores más altos se encontraron en los tallos del mezquite. En cuanto a las hojas, el mezquite tuvo las emisiones más altas de CO_2, seguido del huizache y el pirul. En cuanto a los tallos, el pirul tuvo las emisiones atmosféricas más altas de CO_2, seguido del huizache y el mezquite. En todos los casos, los niveles de emisión superaron los límites establecidos por las regulaciones ambientales mexicanas e internacionales, lo que indica un riesgo significativo para el medio ambiente y la salud pública.

Palabras clave
Dióxido de carbono • partículas finas • temperatura de incineración • límites permisibles

Introduction

Biomass burning (BB) is the combustion of plant materials, which are widely used for energy production. It is increasingly recognized as an environmental indicator, particularly of air quality. Energy sources can be broadly classified as solid or non-solid fuels. The former includes coal, biomass, unprocessed wood, charcoal, manure, and crop residues. The latter includes kerosene, liquefied petroleum gas, natural gas, electricity, and others (8, 45, 51). Furthermore, BB is a significant contributor to air pollution with global, regional, and local implications for air quality, public health, and climate (21, 45). It emits trace gases and particulate matter into the atmosphere (19). It emits trace gases and particulate matter into the atmosphere. Therefore, the quantification of emissions and their impact assessment have been studied in various regions of the world (21, 45). In urban areas, around 50% of households use solid fuels, primarily coal and biomass, for energy, exposing themselves to the harmful effects of combustion residues. This affects nearly 50% of the global population, *i.e.*, over 3 billion people (51). Biomass originates from trees, agricultural crops, and other living plant materials. Furthermore, burning is a common, cost-effective, and time-efficient method of disposing of biomass residues from agricultural processes and other sectors. This practice has become increasingly widespread during the pre- and post-harvest seasons (41). From a health perspective, CO_2 is produced when biomass burns efficiently. Oxygen from the atmosphere combines with carbon from plants to produce CO_2 at a technological level. In the field of biomass-to-energy conversion, several technologies are in use, including combustion, anaerobic digestion (biogas plants), and thermochemical pretreatment. Promising emerging technologies include thermal gasification, torrefaction, and pyrolysis (33). The main technologies used in experimentation to exploit organic waste or biomass focus on chemical-biological processes, bioenergy, environmental treatment, pyrolysis, gasification, combustion, synthesis, hydrolysis, fermentation, and product separation (1). Other sources indicate that biomass conversion technologies fall into three categories: combustion, thermal gasification, and pretreatment. In pyrolysis, a thermochemical route, biomass is heated between 400°C and 600°C in the absence of oxygen. The process produces three products: solid charcoal, liquid pyrolysis oil (bio-oil), and a gaseous product (33). Pyrolysis is characterized by high heating rates, with temperature control close to 500°C (1, 12, 14). In contrast, torrefaction is considered a mild form of pyrolysis (200°C<T<300°C) and is carried out in an inert atmosphere or with steam. This brings the biomass into contact with a heating medium that gradually raises its temperature by less than 50°C per minute until it reaches 200-300°C (13). In practice, these burning processes release various pollutants, mainly gases and particulate matter, into the atmosphere. These pollutants include formaldehyde (HCHO), methane (CH_4), sulfur oxides (SOx), nitrogen oxides (NOx), carbon monoxide (CO), carbon dioxide (CO_2), and different sizes of respirable particulate matter ($PM_{3.5}$), such as PM_1, $PM_{2.5}$, and PM_{10} (9, 43, 51, 53, 55). The process is cyclical because CO_2 and water are produced, which are then used in the photosynthetic process to produce carbohydrates that form the basic components of biomass (9). In contrast, particulate matter emissions have been linked to severe damage, including alterations in photosynthesis, changes in plant growth, and alterations in plant reproduction (36). In line with global monitoring efforts, the United Nations Agenda 2030 for Sustainable Cities and Communities evaluates air quality by considering fine suspended particles $PM_{2.5}$ and PM_{10}, as indicators (38). $PM_{2.5}$ is the environmental factor posing the greatest health risk, contributing to over 4.1 million deaths worldwide in 2016 (31). For instance, a study of 708 European urban areas found that 22% of PM emissions came from urban cores and commuting areas. The average contributions of industrial activity, agriculture, and road transport were 18%, 17%, and 14%, respectively. Furthermore, 27% of the emissions came from a group of cities in northern Italy, while eastern Europe contributed more than 50% (58). The World Health Organization (WHO) recommends annual mean exposures of 10 μg/m^3 of $PM_{2.5}$ and 20 μg/m^3 of PM_{10} to minimize health impacts (34, 40, 56). In Mexico, NOM-021-SSA1-2021 establishes permissible values for suspended particulate matter PM_{10} and $PM_{2.5}$ in ambient air, including evaluation criteria (25). Furthermore, studies of air pollution by BB combine a series of variables and perspectives. These variables and perspectives consider the spatial and temporal scales, as well as the associated implications and impacts on human health, regional air quality, ecosystem health, climate change, and intercontinental pollution (52). Along these lines, studies of biomass derived from organic sources, such as agricultural and forest residues and dedicated energy crops, aim to identify sustainable energy options while evaluating their environmental impact, such as greenhouse gas emissions (8, 26). The species *Prosopis laevigata* (mesquite), *Schinus molle* (pirul), and *Acacia farnesiana* (huizache) have been associated with studies on environmental pollution in the state of San Luis Potosi (3, 4, 5, 6, 23). In some regions of Mexico, species such as mesquite (*Prosopis sp*.) are used as a source of charcoal due to their calorific potential (23). This indicates the need to explore alternatives to assess the impact of biochar (BB) on tree species. In some cases, dry leaves, bark, and pruning residues are used as fuel (45). Thus, this study aimed to evaluate variations in atmospheric emissions from burning biomass (stems and leaves) of these tree species to expand pollution research in San Luis Potosi, Mexico. The hypothesis is that emissions differ among species and between biomass types (leaves *vs.* stems), influencing compliance with environmental regulations in a laboratory-scale pilot test under a controlled pyrolysis/combustion process.

Materials and Methods

The study was conducted at Ejido Palma de la Cruz, Soledad de Graciano Sanchez, San Luis Potosi, Mexico (24°14’58’’N and 100°51’53’’W; 1,836 m a. s. l.) (figure 1, page 72).

Sample Collection

Nine sampling points were randomly selected within stands dominated by *Prosopis laevigata*, *Acacia farnesiana*, and *Schinus molle*, focusing on individuals taller than two meters. For each species, leaf and stem material was collected 1.6-1.8 meters above the ground after flowering. The samples were transported to the laboratory. The leaves and stems were separated, rinsed to remove dust and debris, and air-dried at room temperature. Fresh and dry biomass weights (g) were recorded to estimate total fresh weight per species and per plant organ (leaves and stems) (table 1, page 72). In total, nine composite samples per species were obtained (n=9 per organ per species). To determine the total dry weight per species, biomass was placed in a drying oven at 60°C for 48 hours in a RIOSSA H-48-48 stove.

Figure 1. Study area and sampling points for biomass collection.
Figura 1. Área de estudio y puntos de muestreo de la colecta de biomasa.

Table 1. Estimated total fresh and dry biomass weight of the tree species (g).
Tabla 1. Estimación del peso fresco y seco total de la biomasa de las especies arbóreas (g).

Tree species	Biomass	Fresh weight (g)	Mean	Dry weight (g)	Mean	Difference in %
A. farnesiana	Leaf	18.38	2.04	9.09	1.01	49.49
	Stem	23.4	2.60	15.35	1.71	65.63
S. molle	Leaf	98.24	10.92	30.95	3.44	31.5
	Stem	19.35	2.15	6.13	0.68	31.66
P. laevigata	Leaf	50.88	5.65	22.64	2.52	44.5
	Stem	31.57	3.51	17.3	1.92	54.78

Measurement of Incineration Gases and Atmospheric Particles

Ambient concentrations of carbon dioxide (CO_2), particulate matter (particles smaller than 2.5 and 10 microns), $PM_{2.5}$, PM_{10}, total volatile organic compounds, relative humidity, and temperature were recorded before measurement. The dry weight generated by each species (leaf and stem) was divided into six crucibles, each containing an average sample of 1.5 g, for the dry weight samples of leaves of each species. For the stems, four crucibles were used with an average dry weight range of 1.5 g. This was done because the total biomass of the leaves and stems of each species lost between 31.5% and 54.78% of their weight. To homogenize the distribution of biomass, an average of 1.5 g per sample was used (table 1). This could be a limitation to consider when increasing the amount of experimental dry biomass in future studies. According to certain criteria of some authors, the biomass was subjected to the pyrolysis process at temperatures ranging from 50°C to 450°C (1, 12, 14).

The prepared samples were incinerated in an electric muffle furnace (LabTech® Daiha Lantech Co. LTD) at 50, 100, 150, 200, 250, 300, 350, 400, and 450°C. Measurements of CO_2 (ppm), $PM_{2.5}$ (μ/m^3), PM_{10} (μ/m^3), TVOC (total volatile organic compounds, g/m^3), % relative humidity, and temperature (°C) were performed using HT-9600 (Dust Particle Counter®) and BLATN Smart (Portable Air Quality Monitor®) equipment. These devices were stabilized for an average of two hours for the environmental measurement. Some methodological criteria regarding sample handling and particle measurement were considered in previous studies (7). Results were interpreted using guideline values from the United States Environmental Protection Agency and the World Health Organization (34, 35, 40), as well as those referred to in the manuals of the measuring equipment.

Additionally, the Mexican Official Standard NOM-025-SSA1-2021 (25) was considered by comparing the average emission values with the 24-h permissible limits established by the standard of the real emission (maximum and minimum values).

Statistical Analysis

The variables included total and specific biomass (leaves and stems) by species, ambient temperature, percent relative humidity, incineration temperatures, gas, atmospheric particulate emissions, dry weight, and residual ash. The data were analyzed using Minitab® software, version 16. Analysis of variance was used with Tukey's test at a significance level of $p \leq 0.05$. Correlation analysis (Pearson correlation coefficient) and principal component analysis (PCA) were also performed on all variables studied in this experiment.

Results and Discussion

A significant Pearson correlation ($p \leq 0.05$) was detected between gaseous emissions (CO_2, TVOC) and fine particles ($PM_{2.5}$, PM_{10}) and ambient conditions (relative humidity and air temperature). Additionally, the Tukey test distinguished between total biomass emissions and emissions generated by the pyrolysis of leaves and stems from the three species, revealing pronounced differences at 200-400°C. On the other hand, principal component analysis revealed the set of data (gases and particles) that explains variation in incineration temperatures and species with higher or lower biomass emissions. Regarding the Pearson correlation (table 2), the strongest significant associations among the total emission variables were between $PM_{2.5}$ and TVOC (r^2=0.76) and between $PM_{2.5}$ and PM_{10} (r^2=0.62). Higher values were observed for leaf biomass with $PM_{2.5}$-TVOC (r^2=0.75) and TVOC-PM_{10} (r^2=0.73). Higher correlations were also observed for leaf biomass with $PM_{2.5}$-TVOC and TVOC-PM_{10}. Ten significant correlations were identified in stem biomass; the strongest was between $PM_{2.5}$ and TVOC (r^2=0.79).

Table 2. Results of Pearson's Correlation Coefficient on atmospheric variables in biomass incineration (pyrolysis process) of three tree species ($p \leq 0.05$).

Tabla 2. Resultados del coeficiente de correlación de Pearson en las variables atmosféricas de la incineración (proceso de pirólisis) de biomasa de tres especies arbóreas ($p \leq 0,05$).

Criteria	Variables	Pearson's Correlation Coefficient	Value of p
Total emissions (n=135)	$PM_{2.5}$-CO_2	0.180	0.036
	$PM_{2.5}$-TVOC	0.769	0.000
	$PM_{2.5}$-PM_{10}	0.624	0.000
	CO_2-Temperature	0.151	0.081
	TVOC-PM_{10}	0.674	0.000
	$PM_{2.5}$-CO_2	0.210	0.060
Leaf biomass (n=81)	$PM_{2.5}$-TVOC	0.753	0.000
	$PM_{2.5}$-PM_{10}	0.542	0.000
	TVOC-PM_{10}	0.734	0.000
	$PM_{2.5}$-CO_2	0.482	0.000

Criteria	Variables	Pearson's Correlation Coefficient	Value of p
Stem biomass (n=54)	$PM_{2.5}$-TVOC	0.796	0.000
	$PM_{2.5}$-PM_{10}	0.735	0.000
	$PM_{2.5}$-Temperature	0.288	0.034
	CO_2-TVOC	0.507	0.000
	CO_2-PM_{10}	0.542	0.000
	CO_2-Temperature	0.409	0.002
	CO_2-% HR	-0.272	0.047
	TVOC-PM_{10}	0.631	0.000
	TVOC-% HR	0.283	0.038

Total Biomass Burning Emissions

An analysis of 181 samples revealed that incineration temperature, biomass origin (tree species), and biomass type (leaf or stem) significantly affected total CO_2, $PM_{2.5}$, PM_{10}, and TVOC emissions (Tukey, $p \leq 0.05$). Considering the effect of incineration temperature (50°C-450°C), physically bound moisture is removed at 20-120°C. Above 160°C, chemically bound water is released through thermal condensation.

Between 120 and 150°C, the -H- and -C- bonds break, producing short-chain polymers that condense within the pores. As the temperature increases to between 150 and 270°C, carbon dioxide (CO_2), carboxylic acids, phenol, furfural, methanol, and other organic molecules are generated. This is primarily due to hemicellulose depolymerization and the release of carbonyl and carboxyl groups from cellulose. Lignin also overgoes reactions of aromatic rings in lignin (5, 13, 15, 16, 22, 23, 39). As the process progresses, the biomass darkens and begins to resemble coal in terms of its properties. The most intense heat consumption and mass loss occur in the early stages (13). According to another technical source, volatile gases are released when the temperature of dry biomass reaches 200°C-350°C during pyrolysis. These include carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and high-molecular-weight compounds (tar), which condense into a liquid when cooled. These gases mix with oxygen in the air and burn to produce a yellow flame. This self-sustaining process involves heat from gas combustion, drying fresh fuel, and releasing additional volatiles. Once all the volatiles have burned, the remaining solid is coal (44). Other contributing factors include species-specific chemical compositions and structural differences. For instance, a study of *Schinus molle* L. essential oil identified nineteen compounds, with the major ones being bicyclogermacrene, beta-caryophyllene, and spathulenol (37). As for *P. leavigata*, different compounds have been found in its various organs, including the fruit, leaves, and flowers. These compounds include phenolic compounds and alkaloids, as well as the concentrations of 4-hydroxybenzoic acid, p-coumaric acid, gallic acid, chlorogenic acid, cinnamic acid, and p-coumaric acid (29). Studies on the composition of *A. farnesiana* demonstrate that it essentially contains terpenes, phenolic acids, flavonoids, tannins, alkaloids, fatty acids from seed oils, polysaccharides, non-protein amino acids, and other phytochemicals (20).

CO_2 emissions from the total biomass of the three species were prioritized among the results because of their relevance as a greenhouse gas. The CO_2 emissions data revealed that the highest mean value was reached at 300°C, with a difference of 3,014.7 ppm. The lowest emissions occurred at 50°C (table 3, page 75). Due to its biogenic origin, the CO_2 released during biomass combustion is generally equivalent to the CO_2 absorbed during growth of trees, crops, and other plant-based residues (8). CO_2 is a greenhouse gas present in the global atmosphere at approximately 412 ppm, and it is projected to increase (17). Using this reference level, the emission measured in this study at 300°C (3,639.9 ppm) exceeded the atmospheric reference by 8.83 times and the maximum average reported for the study area by 8.39 times. Additionally, outdoor air typically contains 300-400 ppm of CO_2 and can reach up to 550 ppm in urban areas (49).

Table 3. Ratio of total gas emissions and total atmospheric particulate matter from biomass burning of three tree species (Tukey, $p \leq 0.05$, n=135).

Tabla 3. Relación de emisiones totales de gases y partículas atmosféricas totales de la quema de biomasa de tres especies arbóreas (Tukey, $p \leq 0,05$, n=135).

	Incineration temperature (pyrolysis process)								
Temperature	**50°C**	**100°C**	**150°C**	**200°C**	**250°C**	**300°C**	**350°C**	**400°C**	**450°C**
Variable	Mean								
CO_2 ppm	625.2a	867.8a	821.7a	810.8a	863.3a	**3639.9a**	1333.4a	1703.5a	2239.2a
$PM_{2.5}$ µ/m³	14.2c	13.5c	13.7c	91.7c	384.1b	700.3a	**905.2a**	843.2a	787.2a
PM_{10} µ/m³	290.4d	364.5d	164.7d	342.2d	2,893cd	13,519.2ab	11,087.4bc	20,434.6ab	**21,416.5a**
TVOC mg/m³	0.7c	0.8c	0.9c	0.8c	1.7c	4.6b	6.5ab	**8.1a**	7.9a
Temperature	26.6a	26.8a	27.6a	27.1a	27.8a	27.1a	27.3a	28.3a	28.4a
Relative Humidity (%)	56.8a	56.4a	56.6a	55.9a	56.5a	56.3a	56.2a	55.9a	55.7a

	Gases and atmospheric particles			
	Mean			
Species	CO_2 ppm	$PM_{2.5}$ µ/m³	PM_{10} µ/m³	TVOC g/m³
Huizache	1106.27a	**459.22**a	7166.60a	3.85a
Mesquite	**2140.07a**	407.49a	**8925.40a**	3.85a
Pirul	1055.29a	384.33a	7412.18a	2.99a

	Gases and atmospheric particles			
	Mean			
Biomass	CO_2	$PM_{2.5}$	PM_{10}	TVOC
	ppm	µ/m³	µ/m³	g/m³
Leaf	**1756.48a**	**424.26a**	6913.65a	**3.75a**
Stem	949.96a	406.15a	**9216.33a**	3.28a

Note: Maximum and minimum reference levels for $PM_{2.5}$ (41-25 µg/m³ as a 24-hour average and 10 µg/m³ as an annual average). PM_{10} would range as a 24-hour average from 70-50 µg/m³ to 36-20 µg/m³, as an annual average NOM-025-SSA1-2021 (25) and International Levels References (34, 35, 40). Daily ambient average during the study days: $PM_{2.5}$ (23.03 µg/m³), PM_{10} (88.70 µg/m³), CO_2 (400-433.62 ppm), and TVOC (0.664 g/m³). Columns with different letters indicate significant differences.

Nota: Niveles máximos y mínimos de referencia para $PM_{2.5}$ (41-25 µg/m³ como promedio de 24 horas y 10 µg/m³ promedio anual). PM_{10} oscilarían como promedio de 24 horas en 70-50 µg/m³ y 36-20 µg/m³, como promedio anual NOM-025-SSA1-2021 (25) y Niveles internacionales de referencia (34, 35, 40). Promedio diario en el ambiente durante los días del estudio: $PM_{2.5}$ (23.03 µg/m³), PM_{10} (88.70 µg/m³), CO_2 (400-433.62 ppm) y TVOC (0.664 g/m³). Columnas con letras diferentes indican diferencia significativa.

Other studies indicate that CO and CO_2 are primarily released at temperatures below 450°C and exhibit similar patterns. Increasing the heating rate positively influences the yield of combustible gases (46). At 450°C, PM_{10} emissions were higher, with an average of 21,416.5 µ/m³, compared to an average of 21,251.8 µ/m³ from the incinerated biomass at 150°C. Mexico's NOM-025-SSA1-2021 establishes permissible PM_{10} concentration limits maximum at 70 µg/m³, minimum at 50 µg/m³ (24-hour average) and 36 µg/m³ (annual average) (25). Using the 24-hour criterion (70 µg/m³), the highest emission average over 24 hours was 892.25 µ/m³, and the lowest was 6.86 µ/m³. At 450°C, PM_{10} exceeded the 24-hour permissible limit by a factor of 12.74, highlighting a significant environmental hazard. The value of 892.25 µ/m³ was 10.05 times higher than the average recorded in the study area during the experimental phase. Using the 24-hour criterion (50 µg/m³), the highest emission average over 24 hour at 450°C, PM_{10} exceeded the permissible limit by a factor of 17.84 times. Elevated PM_{10} levels have been linked to adverse effects on plant physiological functions, including photosynthesis and growth inhibition (36).

A study that burned olive tree pruning waste and performed a chemical characterization estimated average PM_{10} concentrations at 2,165 µg/m³, about fifty times higher than the PM_{10} concentrations estimated at reference sites under normal conditions. These emissions were associated with carbonaceous fractions, such as potassium (K), lead (Pb), and polycyclic aromatic hydrocarbons (PAHs), as well as benzo(a)anthracene, benzo(a)pyrene, and benzo(K)fluoranthene, for the biomass combustion source (10).

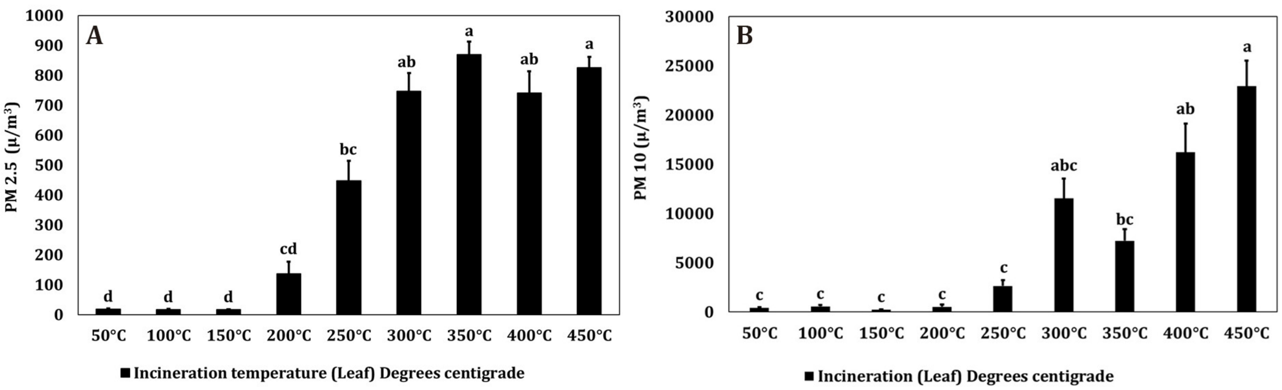
The highest $PM_{2.5}$ emission, 905.2 μ/m^3, was observed at 350°C, which is 891.7 μ/m^3 higher than the average emission at 100°C. In accordance with NOM-025-SSA1-2021 (25), the maximum and minimum permissible limits for $PM_{2.5}$ are 41 μg/m^3 and 25 μg/m^3 (24-hour average) and 10 μg/m^3 (annual average). In this context, the highest recorded emission was 37.71 μg/m^3 over a 24-hour period, not exceeding the permissible limit of 41 μg/m^3. This value was 39.30 times higher than those recorded during the experimental days in the study area atmosphere. However, with the minimum reference level (25μg/m^3), this limit is 1.50 times higher. $PM_{2.5}$ can originate from various sources and therefore exhibits differences in chemical composition and physical characteristics. Common components of $PM_{2.5}$ include sulfates, black carbon, nitrates, and ammonium. Sources of anthropogenic $PM_{2.5}$ are mainly related to combustion engines, industrial processes, power generation, burning coal and wood, agricultural activities, and construction. Natural sources include dust storms, forest fires, and sandstorms (35). On the other hand, $PM_{2.5}$ has been linked to toxic levels of nickel (Ni), chromium (Cr), lead (Pb), arsenic (As), and black carbon (BC). Its main sources of emission include coal combustion, industrial activity, resuspended dust, and biomass burning. This indicates the urgent need for control measures (32, 35). $PM_{2.5}$ commonly contains sulfates, black carbon, nitrates, and ammonium (35). According to the U.S. Air Quality Index, $PM_{2.5}$ concentrations over 250.5 μg/m^3 pose a high risk to public health and the environment (34). In agricultural areas, high levels of PM_{10} and $PM_{2.5}$ have been reported, reaching 800 μg/m^3 and 485 μg/m^3, respectively (57). Populations in low- and middle-income countries are exposed to environmental $PM_{2.5}$ levels between 1.3 and 4 times higher (31). While the interspecific ratio of mean total emissions was not statistically significant, *P. laevigata* emitted 1,084.78 ppm of CO_2, surpassing *S. molle*. Among the evaluated species, *A. farnesian*a exhibited the highest $PM_{2.5}$ emissions, surpassing *S. molle* by 74.89 μg/m^3. *P. laevigata* showed the highest levels of PM_{10}, surpassing *A. farnesiana* by 1,758.8 μg/m^3 (table 3, page 75). This highlights notable interspecific variation in particulate emissions. The chemical analysis of *P. laevigata* wood revealed that it contains 7.36% hemicellulose, 48.28% cellulose, 30.57% lignin, and 13.53% extractives (42).

Other studies on the energy characterization of charcoal from species such as Prosopis have found elements like magnesium (Mg), calcium (Ca), copper (Cu), zinc (Zn), and iron (Fe) in charcoal and ash. These studies reported a higher calorific value of 27,669 kJ/kg for this species. These findings have been linked to particle size distribution, moisture content, volatile material content, ash content, fixed carbon content, and calorific value (23). Another key finding was that total leaf biomass emitted higher levels of CO_2, $PM_{2.5}$, and TVOC than total stem biomass. Leaf emissions of CO_2 exceeded stem emissions by 806.52 ppm across the three species. For $PM_{2.5}$, a difference of 18.11 μg/m^3 was observed between leaf and stem emissions. However, stem biomass emitted 2,302.68 μg/m^3 more PM_{10} than leaf biomass across the three evaluated species (table 3, page 75). In both cases, the emission levels exceeded the limits set by NOM-025-SSA1-2021 for PM_{10}, even when averaged over 24 hours (25).

The values obtained were higher than those measured in the environment during the study (table 3, page 75). This result should consider that the area is influenced by stone extraction, agricultural activities, and climatic factors that can cause environmental variability, even though the experiment was conducted under controlled conditions. The biomass's biomolecular components are lignocellulosic, comprising cellulose, hemicellulose, and lignin, which have recognized potential for bioenergy systems (4, 22, 50). Some authors have studied biomass' potential as a fuel source, emphasizing the importance of the chemical composition of different plant types. Processes such as torrefaction, in which biomass is heated to temperatures between 200 and 300°C, can enhance its energy properties (18). $PM_{2.5}$ emissions in Thailand have been reported to range from 0 to over 4,001 milligrams per year, considering contributions from agricultural residue burning, forest fires, and open biomass burning (50). Factors influencing particle numbers include tree species and combustion rate, which reflect the materials' slow-to-fast burning capacity, such as wood, leaves, and branches (21, 54). The most prominent emission produced during biomass combustion is CO_2, which serves as a proxy for the biomass carbon content and as a principal greenhouse gas. Combustion efficiency is often assessed based on the amount of carbon oxidized to CO_2. While biomass generally contains about 45% carbon weight, coal typically contains over 60% (24, 26).

Leaf Emissions of Three Tree Species

There was significant variation in gas and particle emissions during the leaf BB for the three species (Tukey, $p \leq 0.05$). Table 3 (page 75), shows that CO_2 emissions were higher at an incineration temperature of 300°C, with a difference of 4916.8 ppm compared to the emissions reported at 50°C (5541.2 ppm). The maximum emission detected exceeds the atmospheric concentration of 512 ppm reported in technical documents by 13.44 times (17). The highest PM_{10} emission occurred at 450°C, at 22,910.8 μ/m^3, showing a significant difference of 22,683.4 μ/m^3 relative to values at 150°C (figure 2B). In this case, the estimated 24-hour average concentration was 954.61 μg/m^3, which is 13.78 times higher than the 70 μg/m^3 and 19.09 times higher than the 50 μg/m^3 permissible limit established by the Mexican Official Standard NOM-025-SSA1-2021 for this type of particulate matter (25). The highest concentration of $PM_{2.5}$ emissions was recorded at 350°C, reaching 869.1 μg/m^3. This represents an 852.5 μg/m^3 difference compared to the 16.6 μg/m^3 emission recorded at 150°C (figure 2A). Based on this peak value, the estimated 24-hour average concentration is 36.21 μg/m^3, not exceeding the maximum limit of 41 μg/m^3, but if the minimum limit of 25 μg/m^3 (1.39 times) established by NOM-025-SSA1-2021 (25). Table 4 (page 78), shows atmospheric gas and particle emissions from tree species of leafy biomass origin. *P. laevigata* had higher CO_2 emissions, with a significant difference of 1,980.5 ppm compared to *S. molle* leaves. This difference is 4.8 times higher than the reported average atmospheric concentration (412 ppm) (17). The leaves of *A. farnesiana* emitted higher levels of $PM_{2.5}$ and PM_{10} than those of the other species. *A. farnesiana* had the highest PM_{10} emissions at 8,167.6 μ/m^3, which is 4.86 times higher than the maximum limit (41 μ/m^3) and 6.80 times minimum limit (50 μ/m^3) established by NOM-025-SSA1-2021. The corresponding 24-hour average would be 340.31 μ/m^3. A pairwise comparison between *A. farnesiana* and *S. molle* revealed that $PM_{2.5}$ was 136.4 μ/m^3 higher and PM_{10} was 2,971.5 μ/m^3 higher in *A. farnesiana* (table 4, page 78). The highest $PM_{2.5}$ value in *A. farnesiana* (514.4 μ/m^3) had a 24-hour average of 21.43 μ/m^3, wich is well below the limit specified in NOM-025-SSA1-2021 (25). Regarding the ash generated from the total incinerated leaf biomass (g), *S. molle* was significantly higher (0.444a) than *A. farnesiana* (0.349b) and *P. laevigata* (0.294) (Tukey, $p \leq 0.05$).



The data shown refers to the mean ± standard error (different letters indicate significant differences).

Los datos representados refieren la media ± error estándar (letras diferentes indican diferencia significativa).

Figure 2. Ratio of $PM_{2.5}$ (A) and PM_{10} (B) emissions in leaves of three tree species according to different incineration temperatures (Tukey, $p \leq 0.05$, n=81).

Figura 2. Relación emisiones de $PM_{2.5}$ (A) $_y$ PM_{10} (B) en hojas de tres especies arbóreas de acuerdo con las diferentes temperaturas de incineración (Tukey, p≤0,05, n=81).

Table 4. Ratio of gas emissions and total atmospheric particulate matter from burning leaves of three tree species (Tukey, p≤0.05, n=81).

Tabla 4. Relación de emisiones de gases y partículas atmosféricas totales de la quema de hojas de tres especies arbóreas (Tukey, p≤0,05, n=81).

	Incineration temperature (pyrolysis process)								
Temperature	**50°C**	**100°C**	**150°C**	**200°C**	**250°C**	**300°C**	**350°C**	**400°C**	**450°C**
Variable	**Mean**								
CO_2 ppm	624.4a	887.1a	829.8a	834.6 a	843a	**5541.2a**	1505.6a	1923.7a	2819.0a
TVOC g/m^3	0.7c	1.0c	1.1c	0.8c	1.9bc	5.1ab	7.0a	8.5a	7.7a
Temperature °C	27.5a	27.7a	28.9a	28.0a	28.1a	27.9a	28.0a	28.5a	29.2a
Relative Humidity (%)	55.2a	54.4a	55.7a	53.8a	54.8a	54.0a	54.1a	53.8a	53.0a

Gases and atmospheric particles				
Mean				
Species	CO_2	$PM_{2.5}$	PM_{10}	TVOC
	Ppm	µ/m^3	µ/m^3	mg/m^3
Huizache	1268a	**514.5a**	**8167.6a**	4.1a
Mesquite	**2991.0a**	380.1a	7377.2a	4.1a
Pirul	1010.5a	378.1a	5196.1a	3.1a

Note: Maximum and minimum reference levels for $PM_{2.5}$ (41-25 µg/m^3 as a 24-hour average and 10 µg/m^3 as an annual average). PM_{10} would range as a 24-hour average from 70-50 µg/m^3 to 36-20 µg/m^3, as an annual average NOM-025-SSA1-2021 (25) and International Levels References (34, 35, 40). Daily ambient average during the study days: $PM_{2.5}$ (23.03 µg/m^3), PM_{10} (88.70 µg/m^3), CO_2 (400-433.62 ppm), and TVOC (0.664 g/m^3). Columns with different letters indicate significant differences.

Nota: Niveles de referencia máximo y mínimo para $PM_{2.5}$ (41-25 µg/m^3 como promedio de 24 horas y 10 µg/m^3 promedio anual). PM_{10} oscilarían como promedio de 24 horas en 70-50 µg/m^3 y 36-20 µg/m^3, como promedio anual NOM-025-SSA1-2021 y niveles internacionales de referencia (34, 35, 40). Promedio diario en el ambiente durante los días del estudio: $PM_{2.5}$ (23.03 µg/m^3), PM_{10} (88.70 µg/m^3), CO_2 (400-433.62 ppm) y TVOC (0.664 g/m^3). Columnas con letras diferentes indican diferencia significativa.

Stem Emissions of the Three Tree Species

Table 5 (page 79) (Tukey, p≤0.05) shows significant differences in gas particle emissions from stem biomass. The highest mean total volatile organic compound (TVOC) emission occurred between 300°C and 450°C, reaching 8.2 g/m^3. The highest CO_2 emission was observed at 450°C, with a concentration of 1,284.3 ppm. This represents a difference of 632.3 ppm compared to the emission at 50°C. *S. molle* had the highest mean CO_2 emissions (1,122.4 ppm), which was 338.06 ppm higher than the remaining species, such as mesquite (figure 3, page 79). Based on *S. molle's* emissions at 450°C, atmospheric CO_2 concentrations would be between 2.5 and 2.7 times the normal level (17). The highest PM_{10} emissions occurred at 400°C (26,787.8 µ/m^3), differing in 26,710.4 µ/m^3 relative to emissions at 150°C (figure 4, page 80). Averaging this peak over 24 hours (1,116.15 µ/m^3) shows that the NOM-025-SSA1-2021 (25) standard is exceeded by 15.94 times (maximum level 70 µ/m^3) and 22.32 times (minimum level 50 µ/m^3). As for $PM_{2.5}$, the highest emissions occurred between 300 and 400°C. The peak value was 997.5 µg/m^3, representing a significant mean difference of 989.4 µg/m^3 relative to emissions at 50°C. This elevated emission would result in a 24-hour average concentration of 41.56 µg/m^3, which exceeds the NOM-025-SSA1-2021 limit by a factor of 0.56 µg/m^3, the maximum level of 41 µ/m^3 and 1.66 times the minimum level of 25 µ/m^3 (25). The ratio of residual ash to total biomass differed significantly among species in stem samples. *A. farnesiana* had the highest ratio (0.427 g), followed by *P. laevigata* (0.325 g) and *S. molle* (0.265 g), according to Tukey's test at p ≤ 0.05. Biomass burning causes a loss of organic matter and nutrients from the soil through particle dispersion or volatilization. BB leads to the loss of nutrients, soil biota, and total nitrogen (N) and carbon (C) in the topsoil, and it promotes soil erosion. Although nutrients are retained in ash, ash deposition increases the pH of the surface layer. The presence of ash increases surface concentrations of Ca, Mg, K, Na, and P; however, the high solubility of basic cations enhances leaching and promotes soil crusting (30).

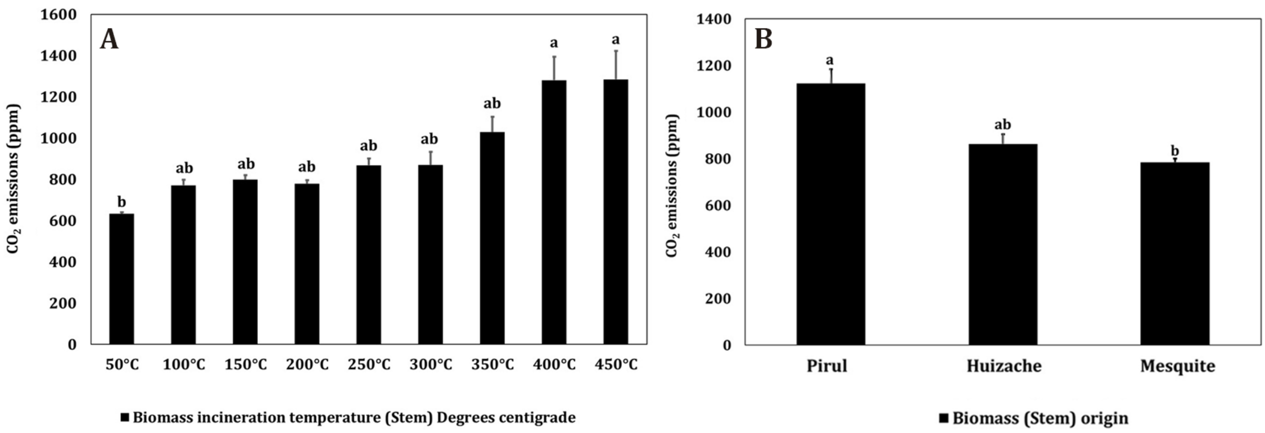
Table 5. Ratio of gas emissions and total atmospheric particulate matter from the burning of stems of three tree species (Tukey, p≤0.05, n=54).

Tabla 5. Relación de emisiones de gases y partículas atmosféricas totales de la quema de tallos de tres especies arbóreas (Tukey, p≤0,05, n=54).

	Incineration temperature (pyrolysis process)							
Temperature	**50°C**	**100°C**	**150°C**	**250°C**	**300°C**	**350°C**	**400°C**	**450°C**
Variable	**Mean**							
TVOC g/m^3	0.6c	0.6c	0.7c	1.4bc	4.0abc	5.6ab	7.6a	8.2a
Temperature °C	25.3a	25.5a	25.7a	27.3a	26.0a	26.2a	28.1a	27.3a
Relative Humidity (%)	59.2a	59.3a	59.4a	59.1a	59.7a	59.2a	58.9a	59.6a
Gases and atmospheric particles								
Mean								
Species	$PM_{2.5}$	PM_{10}	TVOC					
Huizache	376.3a	5665.1a	3.5a					
Mesquite	**448.5a**	**11247.7a**	3.5a					
Pirul	393.7a	10736.2a	2.8a					

Note: Maximum and minimum reference levels for $PM_{2.5}$ (41-25 μg/m^3 as a 24-hour average and 10 μg/m^3 as an annual average). PM_{10} would range as a 24-hour average from 70-50 μg/m^3 to 36-20 μg/m^3, as an annual average NOM-025-SSA1-2021 (25) and International Levels References (34, 35, 40). Daily ambient average during the study days: $PM_{2.5}$ (23.03 μg/m^3), PM_{10} (88.70 μg/m^3), CO_2 (400-433.62 ppm), and TVOC (0.664 g/m^3). Columns with different letters indicate significant differences.

Nota: Niveles de referencia máximo y mínimo para $PM_{2.5}$ (41-25 μg/m^3, como promedio de 24 horas y 10 μg/m^3 promedio anual). PM_{10} oscilarían como promedio de 24 horas entre 70-50 μg/m^3 y 36-20 μg/m^3, como promedio anual NOM-025-SSA1-2021 (25) y Niveles internacionales de referencia (34, 35, 40) Promedio diario en el ambiente durante los días del estudio: $PM_{2.5}$ (23,03 μg/m^3), PM_{10} (88,70 μg/m^3), CO_2 (400-433,62 ppm) y TVOC (0,664 g/m^3). Columnas con letras diferentes indican diferencia significativa.

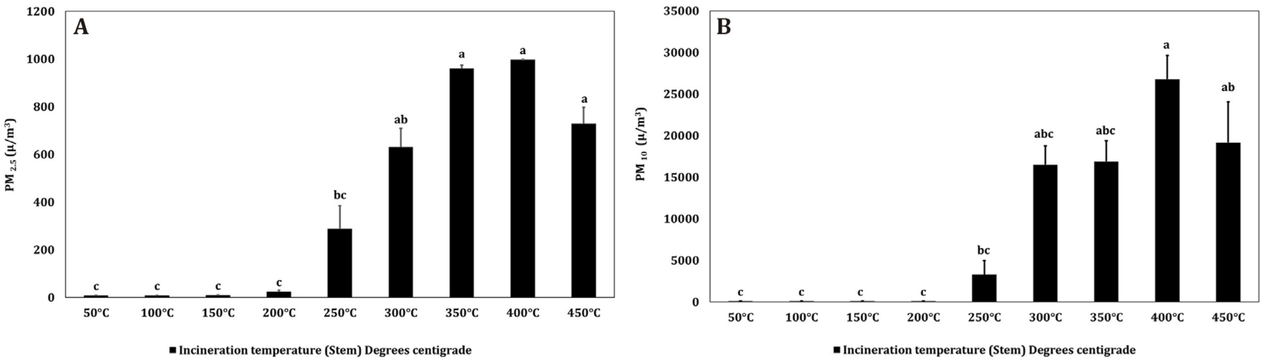


The data shown refers to the mean ± standard error (different letters indicate significant differences).

Los datos representados refieren a la media ± error estándar (letras diferentes indican diferencia significativa).

Figure 3. Ratio of CO_2 emissions (A) according to different incineration temperatures and CO_2 (B) in related stems and the three species of stem origin (Tukey, p≤0.05, n=81).

Figura 3. Relación emisiones de CO_2 (A) de acuerdo con las diferentes temperaturas de incineración y CO_2 (B) en tallos en relación con las tres especies de origen del tallo (Tukey, p≤0,05, n=81).



The data shown refers to the mean ± standard error (different letters indicate significant differences).
Los datos representados refieren a la media ± error estándar (letras diferentes indican diferencia significativa).

Figure 4. Ratio of $PM_{2.5}$ (A) and PM_{10} (B) emissions in the stems of three tree species according to different incineration temperatures (Tukey, p≤0.05, n=81).

Figura 4. Relación de emisiones de $PM_{2.5}$ (A) $_y$ PM_{10} (B) en tallos de tres especies arbóreas de acuerdo con las diferentes temperaturas de incineración (Tukey, p≤0,05, n=81).

Principal Component Analysis

In the leaf-biomass dataset for the three tree species, the first three components explained 74% of the variance (figure 5A, 5B; 6A, and 6B, page 81). PC1 explained 31% of the variance, PC2 explained 29.7%, and PC3 explained 14%. PC1 was driven by % relative humidity (0.528), TVOC (0.316), $PM_{2.5}$ (0.284), and dry weight (-0.440). PC2 was mainly associated with TVOC (0.509), $PM_{2.5}$ (0.478), PM_{10} (0.478), and ambient temperature (0.326). PC3 was primarily defined by CO_2 (0.758), ash weight (-0.540), and dry weight (-0.250). In the stem biomass analysis, the first three PCs explained 80% of the variance. PC1 was mainly driven by $PM_{2.5}$ (0.505), PM_{10} (0.488), CO_2 (0.442), and TVOC (0.467). PC2 accounted for 27% of the variance and had positive loadings on dry weight (0.535) and temperature (0.454), as well as negative loadings on % relative humidity (-0.619) and TVOC (-0.296).

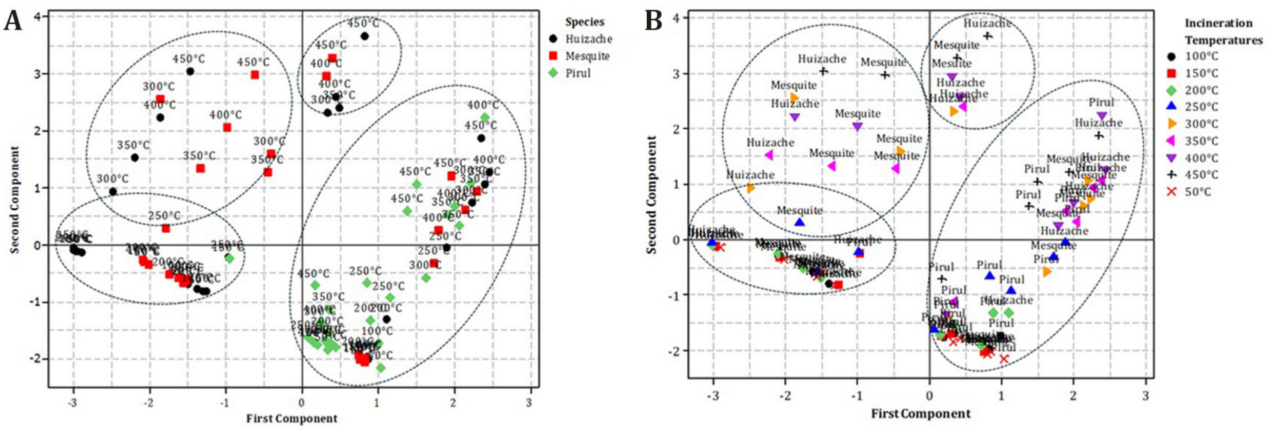


Figure 5. Eigenvalues resulting from principal component analysis of the emission of gases and atmospheric particles from burning leaves of three tree species according to species (A) and incineration temperature (B).

Figura 5. Distribución de eigenvalores resultante del análisis de componentes principales de la emisión de gases y partículas atmosféricas de la quema de hojas de tres especies arbóreas de acuerdo con la especie (A) y la temperatura de incineración (B).

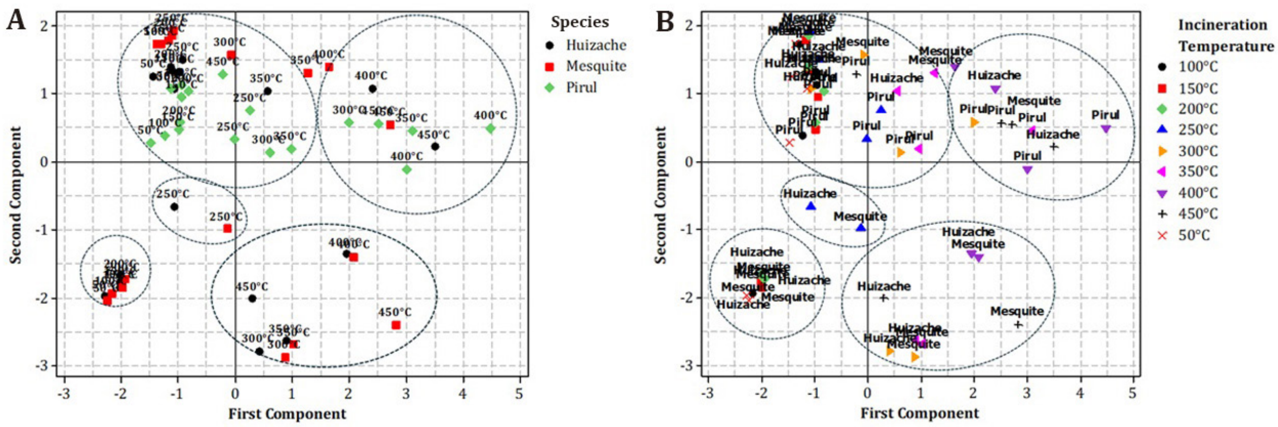


Figure 6. Eigenvalues resulting from the principal component analysis of the emission of gases and atmospheric particles from the burning of stems of three tree species according to species (A) and incineration temperature (B).

Figura 6. Distribución de eigenvalores resultante del análisis de componentes principales de la emisión de gases y partículas atmosféricas de la quema de tallos de tres especies arbóreas de acuerdo con la especie (A) y la temperatura de incineración (B).

These findings revealed significant variation in emission behavior among biomass components, likely driven by differences in the physicochemical structure of leaf and stem tissues across the three evaluated tree species. This variability was also evident across incineration temperatures from 50°C to 450°C, both in the analysis of total biomass and within the leaf and stem fractions. This criterion is important because most emissions are concentrated in the respirable fraction of PM. Emission size distribution and chemical characteristics vary with appliance type, combustion rate, fuel moisture, and biomass type; therefore, measurement is required to comply with air quality standards (2). Particulate matter (PM) is a key indicator of air pollution levels. The type of PM and the ratio between size particles (fine and coarse) determine its effects on human health and atmospheric processes. PM is commonly classified as dust, mixed aerosols, and anthropogenic aerosols (28). Another relevant observation is that leaf biomass from *S. molle* had the highest ash content (0.44 ± 0.03 g), and stem biomass from *A. farnesiana* produced the most ash among stems (0.42±0.06 g). Residual ash can have further environmental impacts. Its accumulation and the combustion of organic matter can significantly alter soil properties. For example, burned soils have a darker color, which results in lower albedo, increased environmental heat absorption, and higher soil temperature (30).

Complete combustion and open-air burning of residues require sufficient heat flux, an adequate oxygen supply, and sufficient combustion time. The magnitude and composition of emissions from this type of combustion depend on factors such as fuel density, moisture content, topography (*e.g.*, slope and terrain profile), and meteorological conditions (*e.g.*, wind and precipitation) (48). Emissions from major contributors to atmospheric particulate matter (PM), especially the $PM_{2.5}$ and PM_{10} fractions, have been linked to biomass burning (BB), forest fires, agricultural residue burning, and motor vehicles. These associations highlight challenges and inform policy recommendations for improving air quality (50).

Burning biomass fuels, especially wood-based ones, releases less CO_2 into the atmosphere than burning coal (26). However, BB is a major source of particulate matter and trace gases. Incomplete combustion likely contributes to global warming, and its overall contribution to climate change remains debated (9). Given the global concern about air pollution, studies like this one can contribute not only to our understanding of the impact of these reported levels on complex environmental processes but also provide opportunities for integral environmental improvements (35). Other studies have linked PM_{10} emissions to phytotoxic effects and elevated heavy metal concentrations (36). Additionally, BB is a significant source of greenhouse gases (GHGs) and air pollutants (35). Another study found that air pollutants generally impact plant species, causing morphological, physiological, and biochemical damage (11).

In Mexico, anthropogenic emissions from stationary sources account for 22.5% of PM_{10}, 20.9% of $PM_{2.5}$, and 4.7% of VOCs. Area sources (pollutant sources that are too numerous and dispersed to be classified as fixed sources) account for 73.0%, 73.3%, and 89%, respectively. Mobile sources account for 4.5%, 5.8%, and 6.3%, respectively (47). The National Air Strategy, under Axis 5 (Responsible and Participatory Society), seeks to establish mechanisms for the community to understand air pollution impact and actively participate in improving air quality. It is recognized that the most commonly used solid fuels in Mexico are biomass, agricultural waste, and primarily firewood, accounting for 80% of the energy consumed in rural households (47). Therefore, it is crucial to acknowledge the risks and impacts that the emissions and residues of these gases and particles pose to public health and ecosystems. Evidence from PM_{10} studies includes data on indoor smoke dispersion among household members engaged in activities such as cooking, doing chores, warming up by the stove, playing, resting, eating, and sleeping. These studies demonstrated an exposure-response relationship, with a higher rate of increase for daily exposures below 1,000–2,000 $\mu g/m^3$ (27). Figure 7 shows how this pilot experiment clarifies the interplay between environmental factors and biomass intrinsic physicochemical characteristics (as in the three evaluated species) and the behavior of biomass components (leaves and stems) during pyrolysis across the laboratory-scale temperature range. The experiment also evaluates atmospheric gases and particles for regulatory compliance and highlights opportunities to extend the study to open field conditions and incorporate additional variables of interest.

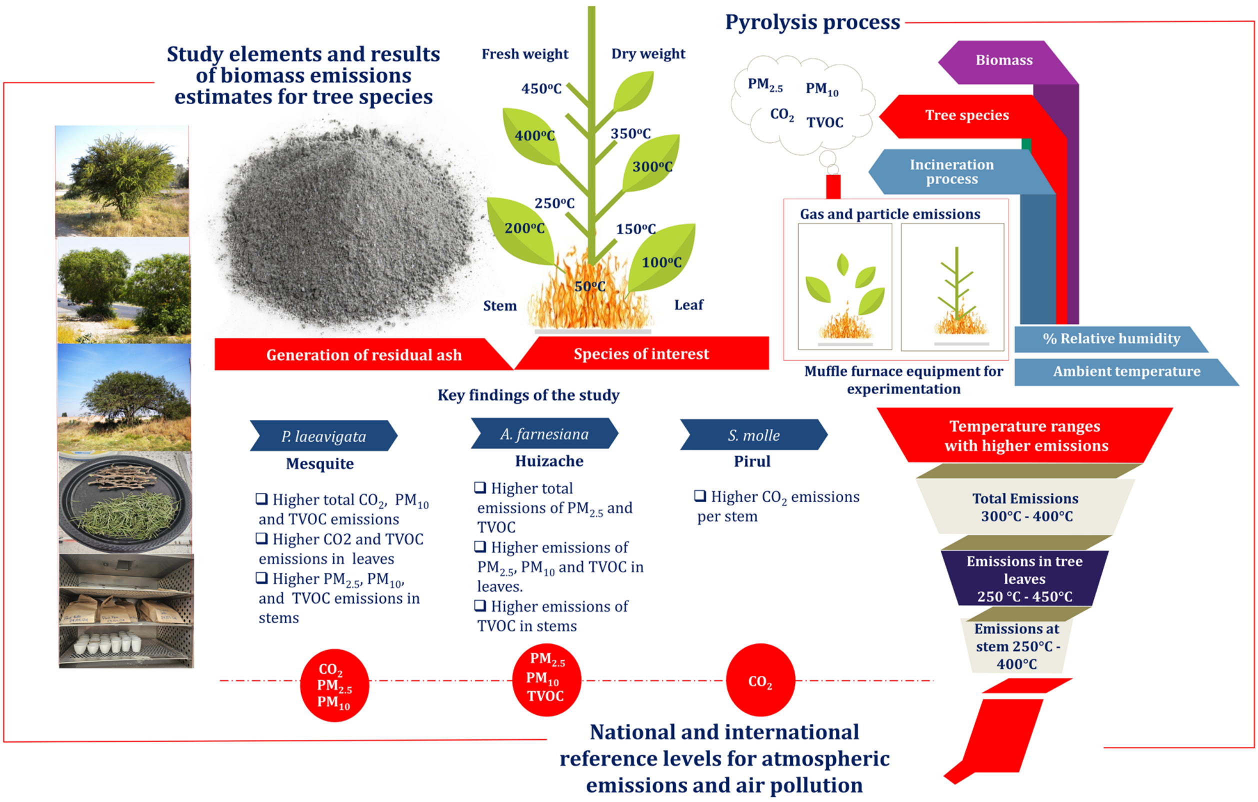


Figure 7. Summary of the main results of the study on atmospheric emissions from tree species (own elaboration).

Figura 7. Resumen de los principales resultados del estudio sobre las emisiones atmosféricas de las especies arbóreas (elaboración propia).

Conclusions

This study experimentally verified the environmental impacts of biomass burning for three tree species under a laboratory pyrolysis process. The emissions of $PM_{2.5}$, PM_{10}, CO_2, and total and specific VOCs varied between leaves and stems. This likely reflects the anatomical and physicochemical differences in the biomass that affect combustion at different incineration temperatures (50°C to 450°C). The highest $PM_{2.5}$ and PM_{10} emissions occurred in *A. farnesiana* leaves and in *P. laevigata* stems. The order of highest CO_2 emissions in leaves was *P. laevigata* > *A. farnesiana* > *S. molle*; in stems, it was *S. molle* > *A. farnesiana* > *P. laevigata*. The $PM_{2.5}$, PM_{10}, and CO_2 levels observed in this study exceeded the limits established by Mexican and international air quality regulations. CO_2 levels exceeded the technical reference for atmospheric averages (412 ppm) by 8.83 times and the average level in the study area by 8.39 times. PM_{10} exceeded the limit allowed by Mexican environmental regulations and international references (*e.g.*, the World Health Organization) by 12.74 times (maximum level) and 17.84 times the minimum level, as well as the level in the environment adjacent to the study area by 10.05 times. Similarly, the level of $PM_{2.5}$ does not exceed the permitted 24-hour maximum limit. However, with the minimum reference level, this limit is 1.50 times higher. The biomass emissions were 39.30 times higher than those measured in the area surrounding the study site. These elevated concentrations pose significant environmental risks and potential public health impacts. They can also harm ecosystems, including phytotoxic effects on plants and broader environmental degradation. Future studies should evaluate differences in residual ash quantities and compare biomass burning technologies and processes, as these differences may introduce additional environmental impacts. Experimental limitations include the need to standardize the mass of biomass and the size of samples when comparing materials such as leaves and stems. This is where variables such as fresh weight, dry weight, and moisture content are critical. To obtain more reliable results across samples, especially when comparing laboratory and field emissions, environmental conditions (temperature, humidity, wind speed, and solar radiation) and proper instrument calibration must also be considered. These results can inform assessments of the environmental impacts of using plants as an energy source and support the integration of additional environmental variables into future research and air pollution monitoring programs. Further comparisons across biomass burning sources and processes should strengthen evaluations of environmental impact considering air pollution.

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